OPTIMISING THE PERFORMANCE OF PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING (PDEC) TOWERS FOR SAUDI HOUSING:

INVESTIGATING THE IMPACT OF ARCHITECTURAL FORM

A Thesis Submitted in Accordance with the Requirements of the University of Liverpool for the Degree of Doctor of Philosophy (PhD)

by

Mohammad Abdullah Saud Alshenaifi

School of Architecture, University of Liverpool

August 2020

DECLARATION

I hereby declare that this thesis constitutes my own work/investigation, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions or writings of another.

I declare that the thesis describes original work that has not previously been presented for the award of any other degree of any institution.

Signed: Mohammad Alshenaifi

Date: August 2020

ABSTRACT

Saudi Arabia is ranked the number one oil-consuming nation in the Middle East. Buildings consume approximately 75% of the total electricity generated in Saudi Arabia, of which 44% goes to the residential sector, and air conditioning represents about 50% of the aggregate national electrical demand. To improve resource efficiency, reducing this demand by using more energy efficient cooling systems is desirable. Passive cooling techniques could be a sustainable, low-energy alternative to conventional air-conditioning systems when appropriately integrated within a building. Passive Downdraught Evaporative Cooling (PDEC) has the potential to be one of the most efficient and cost-effective passive cooling systems in the hot and arid climate of Saudi Arabia.

Despite the emergence of such passive system in the Middle East, there is still a lack of research in the region on the actual performance and applicability of PDEC systems, particularly for residential buildings. Furthermore, there is a shortage of parametric investigations about the impact on PDEC performance when a PDEC tower and a building are integrated together. Therefore, this study firstly investigated the actual performance of an existing PDEC building in Saudi Arabia. Next, a validated computer simulation model was developed of a PDEC tower. Finally, this model was applied to a typical Saudi house to study the integration of a PDEC tower in this type of buildings and to analyse the effect of architectural design on the PDEC performance.

The study was addressed in three different stages. The first stage involved field monitoring (1688 recorded hours) and assessment of an existing PDEC building in Saudi Arabia to determine its actual effectiveness. The results indicated that the PDEC towers could deliver significant cooling for library users. The temperature difference between the external dry bulb air temperature and that delivered at the bottom of the PDEC towers ranged from 6°C in the early morning to 22.5°C during the hottest parts of the days (~3.00pm). The PDEC cooling efficiency reached up to 94% during peak times. It was also revealed that the towers' effectiveness was negatively influenced by stronger wind speeds, leading to reduced tower cooling efficiency from above 90% to below 60%. The second stage included the development, modelling, and validation of an initial computational model to study the performance of a spray PDEC tower in Saudi Arabia. In the third stage, a Saudi villa was monitored and computationally modelled in order to virtually assess a PDEC tower’s performance within the house using parametric changes for each case examined. The research found that modifying the window opening design of the cooled spaces could considerably improve the cooling efficiency of the PDEC tower. The results showed that cooling energy savings increased from 22.2% in the first PDEC case to 36.2% in the optimum case.

ACKNOWLEDGEMENTS

My parents, even when I am very far from you, I always feel you are so close to me with your prayers. I attribute the success in everything in my life to you. I am so grateful to you to the last day of my life for supporting me through thick and thin.

My wife, in every step during my study, I have been inspired by you, and I am sure you will continue to inspire me in everything I will do in the future. Thank you for being such a positive force in my life, for everything you have provided me since the first day we met, and for your patience.

Professor Steve Sharples, thank you so much for being such a wonderful leader, teacher, and great supporter since our first meeting. During my study, you were more than a supervisor for me. The knowledge and experience I have gained from you are so valuable to me. This study will not have been accomplished without your support, help, and valuable knowledge.

Dr. David Chow, thank you for helping me whenever I needed you, and for listening to me generously.

To all my teachers past and present, thank you for providing the path to achieve my goals.

Thanks also to all my classmates in the PhD Program. Every great moment I have spent at University of Liverpool was great because of you.

I would also like to acknowledge Abdulrahman Al Sudairy Cultural Centre for providing full access to Dar Al-Rahmaniah library and sharing all the information and documents needed to conduct this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION TO THE RESEARCH

1.1 OVERVIEW

Global primary energy demand and global CO2 emissions have increased significantly in recent decades (see Figure 1-1 and Figure 1-2). Fossil fuels provided nearly 84% of total global energy in 2019 (BP, 2020), and global crude oil production is predicted to rise from 80 million barrels per day (b/d) in 2018 to roughly 100 million b/d in 2050 (EIA, 2019).

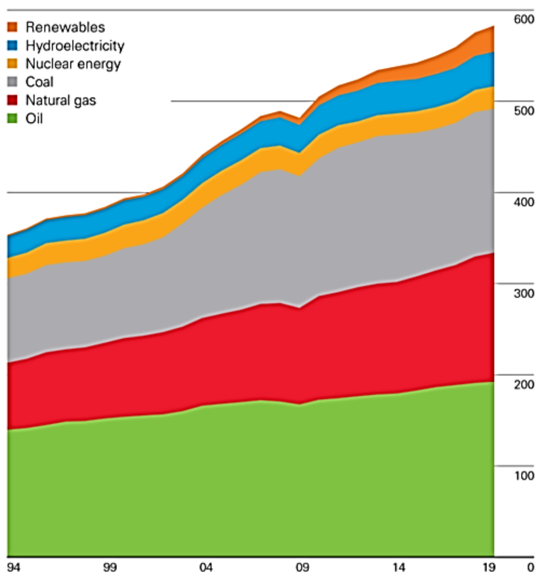


Figure 1-1: Global primary energy demand (Exajoules) 1994-2019 (BP,2020)

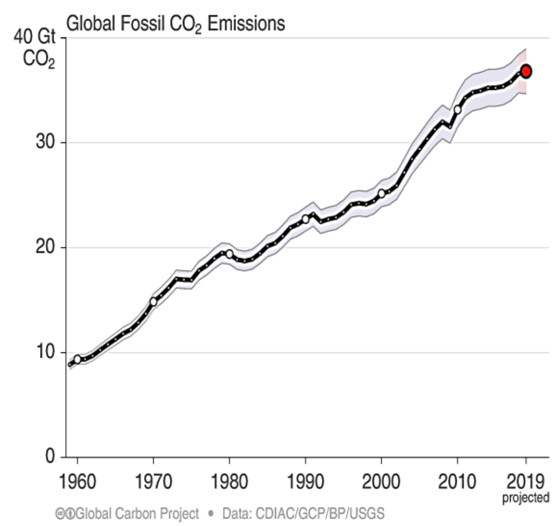


Figure 1-2: Global CO2 emissions 1960-2019 (ICOS, 2019)

Using fossil fuels to produce energy for buildings is a key contributor to greenhouse gas (GHG) emissions, which is now known to be related to global warming (Lechner, 2015; IPCC, 2019). Carbon dioxide (CO2) is the leading greenhouse gas and represents the vast majority of GHG emissions (about 65%) (EPA, 2019). When CO2 concentration grow in the atmosphere, it blocks longwave thermal radiation from being released back into space, creating warming. As CO2 builds up, it essentially causes the planet to heat up, resulting in climate change (UCS, 2018). Due to global increased energy demands, worldwide CO2 emissions rose to a historic high of 33.1 GtCO2 in 2019. This rise in emissions was instigated by the greater energy consumption seen as a result of a strong global economy, and also weather conditions in certain regions, which boosted demand for energy to be used for heating and cooling (IEA, 2018b).

More than one third of worldwide energy consumption, and almost 40% of overall CO2 emissions (both indirect and direct), are because of buildings and the building construction sectors. The demands of these industries increase due to an effort to improve energy access in developing nations, ownership and use of energy-consuming devices rising, and the expansion seen in global buildings' total floor area (Lechner, 2015; IEA, 2018b). The Energy Information Administration (2019), states that electricity use has risen at the fastest rate within the buildings sector, especially in residential buildings, due to personal income growth and widespread urban migration. Usage of electricity in the residential sector is predicted to rise by over 100% between 2018 to 2050 (EIA, 2019). It has already been noted that the majority of this energy is produced by fossil fuel sources, which release the key reason for global warming, carbon dioxide (Lechner, 2015). Cooling energy use in buildings has doubled since 2000, establishing itself as the most rapidly increasing end-use in buildings, encouraged by warmer temperatures and higher activity levels. Due to increases in income levels as well as population growth, widespread use of air conditioners (AC) is commonplace, particularly in warmer areas of the world. Specifically, AC and electric fan usage are responsible for roughly 20% of all building electricity output worldwide (IEA, 2018a). The quickly rising levels of AC use in the building industry brings numerous downsides other than energy consumption and electricity demands, such as environmental issues (e.g.CO2 emissions), and global warming. If efficiency is not improved, space cooling energy output is predicted to double by 2040, because of greater activity levels and AC use (IEA, 2018a).

1.2 ENERGY CONSUMPTION AND CO2 EMISSIONS IN SAUDI ARABIA

The crude oil production of the Organization of Petroleum Exporting Countries (OPEC) is predicted to rise from 35 million barrels per day (b/d) in 2018 to 44.5 million b/d in 2050. OPEC crude oil production is primarily based in the Middle East, and is estimated to rise by 35%, from 26.8 million b/d in 2018 to 36.1 million b/d in 2050 (EIA, 2019). Production stemming from expansive and cheap oil resources in the Middle East is a highly significant segment of worldwide crude oil supply throughout this projection period (EIA, 2019). In the Middle East, Saudi Arabia holds 16% of the world's proven oil reserves and is the leading exporter of total petroleum liquids in the world. It has the world's biggest crude oil production capacity (approximately 12 million barrels per day), predicted to have reached this capacity at the end of 2016 (EIA, 2017).

In 2016, Saudi Arabia was ranked the number one oil-consuming nation in the Middle East, and 10th in the world, with a total consumption of approximately 3.9 million b/d (EIA, 2017). From 2006 to 2018, average oil consumption increased by 7% per year (EIA, 2017; Amran *et al.*, 2020). The rapid increase in oil consumption and electricity production makes Saudi Arabia among the highest increasing rates worldwide (Amran *et al.*, 2020). The direct burn of crude oil for power generation reaches as high as 900,000 b/d, with an average of 700,000 b/d during the summer only from 2014 to 2016 (EIA, 2017). Furthermore, the nation’s oil consumption, as shown in Figure 1-3, has been increasing in the last four decades. Because of the high consumption of oil, Saudi Arabia also produced the 10th largest volume of CO_2 emissions in the world in 2016 (UCS, 2017). In fact, the CO_2 emissions level is rapidly increasing in the country in the last two decades (see Figure 1-4). Saudi Arabia has recorded one of the highest CO2 emissions per capita in 2014, at 19.4 metric tonnes per capita (World Bank, 2014). When looking at the CO_2 emissions per capita, Saudi Arabia has one of the highest emission levels, exceeding the USA and almost triple the European and UK average CO2 emissions per capita (World Bank, 2014; IEA, 2019).

With a 7% increase of its 2015 figure, Saudi Arabia produced 330.5 billion kilowatt hours (kWh) of electricity in 2016. As with numerous developing countries in the Middle East and North Africa, Saudi Arabia has to deal with a rapidly increasing power demand (EIA, 2017). This demand is instigated by rise in population, progress in the industrial sector through the development of petrochemical cities, significant demand for air conditioning in the summertime, and substantially subsidized electricity rates. Saudi Arabia's capacity for generating electricity was roughly 66 gigawatts (GW) in 2016 (EIA, 2017). The kWh per capita in Saudi Arabia is not considered efficient in relation to its population increase rate, thus requiring a plan with which to lower their per capita electricity consumption. The Kingdom had shown a 4422 kWh per capita consumption level in 1993, with this number doubling over the next two decades to 8757 kWh per capita in 2013. For 2016, the rate was 9347 kWh per capita, which dropped to 9167 kWh per capita in 2017 (Al Harbi and Csala, 2019).

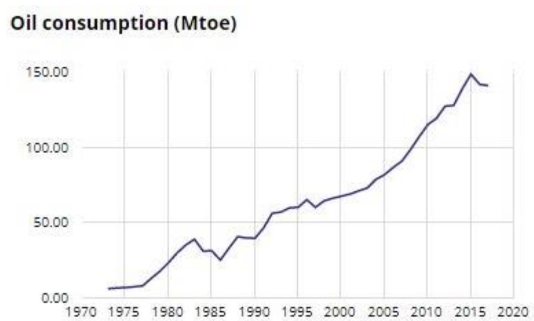


Figure 1-3: Oil consumption in SA since 1975 (IEA, 2019)

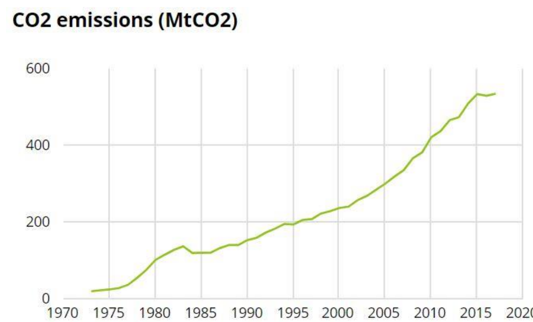


Figure 1-4: CO_2 emissions in SA since 1975 (IEA, 2019)

1.3 BUILDINGS AND ENERGY CONSUMPTION IN SA

Saudi Arabia’s Electricity and Cogeneration Regulatory Authority (ECRA) produced 289.9 GWh of electricity in 2018, over 100% greater than what was produced in 2003 (ECRA, 2018). Saudi Arabia’s electricity production is closely dependent on gas and oil capitals, with up to 240 TWh of electricity used. It is predicted that the state will consume 736 TWh by 2020 (Amran *et al.*, 2020). As a result, the nation has the Middle East's leading electric power generation expansion plan, aiming to boost generating capacity to 120 GW by 2032 in order to handle the quickly rising electricity demands (EIA, 2017).

The construction sector has also seen rapid growth, urbanization and developmental progress, which facilitated a greater standard of living for its rapidly expanding population. Due to the widespread use of AC resulting from Saudi Arabia’s hot and dry climate, the building industry has had robust energy demands, making it the leading contributor to the high energy use. Buildings in Saudi Arabia consumes approximately 75% of the total electricity generated, and air conditioning represents half of this figure (ECRA, 2018; SEEC, 2018). It is evident that buildings play a substantial role in energy consumption. According to ECRA (2018), roughly 44% of the country's total electricity consumption is by residential buildings (see Figure 1-5. Air conditioning accounts for

70% of the overall national electrical demand (SEEC, 2018). The Saudi Energy Efficiency Centre (SEEC) has stated that unsuitable building standards are to blame for the vast domestic energy use and cooling demands in the country, as nearly 70% of existing homes lack any thermal insulation (SEEC, 2018). The hot and arid climate makes Saudi Arabia's case even worse as temperatures can exceed 45°C in the summer, where the peak demand for power generation is apparent. Domestic consumption growth is encouraged by economic progress, resulting from the historically high oil-related revenues which were in place until mid-2014. Also, substantial fuel subsidies, which cost the Saudi government roughly $61 billion in 2015, have pushed demand to grow by roughly 7% per year between 2006 and 2018 (EIA, 2017; Amran *et al.*, 2020).

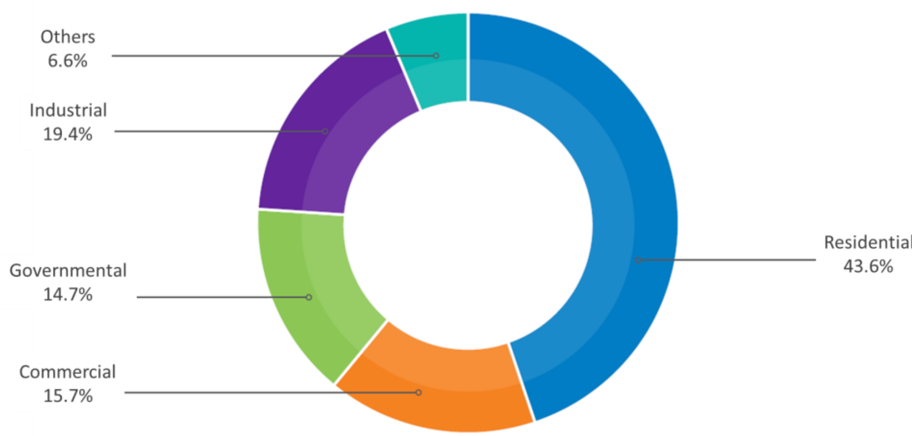


Figure 1-5: Energy use by sector in SA in 2018 (ECRA, 2018)

1.3.1 Residential Buildings Industry

The residential sector accounts for the largest proportion of electricity consumption in the country, with 44% of the total. Electricity demands in Saudi Arabia are in a period of steep increases (ECRA, 2018). A key reason for the residential sector's role in this increase in demand is its cooling needs.

Due to the rising population, economic progress, and small tariffs, electricity demand is predicted to double by 2025 in the residential sector (Alrashed and Asif, 2015). The construction permits issued by the Ministry of Municipal and Rural Affairs in 2019 show that 9 out of 10 construction permits for that year were for residential and commercial buildings, to deal with new housing demands (MOMRA, 2019). The residential sector is predicted to go through a period of growth, as the population is estimated to rise by 2.5% per year, and around 40% of the dwellings, occupied by Saudi nationals, are either rented or provided by their employer (GASTAT, 2018a). As two thirds of the population is less than 30 years old, it was suggested that there was a need for a further 2.32 million homes by 2020, to meet the population needs according to its growth rate (Alrashed and Asif, 2015). In 2017, the Ministry of Housing in Saudi Arabia provided nearly 282,000 housing options followed by approximately 300,000 housing options in 2018 for Saudi nationals (MOH, 2018). This vast development is expected to continue following one of the national long-term strategy programs, Saudi Vision 2030, to increase the ownership of houses to 70%. Therefore, housing and population demands have pushed the need for dwelling construction significantly. This type of growth will bring about more energy demand for air conditioning, subsequently carrying economic and environmental costs. In turn, energy consumption will continue to rise, as a result.

1.3.2 Sustainable Buildings Initiatives in SA

Controlling energy use in buildings has received extensive attention by researchers, architects and building engineers for many years now, due to the sector's importance in the context of worldwide energy demand (Givoni, 1994; Santamouris, 2007; Ford, Schiano-Phan and Francis, 2010; Taleb and Sharples, 2011; Lechner, 2015; Ford, Schiano-Phan and Vallejo, 2019). Energy savings allow residents to pay less for the energy they have used, while countries can sustain energy supplies through reductions or using different energy resources. From a worldwide perspective, GHG emissions are lowered. Building standards, rating systems, and energy-efficient techniques are considered to be the key methods with which to achieve energy saving in buildings.

In Saudi Arabia, the government has established a new long-term strategy for the future, Saudi Vision 2030 (*Saudi Vision 2030*, 2020). This plan was announced in late 2016, focusing on handling the future’s growing requirements. Saudi Vision 2030 is a privatization and economic reform program which involves many industries, with the intention of limiting Saudi Arabia's economic dependence on oil export revenues and government spending (Al Surf and Mostafa, 2017). The Kingdom's energy plan aims to mitigate oil spillage, lower subsidies through raising energy tariffs across the following decade, and to undertake a large-scale energy reform to appraise energy resources available. Furthermore, the Saudi government's goal is to establish more efficient electricity consumption control in the Kingdom by focusing on limiting consumption in high demand periods (Al Harbi and Csala, 2019). In particularly, the Kingdom of Saudi Arabia (KSA) intends to lower its carbon emissions by 130 million tonnes by 2030 under its Vision, through encouraging energy efficiency and the use of renewable energy technologies (Krarti, Dubey and Howarth, 2017). There have been strategic national efforts to support energy-efficient and renewable technology, and allow the manufacturing base to move away from extensive fossil fuel usage (Al-Tamimi, 2017).

To efficiently encourage the production of renewable energy, the Saudi government established the King Abdullah City for Atomic and Renewable Energy (KACARE) in 2010, with the intention of facilitating sustainable development in Saudi Arabia (Al-Tamimi, 2017). In 2018, investments were made by the administration into renewable energy sources in order to reach the projected energy consumption targets for 2035. By July 2018, the KSA government stated they planned to invest $200 billion into the production of 200 gigawatts of energy by 2030, using Concentrated Photovoltaics (PV) solar plants (Felimban *et al.*, 2019). Currently, the KSA government is giving considerable attention to the production of renewable energy, and it is their intention that 9.5 GW of generated power through renewable energy resources is achieved by 2023, fulfilling the first stage of Vision 2030 (Amran *et al.*, 2020).

Furthermore, the Saudi Energy Efficiency Centre (SEEC) was created by the Council of Ministers in 2010, with the intention of increasing rationalization awareness, boosting energy consumption efficiency, and allow for governmental and non-governmental agency collaboration to help achieve Vision 2030 (SEEC, 2018). Al-Tamimi (2017) stated that the building sector's aims are to set energy efficiency standards for air conditioners, produce home appliance specifications, and implement technical regulation of thermal insulation in buildings.

In 2018, oil spillage reduction measures were planned, along with intentions to lower subsidies by raising energy tariffs across the following decade, and undertake widespread energy reform to re-appraise available energy resources (Al Harbi and Csala, 2019).

A building's energy efficiency was not taken into account previously, as energy consumption was not high, and there was no danger from peak loads predicted. However, due to the current energy consumption situation in KSA, particularly in the residential sector, a number of scholars have noted that establishing energy standards can prove crucial in raising energy efficiency in buildings (Abdul Mujeebu and Alshamrani, 2016). To deal with the energy consumption issues brought on by the building sector, the KSA government announced royal Decree No.6927/MB, dated 1st September 2010, under which thermal insulation for all building sectors was implemented, with the intention of raising building energy efficiency through the newly required insulation (SEC, 2016). In November 2014, standard No.2856/2014 Thermal Transmittance Values for Residential Buildings was announced by the Saudi Standards Metrology and Quality Organization, which specifically describes the regulation of maximum thermal transmittance U-values for low-rise residential buildings, involving walls, roofs and window glazing (SASO, 2014). Also, the Saudi government implemented another requirement in 2014, stating that thermal insulation must be installed in new buildings' envelopes in order for the building to receive an electrical service connection with the Saudi Electricity Company (Krarti, Dubey and Howarth, 2017).

1.3.3 The Need for Alternative, Low-energy Cooling Techniques

Most energy consumption in Saudi Arabia's buildings, especially residential buildings, is because of air conditioning. The significant effort performed by the government of Saudi Arabia is expected to contribute in a declining energy demand and to provide alternative energy sources (SEEC, 2018). However, the steps considered can also provide more energy-efficient buildings and slow the increase in energy demand in the future. However, this will not stop the increase as the population and need for new dwellings grows. Reliance on active cooling would ultimately lead to continuous increases in energy consumption in the extreme hot and arid climate of Saudi Arabia. Improving AC efficiency is of great importance, due to the extensive energy use of this technology. As oil is a finite resource, and climate change agreements may reduce its usage in the future, Saudi Arabia must involve energy efficiency measures and low carbon cooling systems in their future plans. It is commonly thought that engineers design a building's heating, cooling, and lighting, but they are actually responsible for the systems and equipment required after the architect has already designed the building's heating, cooling and lighting capabilities. It is considered that the size of the mechanical and electrical equipment involved can describe the architect's level of success in this regard. There have been numerous strategies used to cool buildings in hot climates using vernacular architecture approaches, including internal courtyards and ponds, occasionally alongside stack ventilation (wind towers) to help encourage air movement for the production of evaporative cooling. Contemporary approaches have progressed these vernacular practices in order to provide passive cooling, through the use of an environmental heat sink (Givoni, 1994). In turn, different solutions must be thought of in order to further shift from active to passive cooling, as the latter uses extremely little, or even zero energy. Passive cooling techniques involved in the cooling of buildings exploit natural heat sinks, for example the ground, sky, ambient air and water. Numerous passive cooling techniques are used in various climate conditions, depending on what natural energy sources are available, such as cooling with ventilation, radiant cooling, evaporative cooling and earth cooling (Givoni, 1994; Lechner, 2015). An increased level of attention has been given to integrating passive cooling strategies in buildings in order to lower cooling loads while still providing acceptable indoor thermal comfort (further discussed in CHAPTER 2). Due to the climate-dependency of passive cooling methods, there is always concerns associated with their applicability to specific climates or climatic conditions, which leads to investigating them before considering them as a cooling method for a specific climate or building.

1.4 RESEARCH PROBLEM

It has already been noted that the yearly electricity consumption and CO2 emissions in Saudi Arabia have risen over the previous 20 years as a result of robust population growth and limited electricity tariffs (EIA, 2017; Al Harbi and Csala, 2019; IEA, 2019). Residential buildings use a very large amount of electrical energy, and air conditioning account for almost 70% of all consumed energy (SEEC, 2018). The country's hot climate necessitates this usage for many people, thus leading to high levels of energy consumption and CO_2 emissions per capita. It is predicted that cooling energy consumption is set to rise in line with the increasing housing demand and population growth, requiring even more mechanical air conditioning. Thus, these are matters requiring great attention, underlining the importance of the current study to investigate the viability and applicability of passive cooling. Passive cooling techniques could be a sustainable alternative to conventional air-conditioning systems when appropriately integrated within a building. A Passive Downdraught Evaporative Cooling (PDEC) tower is considered one of the most efficient and cost-effective passive cooling techniques in hot arid climates (Ford, Schiano-Phan and Francis, 2010). It basically relies on the exploitation of evaporation process between air and water as a heat transfer approach to cool the external air passively as it enters a building. This passive technique is normally hosted in a tower or a shaft that is used to deliver evaporatively cooled air to adjacent space/s. Evaporative cooling is most often linked with dry climates, characterized by wet-bulb temperatures (WBT) lower than 22^{o}C (Givoni, 1994). This indicates an opportunity for successful application of PDEC in the hot dry climate of Saudi Arabia with its typically low WBT.

A number of recent applications and assessment studies have been reported around the world. However, according to the researcher’s best knowledge, there is still limited recent applications and reported studies indicating the performance and applicability of such passive cooling method in the Middle East, despite the emergence of this technique in this region. The dry climatic conditions of Saudi Arabia might indicate a successful application of PDEC. Nevertheless, the assurance of successful application requires deep understanding and detailed study of an actual PDEC tower in the Saudi context. Furthermore, most of the previous applications of the PDEC systems were reported in non-domestic buildings. PDEC has demonstrated its viability, both technically and commercially, with respect to non-domestic buildings. However, there is lack of research that assesses the potential applicability of such passive cooling technique in domestic buildings. According to the researcher’s best knowledge, there is little reported in the literature relevant to residential buildings (Ford, 2012). As a result, the performance and applicability of the PDEC system in the extremely hot dry climate of Saudi Arabia, as well as its applicability to domestic buildings, are two key problems worthy of investigation prior to introducing this passive cooling technique as a solution of the high cooling energy demand problems in Saudi Arabia.

1.5 RESEARCH QUESTIONS

The critical problems, which are associated with the high energy consumption and CO_2 emissions, facing the country provided a clear indication of the important of this study. Furthermore, the suggestion of passive alternative cooling methods raised several research questions:

1. What are the possible cooling efficiency and thermal performance of an existing PDEC tower in the extreme hot arid climate of Saudi Arabia?
2. How will the architectural design of a space coupled to a PDEC tower affect the performance of the PDEC tower?
3. How much cooling energy reduction could be achieved by applying a PDEC tower to a typical Saudi dwelling?
4. How will the PDEC efficiency and thermal performance be improved by altering the architectural design of coupled spaces' openings?

1.6 RESEARCH AIMS AND OBJECTIVES

This study is conducted to achieve two linked aims. Firstly, to investigate the effectiveness of an actual PDEC system in a real building in the extremely hot dry climate of Saudi Arabia. Secondly, to study the applicability of a PDEC tower in a typical Saudi villa, and to investigate the impact of the architectural design of the cooled space openings on the performance of the PDEC. The ultimate purpose of the research is to maximise the performance of the PDEC tower in a Saudi house by improving the architectural design of the coupled building openings to act as one integrated design. The research aims will be achieved through the following objectives:

1. To study and assess the cooling efficiency and thermal comfort performance of an actual PDEC tower in a real building in Saudi Arabia.
2. To investigate the impact of the architectural design of a space linked to a PDEC tower on the performance of a PDEC tower.
3. To determine the base case energy consumption of a typical Saudi house during the summer months.
4. To assess the potential cooling energy saving by integrating a PDEC tower to a typical Saudi villa.
5. To study the possibility of improving the PDEC efficiency and thermal comfort performance through altering the architectural design of the linked spaces' openings.

1.7 GENERAL RESEARCH METHODOLOGY

For the purpose of this research, a PDEC tower was investigated as a passive alternative to conventional air-conditioning. In order to achieve the research goals, the research process was substantially addressed in three main stages (Figure 1-6). Each research stage aimed to achieve part of the research objectives and ultimately accomplishing the research aim. The first stage involved the monitoring and assessment of an existing PDEC building in Saudi Arabia that was conducted in order to determine the applicability of such passive technique in the hot arid climate of Saudi Arabia. The second stage included an initial computational model to study the performance of a spray PDEC tower in Saudi Arabia and how architectural form and wind speed/direction can affect the performance of the PDEC tower. IES VE software was selected as it can conduct a dynamic thermal simulation for PDEC systems. The results were analysed and linked to the results from the first stage. In the third stage, a Saudi house was monitored and computationally modelled in order to integrate a PDEC tower within the house. The finding in stage one and two were taken into account when performing stage three. Below is a brief description of the three main stages of the research.

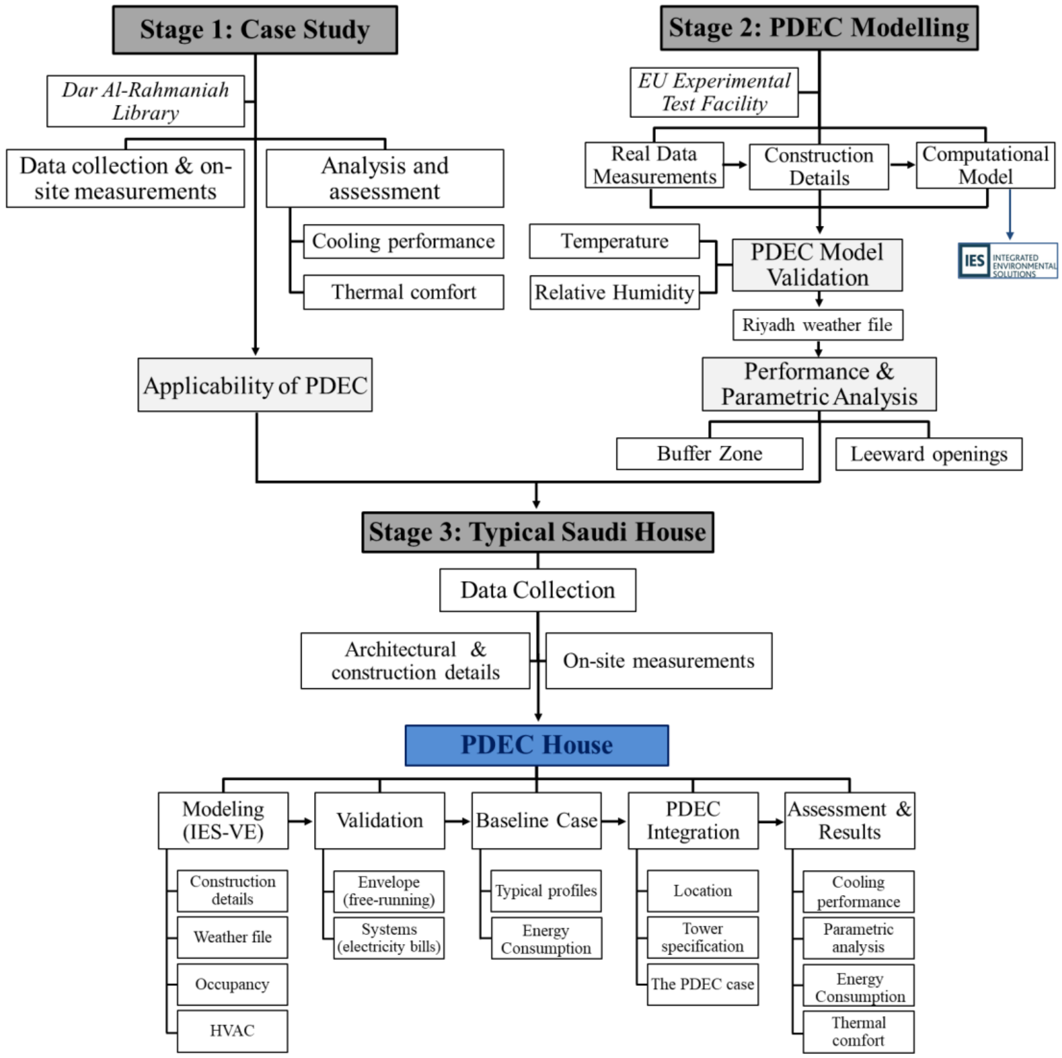


Figure 1-6: General methodology of the three research stages

1.7.1 *First Stage: The Case Study of Dar Al-Rahmaniah Library*

In this stage, a PDEC system in a small public library, Dar Al-Rahmaniah, located in Riyadh province, central Saudi Arabia, was monitored during the summer of 2018. The library has two PDEC towers, with clerestory openings in the roof to exhaust the stale air. A range of data loggers was installed in the case study building to collect data. Different types of data loggers were used to record various parameters inside and outside the towers and the building. The case study provided detailed information about the performance and applicability of the PDEC tower in the climate of Saudi Arabia. The monitoring and analysis process is briefly described below.

- **Data-loggers installation:** several data-loggers were installed including a mini weather station outside, and several other data-loggers within the towers and the occupied spaces.
- **Data Collection:** various external and internal parameters were recorded, including external and internal DBT, WBT, and relative humidity, tower air velocity, and external wind speed and wind directions.

Based on the collected data, the analysis was carried out in two main sections. The first section included an assessment of the performance of the PDEC towers under various weather conditions while the second section was performed to analyse the thermal comfort within the occupied space using two different thermal comfort models.

- **Data analysis:** Based on the measurements, a parametric analysis of the wind effects was conducted by grouping wind data in to ranges of wind speed and direction and then correlating them against environmental conditions in the library. the analysis aims to understand the influence of different wind conditions on the performance of the PDEC towers.
- ***Thermal comfort:*** A thermal comfort analysis investigated the acceptability limits of indoor temperature using both the adaptive thermal comfort model and the PMV model.

The work of this stage aimed to achieve the following research objectives:

- To study and assess the cooling efficiency and thermal comfort performance of an actual PDEC tower in a real building in Saudi Arabia.
- To investigate the impact of architectural design of a space linked to a PDEC tower on the performance of a PDEC tower.

1.7.2 Second Stage: Development and Validation of a PDEC Model

The second stage was basically an initial computational study before moving to the third stage. It included an initial computational model of a PDEC tower coupled to a single storey room. A current weather file of Riyadh was produced from the commercial software package Meteonorm. The analysis aimed to investigate the effect of the coupled building on the performance of the PDEC tower. The results were analysed and linked to the results from the first stage. The analysis of this stage is outlined below.

- **Simulation tool:** IES VE software was selected for the study as it can simulate PDEC systems that use misting nozzles and changeable cooling efficiency rates.
- **Model description:** A PDEC tower was located centrally and internally against the rear north wall of a single-storey room connected to the tower. The model applied the typical construction details followed in Saudi Arabia.
- **Model validation:** To check that the IES model had been configured correctly, the PDEC model was tested against experimental data derived from a European Union (EU) PDEC project. The model of the experimental test facility was created in IES VE. All the building details and opening profiles were considered when running the simulation.
- **Results and analysis:** based on the simulation results, it was necessary to study the impact of different wind conditions on the PDEC performance. Two different weather scenarios were tested in the simulation: a very hot calm day, and a slightly cooler windy day. Furthermore, the development of the architectural elements of coupled building was introduced and examined in order to improve the PDEC performance.

This stage was performed to address the following research objectives:

- To investigate the impact of the architectural design of a space linked to a PDEC tower on the performance of a PDEC tower.
- To study the possibility of improving the PDEC efficiency and thermal comfort performance through altering the architectural design of the linked spaces' openings.

1.7.3 Third Stage: PDEC Performance in a Saudi Villa

This represents the final stage, where the performance and applicability of a PDEC tower was investigated in a Saudi dwelling. In this stage, the previous findings in stages one and two were brought together to study the integration of a PDEC tower in an existing typical

Saudi villa. An existing Saudi villa was modelled in IES-VE after the analysis of the PDEC performance in stages one and two. The Saudi villa was initially monitored in the summer of 2018, along with the PDEC building in stage one. The monitoring and analysis process is briefly described below.

- **Data-loggers installation:** several data-loggers were installed including a mini weather station outside and several other data-loggers within the main occupied spaces in the house.
- **Data Collection:** Hourly external and internal parameters were recorded, including external and internal DBT, WBT, and relative humidity.
- **Model validation:** The building details and monitoring data of the villa were used to model and validate the villa in IES-VE. A PDEC tower was incorporated into the villa model to continue the research analysis. The validation of the model was conducted in two steps. The first step was during a free-running mode to achieve a temperature calibration of the villa. The second step was performed by using the existing occupant profiles to calibrate the model against the electricity bills obtained from the Saudi Electricity Company to assure the validity of the systems.
- **Baseline case:** a typical Saudi family profile obtained from a previous survey study was then applied to create a baseline case model.
- **PDEC integrations:** A PDEC tower was then virtually incorporated into the villa model to continue the research analysis.
- **Results and analysis:** the PDEC performance was examined as well as several developed cases to maximise the PDEC tower. Moreover, energy consumption and thermal comfort levels were also studied.

This stage was conducted to address the following research objectives:

- To investigate the impact of the architectural design of a space linked to a PDEC tower on the performance of a PDEC tower.
- To determine the base case energy consumption of a typical Saudi house during the summer months.

- To assess the potential cooling energy saving by integrating a PDEC tower to a typical Saudi villa and.
- To study the possibility of improving the PDEC efficiency and thermal comfort performance through altering the architectural design of the linked spaces' openings.

1.8 THESIS STRUCTURE

The thesis has been structured into seven chapters, as follows:

- **Chapter 1** introduces the significance of increasing energy consumption, particularly in the hot, dry climate of Saudi Arabia, due to the growing use of air conditioning, and the risk associated with this rapid expansion. It also highlights the need for developing alternative, low-energy cooling methods such as passive cooling techniques and, in particular, Passive Downdraught Evaporative Cooling (PDEC) towers to face the growing demand for cooling energy. In addition, this chapter outlines the research aim, objectives, and questions, as well as a general research methodology of the study.
- **Chapter 2** presents an introduction and overview of the concept of passive cooling, as well as a literature review of the main principles of different passive cooling strategies. The chapter also highlights the possible appropriate methods with a higher cooling performance for hot, dry climates, particularly PDEC towers, thereby becoming most appropriate for addressing the increasing need for providing cooling energy in the hot, dry climate of Saudi Arabia.
- **Chapter 3** consist of the background literature needed to project and develop this study. This chapter seeks to describe five key areas particularly relevant to PDEC technology. The first provides an overview of the PDEC system and the physical principles of the evaporative cooling process. The second describes the classification and different applications of the PDEC system. It also explains the different design geometries and airflow strategies found in the recent application of the system. It subsequently discusses the methods and recent contributions of

previous studies on PDEC techniques and finds out the possible opportunities for further investigations and developments. The final part describes the advantages and disadvantage associated with the PDEC system and the potential applicability in the climate context of Saudi Arabia.

- **Chapter 4** discusses the work conducted in the first stage of this research. It demonstrates the monitoring, assessment, and results of the thermal performance of an existing PDEC building in Saudi Arabia.
- **Chapter 5** presents the work achieved during the second stage. The chapter includes the development and validation of a virtual model of a PDEC tower. Moreover, initial computational evaluation and further the performance enhancement of the PDEC tower in the Saudi hot arid climate are presented.
- **Chapter 6** introduces the first part of stage three (inputs). The chapter presents the monitoring process and computational modelling and validation of an existing typical Saudi house. It describes the modelling process in detail, including weather file, architectural and construction details, systems, and profiles. The base case energy consumption of a typical Saudi villa is determined in this chapter.
- **Chapter 7** discusses the second part and the main research aspects of stage three (outputs). It demonstrates the virtual integration and analysis of the PDEC tower in the house, followed by additional examinations of developed cases to maximise the PDEC tower efficiency. Comparison between the different cases is discussed. Finally, energy consumption and thermal comfort analysis are discussed in this chapter.
- **Chapter 8** summarises the work and key research findings of this research. The research questions are answered. Finally, it outlines sets of recommendations and opportunities for future work.

CHAPTER 2. LITERATURE REVIEW

2.1 INTRODUCTION

In the majority of developing countries that have hot climates, buildings tend to be constructed in a significantly energy wasteful manner. In such buildings, the interiors have to be air-conditioned to ensure thermally comfortable conditions. This leads to significant financial expenditure for installing and operating the plant that generates the electricity required to cope with the substantial summer cooling demand (Batty, Al-Hinai and Probert, 1991). Today, space conditioning in executed in the majority of the world, using air conditioners that are conventional and based on vapour compression refrigeration that need a considerable amount of high grade electrical energy to function (Jani, Mishra and Sahoo, 2016). Buildings tend to have high energy consumption which will probably increase with the rising global population, rapid industrialization, and improved standards of living.

It is important to note that the constantly increasing demand for building construction results in several concerns related to supplying high grade electricity. This also leads to numerous environmental issues, such as global warming (Kamal, 2012; Jani, Mishra and Sahoo, 2016; Jani, 2019). In the past, people who lived in such hot countries resided in buildings in which thermal comfort was ensured only through natural cooling methods which were comparatively cheap. Presently, using a mechanical cooling system in the majority of the households as well as industrial applications, has led to the underutilization of natural cooling methods. Further, the growing environmental damage has resulted in increased global awareness, thus leading to the development of green energy buildings. Therefore, researchers, environmentalists, architects, and policy makers have been focusing on the ways in which energy conservation can be incorporated to buildings. Substitutes for energy sources, systems, and techniques have also been noted to fulfil a significant part of buildings' cooling requirements (Geetha and Velraj, 2012). Hence, to deal with the variable climate, passive cooling methods were accepted for reducing the energy supply necessary to ensure thermal comfort and building residents' health. An effective passive building design intends to optimally use regional environmental conditions.

This chapter examines different passive cooling techniques that provide economic as well as energy-efficient cooling methods, thereby becoming most appropriate for addressing the increasing need to provide low carbon cooling energy. In addition, climate analysis is discussed to determine the potential applicability of passive downdraught evaporative cooling (PDEC) technique in Saudi climate.

2.2 PASSIVE COOLING STRATEGIES - PRINCIPLES & TECHNIQUES

In terms of environmental design, the passive techniques for cooling generally follow a framework involving three steps. First is preventing or reducing heat, or protecting against heat gains; second is altering or modifying heat gains; and third is dissipating heat, or removing internal heat (Antinucci *et al.*, 1992; Santamouris and Asimakopolous, 1996; Geetha and Velraj, 2012; Jani, 2019). The first step intends to reduce a building's internal heat gains, in which implementing various early design measures are involved, including landscaping, insulation, shading, and building form and design. These methods can often be applied in every climate as well as for many site conditions whilst also being implementable for all types of buildings. The second step concerns the building structure's heat storage capacity, or thermal mass. This is located in the building's walls, partitions, or floors, and is created from materials having high thermal heat capacity. Heat is absorbed in the day which then limits the range of indoor temperature changes, decreasing the maximum cooling load, as well as transferring the heat which is absorbed to its surroundings during the night. This storage capacity has a higher impact when there is an large swing in the outdoor air temperature. It is important to merge this heat storage and discharge cycle through passive cooling or heat dissipation. Avoiding and altering heat gains often fails to maintain a controlled indoor temperature. Thus, heat dissipation methods, or passive cooling techniques, address the excess heat disposal using natural means. Moreover, there are two major conditions for dissipating excess heat using passive cooling. The first is the availability of a suitable environmental heat sink to reject the heat, and the second is suitable thermal coupling as well as adequate differences in temperature to ensure the heat to transfer from indoor spaces to the sink.

The term ‘passive cooling’ describes the cooling process (technique) that is achieved by exploiting a natural environmental heat sink (Cook, 1989; Givoni, 1994). Although ‘passive cooling’ is a relatively new term, passive cooling is an age-old method implemented across the world (Givoni, 1983). Passive cooling methods can be classified into four major types based on the exploited natural heat sinks: (i) Natural ventilation, (ii) radiative cooling, (iii) ground cooling, and (iv) evaporative cooling (Givoni, 1991; Antinucci *et al.*, 1992; Santamouris and Asimakopolous, 1996; Ford, Schiano-Phan and Francis, 2010; Choudhary, Thakur and Dogne, 2014; Lechner, 2015) Table 2.1 presents the major processes involved in passive cooling.

Table 2-1: Process of heat dissipation in passive cooling techniques (Santamouris and Asimakopolous, 1996; Ford, Schiano-Phan and Vallejo, 2019)

Process	**Heat sink**	**Heat transfer mode**
Natural Ventilation	Air	Convection
Radiative cooling	Night sky	Radiation
Ground cooling	Earth	Conduction
Evaporative cooling	Water/Air	Evaporation

2.2.1 Natural Ventilation

Natural ventilation involves providing as well as removing air through ventilators or openable windows using natural forces such as temperature, wind, and pressure difference (updraught). There are two types of natural ventilation which are infiltration and controlled natural ventilation (Geetha and Velraj, 2012). While controlled natural ventilation involved intentionally dislodging air using natural forces via particular openings, including doors, windows, and ventilations, infiltration refers to uncontrolled air flow via unintentional cracks or openings. For a naturally ventilated building to be designed successfully, it is necessary to gain an in-depth understanding of its surrounding air flow patterns as well as the influence of nearby buildings. The aim here is ensuring that the indoor space is well-ventilated in a controlled manner. This relies on the wind characteristics, interior design, and window location. Airflow patterns through buildings differs based on opening design and placement, and can be categorized into three different types (Figure 2-1): single-sided ventilation, cross-ventilation, and stack ventilation (buoyancy-driven) (Geetha and Velraj, 2012; Ford, Schiano-Phan and Vallejo, 2019).

As single-sided ventilation is generally seen in single rooms, it offers local ventilation. Single-sided ventilation can be considered as the simplest airflow method because it enables the entry of cooler air at a low level while ensuring that the internal warmer air rises and exits the space through the opening's upper area (Geetha and Velraj, 2012). Compared to the other strategies, it results in lower ventilation rates, with the ventilating air entering a smaller distance into the space. The limiting depth in terms of effective ventilation tends to be approximately double the floor-to-ceiling height. Buoyancy driven exchanges can also be attained using a single opening if the opening has a feasible vertical area (CIBSE, 2005).

Cross ventilation resulting from wind takes place through ventilation openings that are on an enclosed space's opposite sides (CIBSE, 2005). This type of ventilation is efficient as air in the building is pushed as well as pulled through a positive windward side pressure and a negative leeward side pressure. The limiting depth in terms of effective ventilation for openings in two opposite façades tends to be around five times the floor to ceiling height as a rule of thumb (CIBSE, 2005). For ensuring adequate ventilation flow, it is important that the inlet wind pressure differs significantly from the outlet openings and that there is limited internal flow resistance (Geetha and Velraj, 2012). Several computational as well as field studies have observed cross-ventilation strategies being used to create acceptable and improved indoor air ventilations as well as comfort temperatures (Awbi, 1996; Raja *et al.*, 2001)

Buoyancy-driven stack ventilation depends on density variations for pulling in cool outdoor air through low ventilation openings after which an upward vertical flow path is used for exhausting the air (CIBSE, 2005; Ford, Schiano-Phan and Vallejo, 2019). Thus, there is cross-ventilation in the occupied zones as air enters and exits through opposite sides. Similar to wind-driven cross ventilation, the limit for buoyancy-driven stack ventilation is approximately five times the floor to ceiling height. Typically, an atrium or chimney is utilised for creating adequate buoyancy forces for the required flow. It should, however, be noted that the smallest wind can create pressure distributions across the building envelope which can affect the airflow (CIBSE, 2005; Geetha and Velraj, 2012).

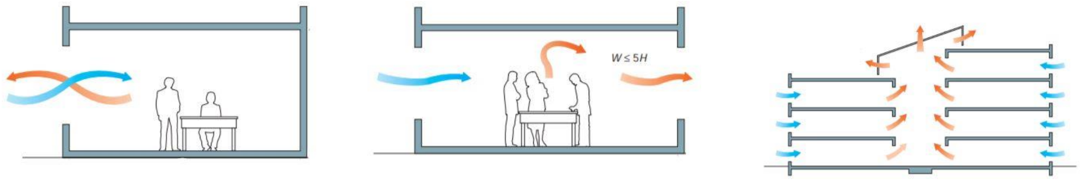


Figure 2-1: Air flow strategies from left to right: single sided, cross ventilation, stack ventilation (CIBSE, 2005)

There are two methods of attaining cooling using natural ventilation: comfort and night-flush (Givoni, 1991; Santamouris and Asimakopolous, 1996; Lechner, 2015). In comfort ventilation, outdoor air is brought in during the day as well as night. Then, this air flows over people for improving the evaporative cooling effect occurring on the skin. For using natural convection for heat removal from a space, the external air temperature must be less than the internal requirement. For example, in northern Europe, the external air temperature tends to be less than the required internal temperature, and thus, it is possible to use natural comfort ventilation in the day for eliminating unwanted heat. Such a passive cooling technique can help during some periods of the day as well as year in the majority of climates and is particularly suited for hot and humid areas with the coincident air temperature as well as relative humidity tending to cross the comfort zone. It is also noted that it is possible for air motion to help move the comfort zone and develop thermal comfort. This cooling strategy was used in Frank Lloyd Wright's Robie House in Chicago that has extremely large roof overhangs that can provide shade to walls. These walls are all created using glass doors and windows which offer cross-ventilation as they can be opened (see Figure 2-2). As Chicago is hot and humid in the summer, it was necessary to ensure good ventilation as well as full shade as cooling strategies for the house, which was built prior to the availability of air conditioning. The design enabled the expansion of the interior space towards the outdoors and yet provides a semblance of enclosure to the space (Givoni, 1991; Santamouris and Asimakopolous, 1996; Lechner, 2015).

On the other hand, night-flush ventilation cooling offers a very different effect. In areas experiencing comparatively large diurnal (daily) air temperature swing during summer, as temperatures in the night drop to less than the necessary comfort temperature threshold, it can be utilised for cooling the building (Lechner, 2015; Ford, Schiano-Phan and Vallejo, 2019). This method can help use the cool night air for flushing out the building's heat, and as the outdoor air that comes inside the building in the day is limited, the building's heat gain is also minimized. In the day, this relatively cool structure functions as a heat sink in terms of the indoor air. Such a cooling strategy is most effective in hot and dry climates as these areas have significant diurnal temperature ranges. Humid climates that only have modest diurnal temperature ranges can also benefit from this (Givoni, 1991; Lechner, 2015; Ford, Schiano-Phan and Vallejo, 2019). A recent implementation of this technique was in the Malta Stock Exchange in Malta as one of the main cooling methods in the building. At night, the cool air flushes out any residual daytime heat gains through a central atrium. This cooling approach is achieved by supplying the night's cool air via motorized dampers at a lower ground level and exhausting it through the top openings at the ridge level. Figure 2-2 shows the application of this cooling strategy in the Malta Stock Exchange (Ford, Schiano-Phan and Vallejo, 2019).

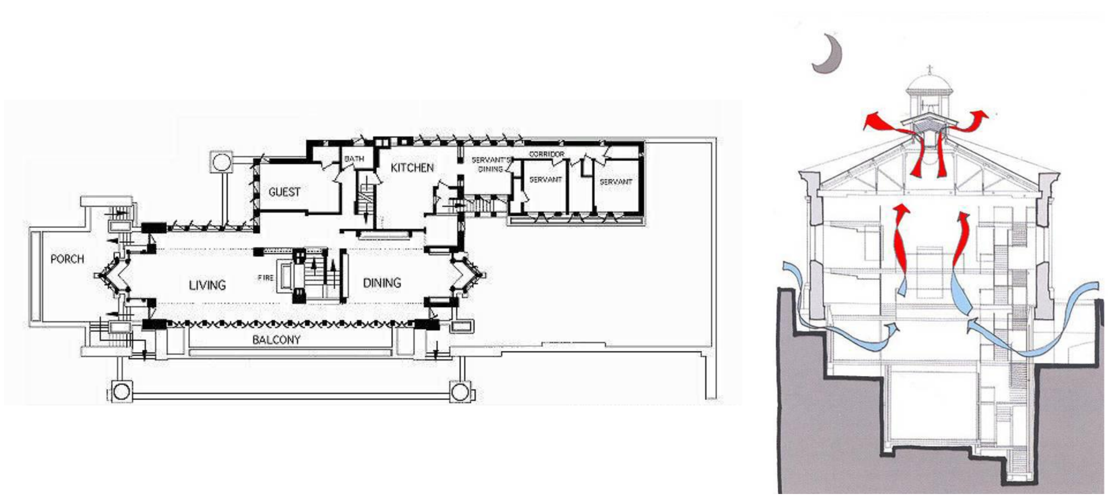
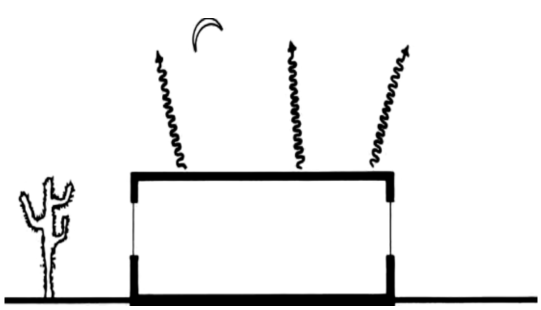


Figure 2-2: Concept of natural comfort ventilation (Left), and night-flush ventilation (Right) (Ford, Schiano-Phan and Francis, 2010; ArchDaily, 2020)

2.2.2 Radiative Cooling

A body or surface will continuously absorb and emit thermal radiant energy from or to its surroundings. As hot objects' radiant energy emissions are higher than their absorption, these objects experience a net heat loss through radiation exchanges (Lechner, 2015). The nights in hot dry regions tend to have clear skies that may create a heat sink as the amount of long-wave radiation emitted from the night's clear sky tends to be less than the long-wave radiation emitted by a building i.e. the building experiences a net cooling effect (Givoni, 1994; Lechner, 2015). Moreover, as the roof is the building element most exposed the night sky, a building roof's comparatively warm surface radiates heat to the cold upper atmosphere. It is possible for night sky radiation to go 7°C less than the cool night air (Lechner, 2015). Additionally, because the roof is used as the 'cold collector' in radiant cooling, it can only be applied to low rise buildings, particularly single storeyed buildings having flat roofs, or to cool a multi-storeyed building's top floor (Geetha and Velraj, 2012).

The roof surface is used in two forms of radiative cooling strategies, which are direct and indirect (Figure 2-3) (Santamouris and Asimakopolous, 1996). Direct radiant cooling involves a building that is designed for making the most effective use of direct radiation cooling. The building roof functions like a heat sink that absorbs the internal loads every day. The roof is the largest surface that is exposed to the night sky and thus can function as the best heat sink. Heat can be removed from the roof of a building by radiating heat to the night sky, and thus, the building structure can be cooled. This technique is used, for example, in roof ponds. In indirect radiant cooling, a fluid (water/air) is cooled by radiation to the sky. Then, a storage mass like water tank or the building structural mass is used to store the coolness. In this technique, a well-known design is using a plenum between the radiator surface and the roof of a building. Here, air is pulled into the building using the plenum, and is then cooled because of the radiator, thus cooling the entire building structure. The building's mass functions like a heat sink in the day. (Santamouris and Asimakopolous, 1996; Jani, 2019).



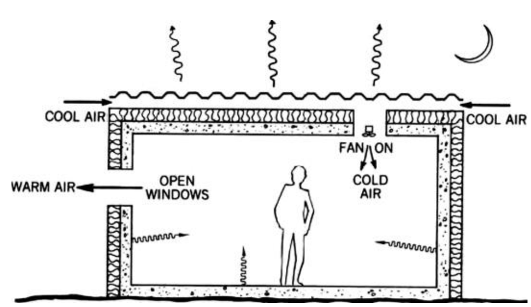


Figure 2-3: Concept of direct (left), and indirect (right) radiative cooling (Lechner, 2015)

There is also a simple technique that is used contemporarily in which water is circulated over the roof surface, which creates cooling through the night sky radiation and through evaporation occurring in the day. Stanford University's Global Ecology Centre can be considered as a case study in which this technology was applied as the primary cooling source (Figure 2-4) (Ford, Schiano-Phan and Vallejo, 2019; CBE, 2020). In this case, water was sprayed on the roof which was cooled because of the night sky evaporation/radiation, then accumulated in the gutters, and finally cleared out in an outside tank. (Ford, Schiano-Phan and Francis, 2010; Ford, Schiano-Phan and Vallejo, 2019; CBE, 2020).

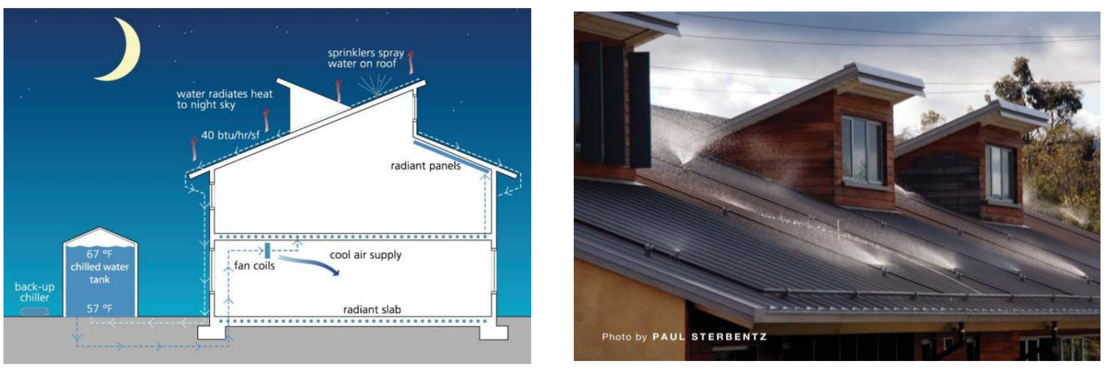


Figure 2-4: Concept of night sky radiation, the Global Ecology Centre (CBE, 2020)

2.2.3 Ground Cooling

As an increase in depth leads to a decrease in ground temperature, this means the earth can be used as a heat sink (Givoni, 1994). Ten metres below ground level, the earth's temperature tends to be overall stable and is the same as that area's yearly mean air temperature (Santamouris and Asimakopolous, 1996; Florides and Kalogirou, 2005a). Generally, earth cooling systems use the soil's consistent temperature to function as a sink/dump so that heat can be extracted and the building cooled. A building can be cooled and heated in the summer and winter, respectively, by adding air into it using a web of buried pipes or an underground labyrinth (Geetha and Velraj, 2012; Kamal, 2012; Ford, Schiano-Phan and Vallejo, 2019; Jani, 2019). Such a passive cooling strategy can be more efficient when the temperature of the earth is considerably cooler or hotter in the summer or winter, respectively, compared to the air temperature.

This technique has been successfully implemented in various buildings on a global scale. The Earth Centre Galleries in Doncaster, UK as well as Federation Square in Melbourne, Australia have recently implemented this passive cooling system, as shown in Figure 2-5 (Ten, 2020). A gallery in the Earth Centre that is buried in the earth included a massive underground air distribution as well as thermal storage system that is embedded in the centre's foundations which actively cools and warms the air supply in the summer and winter, respectively. Moreover, the Federation square's designer has created a labyrinth under a public plaza that provides air that is pre-cooled to major atrium spaces. According to the hottest month's measured data, air supply from the labyrinth does not often rise above 23°C despite external air temperatures being more than 35°C (Ford, Schiano-Phan and Vallejo, 2019).

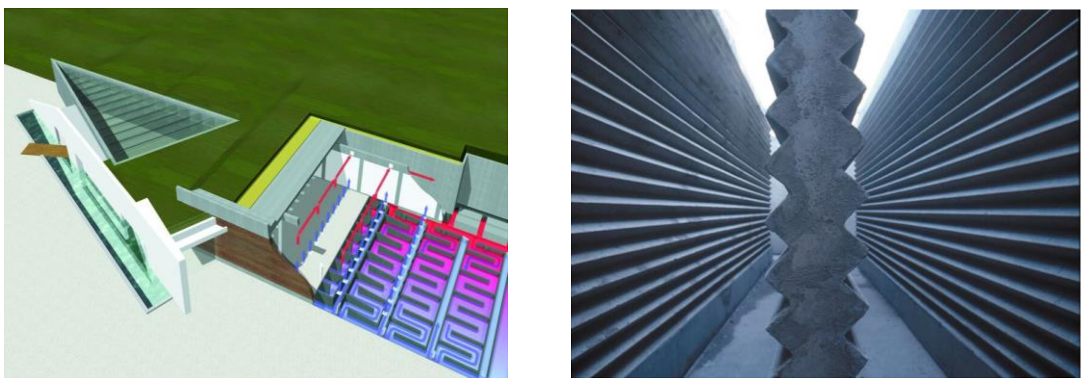


Figure 2-5: Underground labyrinth in Earth Centre Galleries (Left), and Federation Square (right) (Ten, 2020)

2.2.4 Evaporative Cooling

When evaporating, water attracts sensible heat in large amounts from its surroundings. This heat is then converted into latent heat as the water vaporises, because of which the air temperature drops (Givoni, 1995; Kang, 2011). That is, evaporative cooling concerns the transfer of heat and mass in which water evaporation is used to cool air, with heat transferred to the water from the air, thereby leading to a fall in the air temperature (Givoni, 1991, 1994; Lechner, 2015). This process can help in cooling buildings through two means. The air can be cooled as well as humidified if the water evaporates in the building or fresh-air intake, which is known as direct evaporative cooling. However, the building or indoor air being cooled through evaporation without the indoor air getting humidified is known as indirect evaporative cooling (Chan, Riffat and Zhu, 2010; Cuce and Riffat, 2016).

Sensible as well as latent heat transfer are both part of the direct evaporative cooling process. While sensible heat only impacts the temperature, latent heat only impacts the mixture's moisture level. When there is a combination of air and water, both their temperatures are increased or decreased because of sensible heat flow. Further, latent heat leads to water vapour getting transferred into the air because of evaporation, and hence there are changes in the temperature as well as moisture content of this air and water combination (Kang, 2011).

An evaporative cooling process involves the dry bulb temperature (DBT) getting lowered while the water content is increased with a wet bulb temperature (WBT) that remains constant. The wet bulb temperature depression (WBD) defines the difference between the ambient DBT and WBT (Givoni, 1994). The cooling efficiency of an evaporative cooling system is identified by the percentage of reduction in WBD. As a result, the WBT is the most important parameter when considering an evaporative cooling system. Amer (2006) observed that, in certain passive cooling systems, the best cooling effect that was gained from evaporative cooling lowered the inside air temperature by 9.6°C (Amer, 2006). Moreover, in hot dry regions, passive evaporative cooling is regarded as an efficient passive cooling strategy that can function as a substitute for active mechanical cooling (Givoni, 1994; Ford *et al.*, 1998).

The passive evaporative cooling technique was recently implemented in the Federal Courthouse in Phoenix, Arizona (Ford, Schiano-Phan and Francis, 2010). The courthouse includes a six-storey office block as well as a six-storey atrium. A Passive Downdraught Evaporative (PDEC) cooling system was used in the atrium on the top of the roof for cooling the massive space (Figure 2-6). It reduces the overall air-conditiong electricity costs by 75%. Moreover, 2007 spot measurements showed that the temperature in the atrium was 7^{o}C below that outside (Ford, Schiano-Phan and Francis, 2010).

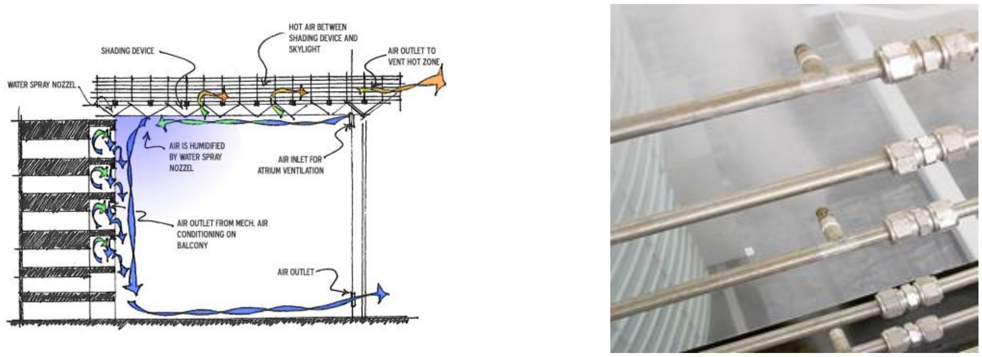


Figure 2-6: The cooling strategy and the PDEC system in the Fedral Courthouse, Arizona
(Ford, Schiano-Phan and Francis, 2010).

2.3 METHODS AND TECHNIQUES OF EVAPORATIVE COOLING

There are three major types of evaporative cooling. The first is direct evaporative cooling where the working fluids (water and air) have direct contact; the second is indirect evaporative cooling where the working fluids are separated by a surface/plate, and the third is a combined system involving direct as well as indirect evaporative cooling (Amer, Boukhanouf and Ibrahim, 2015; Lechner, 2015; Cuce and Riffat, 2016).

2.3.1 Direct Evaporative Cooling (DEC)

Direct evaporative cooling refers to a popular, simple and well-established cooling technology in which both fluids have direct contact with one another throughout the process of evaporative cooling (Batty, Al-Hinai and Probert, 1991). Here, the evaporation of water humidifies the air and reduces the temperature while increasing humidity. The air's WBT is the air's lowest possible temperature beside the evaporative cooling system. Hence, it can be applied in hot dry climates, such as the climate of Saudi Arabia, because of the significant difference between the DBT and WBT. In the case of the process involving no external heat, the air's sensible heat is placed into the water and this heat turns into latent heat after it evaporates the water. The sensible heat getting transformed into latent heat is green net heat conversion and is adiabatic saturation, which controls the majority of the direct evaporative air cooling processes (Kang, 2011). It should be noted that, in desert regions which are arid in the hot period and have extremely low humidity in terms of comfort, the direct evaporative cooling may be considered as a cost-effective and physiologically desirable method (Givoni, 1994). Givoni suggested that direct evaporative cooling is applicable where maximum WBT and DBT are 24°C and 44°C respectively (Givoni, 1991). This technique is commonly implemented in hot arid regions through a wind tower, recently known as Passive Downdraught Evaporative cooling towers (PDEC tower), as shown previously in Figure 2-6 (Cunningham and Thompson, 1986; Bowman. *et al.*, 1997; Ford, 2002).

The wind tower, or wind catcher, can be regarded as a traditional passive cooling method for buildings that was used in Iran and the Middle East centuries ago (Bahadori, 1979, 1994). This process involves a capped tower that has either a one face opening or it can have multi-face openings on top of the tower, and this tower is located on a dwelling's roof. In wind towers, the air flow enters at the top of the tower, flowing through the tower into the building to provide fresh air. There are also various ways in which water is added to the tower geometry such as water-filled porous jars placed in the tower airstream, a water pool at the bottom of the tower, or a spray or wetted pads (PDEC) system that are hung on the top of the tower (Bahadori, 1994; Amer, Boukhanouf and Ibrahim, 2015).

PDEC cooling can help reduce the air temperature by 70–80% of the WBD, and can thus be considered to have the potential to provide considerable cooling in hot arid areas (Bowman. et al., 1997). A major advantage of such applications is the substantial energy savings they ensure. Adding outside air which then moves within the space inside significantly enhances thermal comfort as well as the air quality of any space (Givoni, 1994; Bowman. *et al.*, 1997; Ford, 2002; De Melo and Guedes, 2006).

2.3.2 Indirect Evaporative Cooling (IEC)

Compared to direct evaporative cooling, there is less use of indirect evaporative cooling. Not only does this process provide significantly lower cooling performance but it also needs extra heat exchangers so that humidity is not added to the relevant air stream (Kang, 2011; Cuce and Riffat, 2016). In an indirect evaporative cooler, evaporation is used in a secondary stream, after which heat is exchanged between the primary air stream and secondary air stream for ensuring cooling with no moisture being added to the primary air stream. Indirect evaporative cooling has been implemented in water ponds as well as in roof spray cooling systems. This process can serve as a substitute for direct evaporative cooling in hot and humid areas (Amer, Boukhanouf and Ibrahim, 2015; Cuce and Riffat, 2016).

2.3.3 *Direct/Indirect Evaporative Cooling (two-stage evaporative cooling)*

Two-stage evaporative cooling combines direct evaporative cooling with indirect evaporative cooling. Such systems are utilised in the case of dry-bulb temperatures being below that attained through a single-stage system. A two-stage evaporative system involves an indirect evaporative cooler as the first stage while a direct evaporative cooler is implemented in the second stage (Al-Hassawi, 2020). The indirect evaporative cooler is used to cool the air sensibly until a given point is reached. As there are no changes in the air's water content, this air moves on to the second stage and reaches a cooler point because of the Direct Evaporative Cooling process. This can be referred to as a constant wet bulb temperature process. Such a combined effort of the direct and indirect evaporative cooling methods leads to lower dry bulb temperatures compared to that in a single stage (Al-Hassawi, 2017, 2020).

2.4 CLIMATIC APPLICABILITY OF PDEC IN SAUDI ARABIA

Ambient environmental parameters (DBT, WBT, relative humidity, wind speed, and wind direction) represent key considerations for passive cooling design. As PDEC is one such climatic dependent, passive cooling technique, it is significant to consider the location and climatic conditions to determine its applicability. According to the Koppen-Geiger climate type map (shown in Figure 2-7), the climate of Saudi Arabia is generally classified as hot and arid (BWh) (Peel, Finlayson and McMahon, 2007). Except for parts of the coastal regions in Saudi Arabia, which are humid, the hot and dry conditions covers the majority of the country. For instance, Riyadh, the capital city of the Kingdom, was initially viewed to determine the applicability of the PDEC tower in Saudi Arabia as it represents the largest region with the highest population in the country with a hot and dry climate. Riyadh, latitude 24.65°N, is located in the central region of Saudi Arabia. The winter season is considered cold. However, the overall weather is hot and dry most of the year.

The current weather file of Riyadh was produced from Meteonorm software in the EnergyPlus Weather (*.epw) format. Meteonorm is a commercial weather reference tool that has weather data for thousands of location around the world (Meteonorm, 2019a). The recent version of the software Climate Consultant 6.0 was initially used to conduct a climatic analysis of the region (Climate Consultant, 2019a) Climate Consultant is a weather tool developed by the UCLA Energy Design Tool Group. It is based on the theoretical investigations by Baruch Givoni and Kenneth Labs. Climate Consultant reads regional climatic data in EPW format and displays multiple variations of graphic charts indicating a variety of weather parameters. It can determine the most appropriate set of passive design strategies via a display on a Psychrometric Chart for the chosen weather area (Climate Consultant, 2019a).

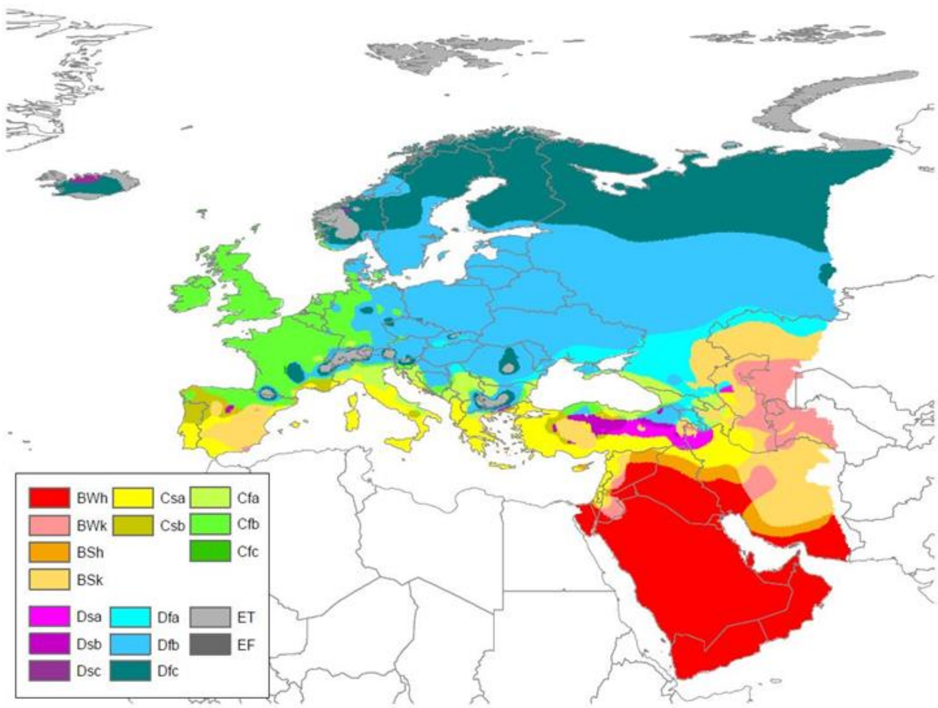


Figure 2-7: Koppen-Geiger Climate Type Map for the region (Peel, Finlayson and McMahon, 2007)

As mentioned previously, the climate of Riyadh is very hot and dry during the summer (May-September). External DBT exceeds 46°C and WBT is normally below 23°C from June to August. The average DBT and WBT is 36.5°C and 18.8°C, respectively. The daytime relative humidity is below 20% during the same period. The low humidity levels reflect the large difference between the DBT and WBT. The prevailing wind direction during the summer season is north and north-west. The average wind speed is approximately 3.5m/s with a peak wind speed of around 12m/s. Although all the ambient weather conditions can affect the performance of a PDEC tower, it is evident that the WBT is the most important parameter to determine the viability of a PDEC tower. The hourly data of the EPW file were plotted on a psychrometric chart generated by Climate Consultant and shown in Figure 2-8 below. The plotted data reveal that passive evaporative cooling could theoretically achieve comfort conditions for approximately 78% of the summer period. Based on the previous weather data, a higher reduction in ambient DBT is achievable in Riyadh. The potential higher evaporation rates occur because of the significant difference between ambient DBT and WBT, thus a higher percentage of reduction in wet-bulb depression WBD (higher cooling efficiency).

Due to the climatic dependency of the PDEC tower, determining prevailing wind direction and wind speed is also necessary to identify opportunities and constraints. Design strategies for the windcatcher and associated building need to take variations in wind pressure, speed and direction around the building into consideration.

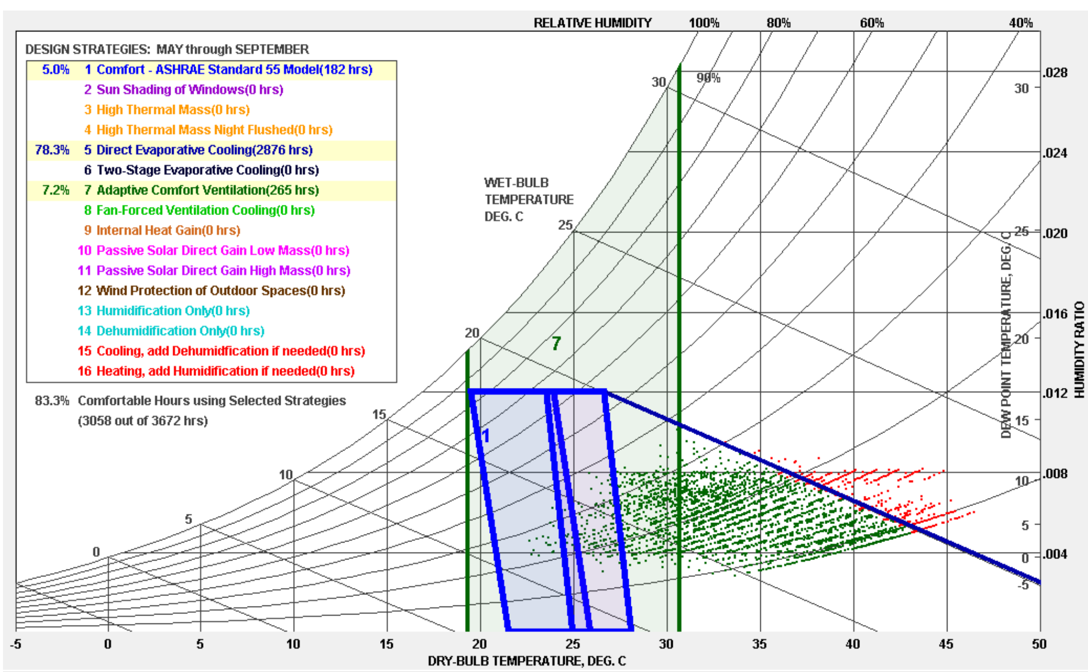


Figure 2-8: Psychrometric chart of Riyadh

2.4.1 Water and Evaporative Cooling

Water is as significant a resource as energy, particularly in environments where PDEC is mostly applicable i.e. hot and arid climates. Hence, care must be taken to manage water consumption in such a passive system. In Saudi Arabia, domestic water comes from different sources around the country. Underground water represents more than 80% of the water used in the country for domestic and agricultural use (GASTAT, 2018b). This water is generally kept in reservoirs and conveyed to domestic areas by sloped pipes (gravity force). Desalinated water in Saudi Arabia accounts for a considerable part of the produced water. It is known that desalinating water can consume a significant amount of energy. However, this water resource is mostly used in the coastal regions of Saudi Arabia, where PDEC may not be applicable due to high humidity levels (SWCC, 2017). In addition, the energy produced in Saudi Arabia is mostly used for power generation, as discussed previously in CHAPTER 1 (ECRA, 2018).

In addition, advances in PDEC systems have shown development in PDEC efficiency with less water consumption. These developed techniques are discussed in CHAPTER 3. Typical water consumption for a single nozzle in a spray system is 5 l/h at 30 micron droplet size if the PDEC is running continuously (Ford, Schiano-Phan and Francis, 2010; Ford, Schiano-Phan and Vallejo, 2019). The development in spray (misting) nozzles resulted in a novel design that was installed in a prototype house built for the 2010 Solar Decathlon Europe event in Madrid. Eight nozzles were installed in the house. The design and application of such an advanced spray system showed low water consumption with a peak of 8 l/h if run continuously (Ford *et al.*, 2012; Salmerón *et al.*, 2012).

Moreover, an experimental study conducted by Givoni (1997) introduced the possibility of using seawater to overcome the limitation of the availability of water in a hot dry climate (Givoni, 1997). Other computational studies conducted by Kang (2011) and Kang and Strand (2016) revealed a significant reduction in ambient temperature with significantly less water consumption is achievable with smaller water droplet sizes (Kang, 2011; Kang and Strand, 2016).

It should also be noted that the heat transfer between the air and water reduces the ambient air temperature regardless of the water temperature. The evaporation of the water occurs as sensible heat of the ambient air is converted into latent heat in the vapour state of the water, and the air temperature decreases as the relative humidity level increases following an adiabatic process (WBT remains constant). As a result, the relatively higher water temperatures in the hot arid region would not become a major problem when considering a PDEC system for cooling. This is further explained in section 3.3 in CHAPTER 3.

Ultimately, despite the importance of studying water consumption when considering such passive cooling systems, this study mainly focused on investigating the actual performance of PDEC and its applicability to the domestic building in order to reduce energy consumption for cooling. Hence, issues associated with water consumption are suggested to be valuable opportunities for future studies in the field.

2.5 CONCLUSION

Unlike active (mechanical) cooling, passive cooling methods rely on different environmental heat sinks to achieve cooling. In some cases, they can function as alternatives to mechanical cooling if they are properly designed and integrated in buildings. This chapter reviewed the different passive cooling techniques noted in the literature because they provide the most economical as well as energy-efficient cooling methods and can thus best address the increasing need for low carbon cooling energy. Because of the climatic dependency of most of the passive cooling techniques, some techniques were more suitable in specific climates than others, depending on the exploited natural heat sink. Based on the literature review and climatic analysis discussed previously, the direct evaporative cooling towers, known as Passive Downdraught Evaporative Cooling (PDEC), can be considered as a viable solution to the increasing energy demand for cooling in the hot arid climate of Saudi Arabia. As a result, PDEC will be considered and further investigated in this study as it has shown significant cooling performance and energy-saving potential in hot arid climates. The next chapter will review and discuss PDEC systems in detail.

CHAPTER 3. PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING TOWER (PDEC)

3.1 INTRODUCTION

The modern development of Passive Downdraught Evaporative Cooling (PDEC) began over four decades ago in Tucson, Arizona (Cunningham and Thompson, 1986), with subsequent evolutions of the technique being progressed worldwide to both demonstrate its suitability, and also broaden its scope of application within the construction sector. Providing a context for the initiation of PDEC developments, its various categorisations, the focal point of recent relevant investigations and design parameters for PDEC towers represents a key foundation for this study and its approach to analysing the data identified.

This chapter seeks to describe five key areas particularly relevant to PDEC technology. The first provides an overview of the PDEC system and the physical principles of the evaporative cooling process. The second describes the classification and different applications of the PDEC system. It also explains the different design geometries and airflow strategies found in the recent application of the system. It subsequently evaluates the procedures utilised in prior investigations on PDEC techniques and finds out the possible opportunities for further investigations and developments. The final part describes the advantages and disadvantage associated with the PDEC system.

3.2 OVERVIEW

Passive Downdraught Evaporative Cooling (PDEC) refers to a non-active, minimal energy-requiring process for removing heat and facilitating airflow in hot, dry climates (Bowman. *et al.*, 1997). PDEC is frequently referred to as a 'reverse thermal chimney' as air is drawn downwards, instead of upwards, as in an ordinary thermal chimney (Lewis Thompson, Chalfoun and Yoklic, 1994). PDEC catches external air at the tower's top, lowering its temperature via evaporative cooling, before finally releasing the cooled air to the desired internal environment. The whole process operates passively, as evaporative cooling leads to a raised air density, which in turn results in the air dropping through the tower and into the desired location, with no requirement for mechanical ventilation. The underlying basis for PDEC is evaporative cooling of ambient air, leading to a mass differential between external and internal air which in turn generates the required flow of air, due to the transfer of momentum between water in the liquid and gaseous states (Bowman. *et al.*, 1997; Pearlmutter, Erell and Etzion, 2008). The primary physical phenomenon is, therefore, simultaneous heat and mass transfer (Kang, 2011).

The PDEC technique has been employed for hundreds of years in certain areas of the Middle East (Bahadori, 1978, 1979). In more recent times, particularly post the 1970s energy crisis, it has become a subject of growing interest. A number of investigations have been conducted, particularly by Cunningham and Thompson, Givoni, Pearlmutter, and Ford (Cunningham and Thompson, 1986; Givoni, 1994; Al-hemiddi, 1995; Pearlmutter *et al.*, 1996; Bowman. *et al.*, 1997; Pearlmutter, Erell and Etzion, 2008; Ford *et al.*, 2012). For example, Cunningham and Thompson (1986), constructed a downdraught tower in a test building in Tucson, Arizona which employed wetted cellulose pads to evidence the efficiency of direct evaporative cooling to provide a significant flow of cooled air through the building. The test results were analysed by Givoni, who validated the success of this approach (Givoni, 1991, 1994). The measured performance data obtained were highly impressive: an external dry-bulb temperature (DBT) of 40.6°C and wet-bulb temperature (WBT) of 21.6°C, resulted in a supply air temperature of the tower exit of 23.9°C. The relevant air velocity of the exit air was 0.75 m/s. This significant temperature reduction obtained via the cooling tower, together with high rates of air change, is indicative of this technology's impressive cooling potential as well as its ability to facilitate airflow through the building. Such investigations by Cunningham and Thompsons showed that buoyancy forces acting in isolation are able to attain high rates of air change (movement of 30 units of air /hour were reported) (Cunningham and Thompson, 1986).

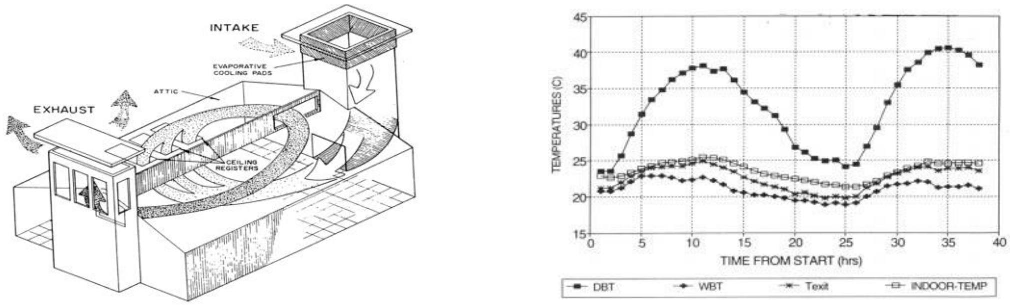


Figure 3-1: Experimental building (left), and graph of measured data by Cunningham and Thompson (Cunningham and Thompson, 1986)

Following the optimistic results of the PDEC performance, the technique was developed by Givoni (1994). His research investigated a more advanced model named the Shower Cooling Tower where he incorporated a shower (spray) head at the top of the tower instead of wetted pads. The world's initial innovative, practical application of a PDEC tower combined with a spray system was exhibited at EXPO'92 in Seville, Spain (see Figure 3-2). Its purpose was to reduce the temperatures of external rest areas. The PDEC design utilised spray towers with heights of 30m and injected fine water droplets with diameters of up to 14μm at the top of the tower. The greatest temperature reduction of 12°C was observed within the first 2m from the top of the tower when the smaller droplets were sprayed; a more gradual temperature decrease was observed with larger droplets (Alvarez *et al.*, 1991; Givoni, 1998)

Figure 3-2: PDEC (Shower) towers at Seville EXPO'92

Such application demonstrated the benefits of this approach for low energy cooling and raised the reputation of passive cooling strategies. As a result, PDEC technologies became of interest globally and started to feature more highly in state-funded research activities. The European Union's Joint Opportunities for Unconventional or Long-Term Energy

Supply Program (Joule) funded a huge research project in Europe (Bowman. *et al.*, 1997). The aim of the research was to study the application of PDEC in non-domestic buildings. This research involved investigations conducted on an experimental test facility in Catania (Italy), post-occupancy evaluation of buildings with PDEC, and development of PDEC systems that employed porous ceramic units (Bowman. *et al.*, 1997; Ford, Schiano-Phan and Francis, 2010).

The test building in Catania was constructed to mimic a standard section of a full-size office building cooled by PDEC (Ford, Schiano-Phan and Francis, 2010). The test facility consisted of a tower with two rooms attached to the north and south sides of the tower, as shown in Figure 3-3. The PDEC tower dimensions were 4.1m x 4.4m x 10.7m. The windcatcher had two openings, each measuring 1.7m x 3.7m, and facing the east and west, which represented the prevailing wind direction (Galatà and Sciuto, 1997). A fine spray system consisting of 20 micrometre diameter holes was installed at the top of the tower to cool ambient air prior to entering the linked spaces. Data loggers were placed outside and within the building. The outdoor data recorded included solar radiation, air temperature, relative humidity, wind direction, and wind speed. Air temperatures and relative humidities were measured at different locations within the tower and the room. The mean internal vs external temperature differential ranged between 4^{o}C - 10^{o}C, and relative humidity values ranged between 10% - 30% (Bowman. *et al.*, 1997).

Figure 3-3: Experimental Building in Catania, Italy (Galatà and Sciuto, 1997; Belarbi, Ghiaus and Allard, 2006).

Typically, reductions in supply air temperature of 70% -80% of wet-bulb temperature depression (WBD) were attained, with impressive energy savings providing the primary advantage of this approach (Givoni, 1994; Bowman. *et al.*, 1997). The provision of fresh external air, along with its associated movement, offer a significant asset with respect to thermal comfort and air quality in the internal space (Givoni, 1994; Bowman. *et al.*, 1997; Ford, 2002; De Melo and Guedes, 2006)

There is no consensus on technical terminology on PDEC technology at present. The phrase 'PDEC tower' is generic for the tower component. Several different names for this type of technology have been used with reference to the relevant structure, evaporative technique and geographical location: passive and hybrid downdraft cooling (PHDC) systems, natural draft cooling towers (Cunningham and Thompson, 1986), shower cooling tower (Givoni, 1994; Al-hemiddi, 1995; Carew and Joubert, 2006), down-draft evaporative cool tower (DECT) (Pearlmutter et al., 1996), passive downdraught evaporative cooling (PDEC) (Ford, Schiano-Phan and Francis, 2010). A typical PDEC tower/system consists of four main architectural elements including windcatcher, evaporation zone (water medium), supply tower/shaft/atrium, and exhaust openings. Further details about PDEC system and its classifications will be discussed later in this chapter.

3.3 HEAT AND MASS TRANSFER

The simultaneous transfer of both heat and mass is the primary physical principle of the evaporative cooling mechanism within PDEC towers. Typically, the cooling fluids are tightly coupled so that both fluids can influence each other's thermal properties. (Kang, 2011; Kang and Strand, 2013). The Evaporative Air Conditioning Handbook states that, for direct evaporative cooling, simultaneous heat and mass transfer will take place between fluids when temperatures and vapour pressures of both fluids are different (Watt, 1986). For air and water combinations (the most usual evaporative cooling processes), such exchanges will take place when water vapour and non-saturated air meet at a thermally isolated boundary. Here, the heat in the warmer fluid transfers to the cooler fluids. Mass is also transferred along with a high to a low gradient of water pressure, so that the water vapour resulting from evaporation from the water surface, will move into the adjacent, and drier air. Eventually, both temperature and vapour pressure will attain equilibrium as heat transfer will tend to equalise temperature and, evaporation will tend to equalise vapour pressure in each fluid. The efficiency of temperature reduction associated with direct evaporative cooling will therefore become 100% once air is saturated at the equilibrium temperature as a function of adiabatic cooling (Kang, 2011; Kang and Strand, 2013; Alaidroos, 2016).

In direct evaporative air cooling, the warm air is directed through a spray or porous wet pads, where its sensible heat energy leads to evaporation of some of the water present. Transfer of heat and mass between the air and water leads to an adiabatic process which reduces the DBT whilst raising the air's moisture content (WBT remains constant). In other words, when hot, dry air passes through a water medium, the evaporation of the water occurs as sensible heat is converted into latent heat, and the air temperature decreases as the relative humidity level increases. The DBT of the almost saturated air approximates the ambient air WBT. As a result, WBT is the most important parameter when considering an evaporative cooling system (Givoni, 1994; Kang, 2011).

A primary factor in determining evaporative cooler effectiveness is saturation efficiency. This is defined as the extent to which the temperature of the air exiting from a direct evaporative cooler approximates the WBT of the entering air. The difference between the ambient DBT and WBT is defined as the wet-bulb temperature depression (WBD). The more closely the air supply DBT matches the ambient air WBT, the greater the evaporative cooling efficiency. In other words, the percentage of reduction in WBD defines the cooling efficiency of an evaporative cooling process. This can be determined from Equation 3.1 as described below (Santamouris and Asimakopolous, 1996; Salmerón *et al.*, 2012):

Evaporative cooling efficiency

$$Saturation\ Efficiency = \frac{DBTin - DBTout}{DBTin - WBTin} \tag{3.1}$$

where:

DBTout= Exiting air dry-bulb temperature (°C)

DBTin= Entering air dry-bulb temperature (°C)

WBTin = Entering air wet-bulb temperature (°C)

A 70% saturation efficiency associated with such cooling processes is considered acceptable (Santamouris and Asimakopolous, 1996). Whilst direct evaporative cooling is a simple and cost-effective option, its cooling capability has lower efficiency for achieving satisfactory indoor comfort when the ambient WBT is greater than around 24°C. This highlights the importance of the ambient wet bulb temperature for the evaporative cooling design process (Givoni, 1991, 1994).

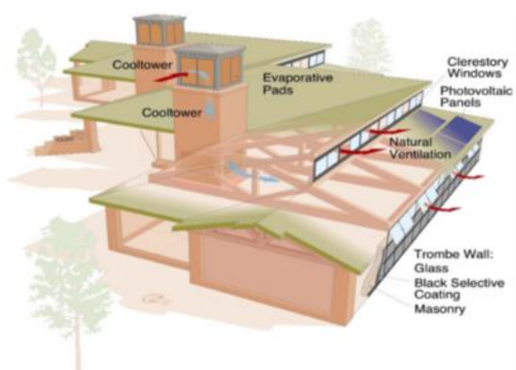
3.4 APPLICATIONS OF PDEC SYSTEMS

Research literature reporting on PDEC system applications in real buildings are generally categorized into two types: technological and typological. Technological research tend to be classified by the evaporative cooling technique employed to generate the downdraught: wetted pads; shower tower (coarse spray); misting tower (fine spray); and porous media (Ford, Schiano-Phan and Francis, 2010; Chiesa and Grosso, 2015). Subsequently, they are further categorized by building structure, or the location of where the downdraught is generated (Ford, Schiano-Phan and Francis, 2010; Qiu, Li and Qiu, 2013; Chiesa *et al.*, 2017; Ford, Schiano-Phan and Vallejo, 2019): central atrium (open), central shaft (enclosed atrium), and Perimeter PDEC tower. Summary explanations for all cooling processes, including existing project examples and studies, are detailed below.

3.4.1 PDEC Tower with Pad

The PDEC tower investigated by Cunningham and Thompson (1986) in Tucson, Arizona was probably the first to use the wet pad approach, while similar conceptual system designs were described by Bahadori (1985) at a very similar time. Such PDEC towers, utilising wetted pads that typically located in the tower or shaft, are classified as direct evaporative cooling systems. High-temperature ambient air is directed through vertical cellulose pads, and these resemble those typically used in desert coolers, that lead to raised moisture content and air density on the internal boundary of the pad. Whilst this technology offers potential cost savings, the use of cellulose pads integral to a PDEC tower cause substantial airflow resistance as well as high levels of water consumption resulting from significant losses to ambient air (Ford, Schiano-Phan and Francis, 2010). PDEC towers with cellulose pads have been implemented in several buildings around the world, such as the Botswana Technology Center (BTC) in Gabarone in Southern Africa, and the tower at the Ministry of Municipal and Rural Affairs (MOMRA) in Riyadh, Saudi Arabia (Chalfoun, 1997).

One recent successful application is the PDEC towers in Zion National Park in Utah (Torcellini *et al.*, 2004). Two cooling towers are incorporated in the building (Figure 3-4). Clerestories are designed in the roof to maximize daylighting and improve the air movement with the cooling towers. These cooling towers have, since 2000, operated satisfactorily at the Visitor Centre, which additionally employs natural ventilation as far as practicable, keeping the cool towers as a back-up for the hottest days only. The building was assessed over two years (Torcellini *et al.*, 2004). Results showed that the PDEC towers met most of the cooling requirements and that they contributed significantly to eliminating the use of conventional cooling. In the summer of 2007, the maximum external air temperature in Zion was recorded as around 42°C, while the internal temperature did not exceed 27°C (Ford, Schiano-Phan and Francis, 2010). The building consumes 70% less energy when compared with a building that meets U.S. federal codes. (Torcellini, Judkoff and Hayter, 2002; Torcellini *et al.*, 2004).



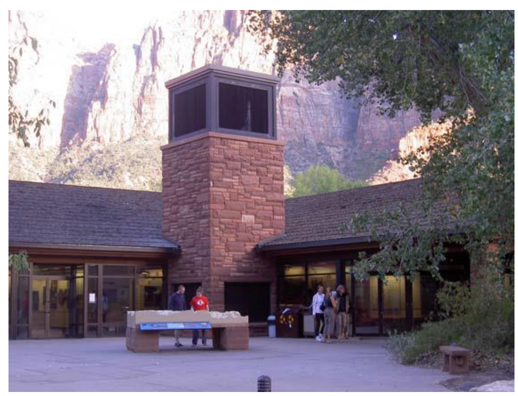


Figure 3-4: 3D model and a picture showning the PDEC design in the Zion National Park Visitor Centre (Torcellini, Judkoff and Hayter, 2002)

Another application of this PDEC mechanism is found in Al-Rahmania mosque in Al-Jouf, Saudi Arabia (Al-Saud, K. A. M., & Al-Hemiddi, 1999). Ten PDEC towers were placed along the east and west perimeter of the building to cool its 2500m^2 floor area indoor space. The building was monitored during the summer months by Al-Saud, K. A.

M., & Al-Hemiddi (1999). During the peak times (around 2.00 pm) the temperatures were recorded around 36ºC - 39ºC while the indoor temperatures during the same time were between 22ºC and 24ºC. The PDEC towers have shown an overall significant cooling performance, with an average temperature reduction of about 14.5ºC during the peak time. The cooling efficiency of the towers did fluctuate, reaching as low as 40% during sometimes. This reduction in the cooling efficiency was attributed to the airflow design within the building as the air was exhausted through the external doors only. No conventional cooling was used in the mosque as the building is entirely cooled by the PDEC towers (Al-Saud, K. A. M., & Al-Hemiddi, 1999). In August 2017, the mosque was visited by the author in addition to another building (Dar Al-Rahmaniah Library) in Saudi Arabia at the early stage of the research for the purpose of data collection and knowledge development. Figure 3-5 below shows pictures of the mosque taken by the author. Initial spot measurements were taken during peak time (around 2.00pm). Outdoor temperature was recorded at around 44ºC while the supply temperature of one of the towers was approximately 24.5ºC. The measurements and previous analysis by Al-Saud, K. A. M., & Al-Hemiddi indicated the applicabilty of such system under the extremely hot Saudi conditions.

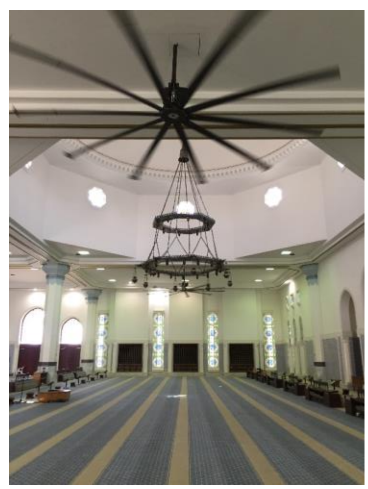


Figure 3-5: External and enternal pictures of Al-Rahmania mosque showing the cooling towers and supply openings

3.4.2 Shower PDEC Tower

Shower towers are classed as a direct evaporative cooling system, and these are also typically located within a tower. Water drops are sprayed vertically downwards from the top of the tower, mimicking a ‘shower’ (Ford, Schiano-Phan and Francis, 2010). Because of the large water droplet size, not all the water evaporates, so the water which has not undergone the evaporative state change is collected at the base of the shaft prior to recirculation to the shower head. Initially, the performance of simple shower towers was experimentally tested by Givoni and Alhemiddi (Al-hemiddi, 1995; Givoni, 1997). Falling water transfers its momentum to the airstream generating an inertial airflow downwards in the tower. The benefits of this PDEC design in comparison to one which utilises wetted pads is its ability to employ any type of water, even low-quality saline water if appropriate. (Givoni, 1994; Al-hemiddi, 1995). Furthermore, PDEC towers based on shower designs also offer lower aerodynamic resistance and therefore increased airflow through the tower and maintenance of such towers is easier in desert conditions, than PDEC towers relying on wetted pads (Ford *et al.*, 2012; Qiu, Li and Qiu, 2013).

This cooling mechanism has been used in several projects in Australia, the Middle East, and the USA. The Blaustein International Center for Desert Studies, designed by the Desert Architecture Unit in Sde Boqer, Israel represents one of the initial shower PDEC constructions (Pearlmutter *et al.*, 1996; Etzion *et al.*, 1997). It was built from 1989 to 1991, in a location with hot and arid summers, where average daily maximum temperatures are reaching 32℃, but relative humidity is exceptionally low, ranging from 20% to 30% for the majority of the day. The building comprises a large central atrium surrounded by different spaces. The large atrium is cooled by a shower PDEC tower located near the centre of it as shown in Figure 3-6. The building specification included a floor area of 1500m^2, atrium area of 500m^2, with a cooling tower height of approximately 12m and 3.75m octagonal width. The windcatcher was constructed to increase airflow in an entirely passive (buoyancy-driven) approach. Furthermore, an intake fan was located at the apex of the tower to maximise convective downdraught resulting from the air temperature differential between the upper and lower tower regions. Relatively large drops of water are sprayed into the air stream, and any excess water that does not evaporate falls to a shallow collection pool at the base of the tower prior to recirculation to the shower head. The air is expelled from the system either via low-level open doors or high vents in the atrium or, via the external offices. Results for a standard day in the summer show that, at midday, ambient air at around 35-36℃ is drawn into the tower and, following evaporative cooling, is eventually supplied at 21-22℃ (Pearlmutter *et al.*, 1996; Etzion *et al.*, 1997).

In 2001, the Interactive Learning Center (ILC) at Charles Sturt University in Australia installed four shower towers in an open plan, as shown in Figure 3-7 (Webster-mannison, 2003). Webster-mannison, (2003) reported that, although efficiency was suboptimal on commencement of operations as a result of the inappropriate design of the windcatcher, following the installation of wind deflectors and baffles high up in the tower to rectify these early problems, the system's performance was greatly improved. This installation was also able to offer convective night cooling and used filtered rainfall for the water input. Maximum temperature reductions of 16.42°C were noted for ambient air temperatures of around 42.28°C.

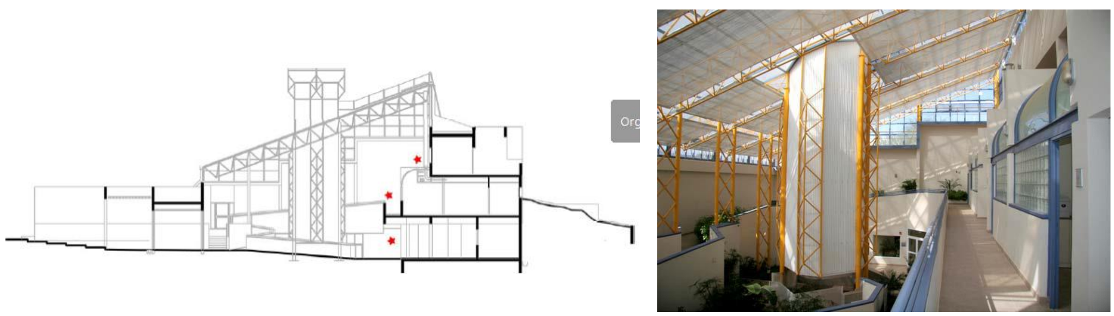


Figure 3-6: Section and internal view of the shower PDEC tower within the atrium of the Blaustein International Center (Ford, Schiano-Phan and Francis, 2010)

Figure 3-7: External and internal views of the Interactive Learning Centre (ArchitectureAU, 2020)

3.4.3 PDEC with Porous Ceramics

PDEC processes utilising wet porous ceramic media are typically classed as direct evaporative cooling systems, with the wet ceramic media generally located in air streams such as a tower or window. Evaporation takes place when the high-temperature ambient air traverses the wet ceramic surface leading to raised air moisture content and density (Ford, Brian and Schiano-Phan, 2003; Schiano-phan, 2004; Ford, Schiano-Phan and Francis, 2010). Porous ceramic media are frequently associated with conventional examples of passive evaporative cooling methods integrated into building elements, including clay water jars located within wooden windows (mashrabiya) or at the wind tower base (Cain *et al.*, 1976). The Iranian wind tower (baud-geers) proposed by Bahadori, as shown in Figure 3-8, is an example of this mechanism (Bahadori, 1985). This proposal is developed to reduce the temperature of the ambient air and enhance natural ventilation throughout the building. Heat transfer is enhanced in conventional wind towers by employing clay conduits within the upper part of the tower subject to cooling from water spray from above. Modular porous ceramic evaporators provide the modern equivalent of the conventional water jar integrated within the building (Ford, Brian and Schiano-Phan, 2003). These can be viewed as a type of PDEC system; however, their primary benefit is their integration with the building fabric. Several recent studies have investigated the development and integration of this technique in wall cavities, namely by Brian Ford and Rosa Schiano-Phan (Ford, Brian and Schiano-Phan, 2003; Schiano-Phan, R. and Ford, 2003; Schiano-phan, 2004; Schiano-Phan, 2010).

To date, there are only a few applications of porous ceramics known. Figure 3-9 shows an example of the use of this mechanism in the Spanish Pavilion at EXPO 2008 in Zaragoza, Spain (Schiano-Phan, 2010). The project employed an array of 750 clay columns structured to support the roof. These columns were designed for emerging from shallow pools interspersed with glazed exhibition areas. The initial design concept aimed to generate a passive evaporative cooling of the semi-open space from wetting resulting from passive osmotically driven ceramic columns (Schiano-Phan R, 2010).

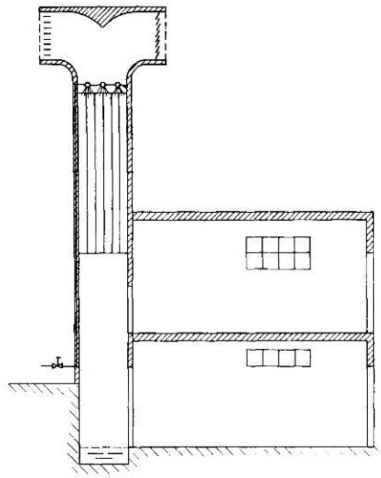


Figure 3-8: Wind tower improved by Bahadori (Bahadori, 1985)

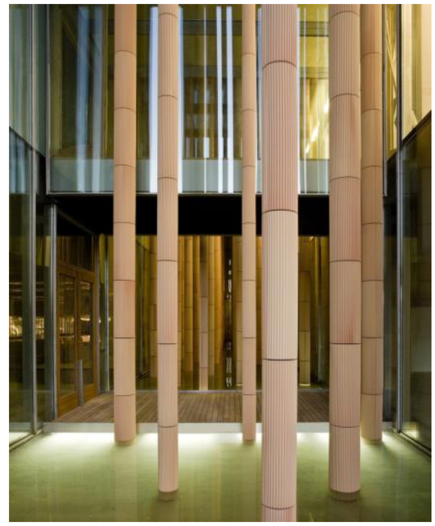


Figure 3-9: Interior view of the Spanish Pavilion at EXPO'08 (ArchDaily, 2014)

3.4.4 PDEC Tower with Spray

PDEC systems using misting nozzles are also classified as direct evaporative cooling systems. The cooling mechanism of spray and shower PDEC towers are essentially similar. However, the shower cool towers are generally enclosed because of the supply of the relatively coarse water drops (Ford, Schiano-Phan and Francis, 2010). The evaporated cool air is then delivered at the base of the tower because of the collection of the remaining unevaporated water. In a spray PDEC system, very fine water mist is sprayed into the air path to maximise air and water contact, whilst keeping air pressure losses to a minimum. The evaporation that takes place cools both the water and the air to levels approaching the ambient WBT (Givoni, 1998). As mentioned previously in section 3.2, the PDEC tower launched at EXPO '92 in Seville, Spain represented the first example of a modern PDEC system (Alvarez *et al.*, 1991; Givoni, 1998). The cool air in spray PDEC system can be supplied throughout the height of the building as the fine droplets allow complete evaporation of water, permitting pedestrian access below, whilst optimizing cooling performance (Santamouris, 2007). The complete evaporation and improved performance of the spray PDEC system expanded its application as this mechanism has been incorporated in to a shaft, tower or an atrium space in recent applications. The inclusion of evaporative cooling components, such as spray nozzles, as part of the windcatcher in downdraught evaporative cooling wind-tower, has been the subject of extensive study

(Belarbi, Ghiaus and Allard, 2006; Kang and Strand, 2013, 2016; Kassir, 2016; Alaidroos and Krarti, 2017). It is generally accepted that the degree of cooling attainable via evaporation increases with reducing water droplet size (Kang and Strand, 2016). recent innovations in PDEC technology permits evaporation at low pressure, and this is viewed as the most efficient and cost-effective direct evaporative cooling design for PDEC systems, and this is the reason why so many full scale and research PDEC projects have employed this design (Ford, Schiano-Phan and Francis, 2010; Ford, 2012).

The Torrent Research Centre (TRC) in Ahmadabad, India involved the first large application of the use of misting nozzles sprayed into the top of the tower inlet (see Figure 3-10) (Thomas and Baird, 2006; Ford, Schiano-Phan and Francis, 2010)t. This project showed that it was feasible for such a technique to be effective for cooling a large building. The Centre consists of six laboratory buildings with administrative spaces arranged on three levels. The PDEC system is incorporated into four of them. In each building, the PDEC system is located above an enclosed central shaft separating the offices from the laboratories. As shown in Figure 3-11, this scenario permits air that has been evaporatively cooled to be directed to areas of occupied space on each floor. On the long sides of each building, several stacks are integrated to maximise air circulation and exhaust the warmer air out of the building. This enables thermal and physical buffering of working spaces from the external ambient air. In April 1998, air temperature and relative humidity data from various areas of the building highlighted that extremely significant cooling with high air change rates were attained. When the outside temperature reaches its maximum, the PDEC drops the interior temperature by between 10 - 15°C. Temperature maximum of 27^{o}C in the ground floor laboratory and 29^{o}C on the first floor were recorded where external peak temperatures were recorded at 38^{o}C. During the same timeframe, air change rates of 9 per hour on the ground floor and 6 per hour on the first floor were observed. In the first year, the system had achieved 64% energy savings in cooling demand when compared to a conventional air conditioning system (Ford *et al.*, 1998). Post occupancy evaluations of the buildings were conducted by Thomas and Baird, (2006) and showed that a good occupant satisfaction with substantial energy reductions was attainable in large commercial constructions by utilising downdraught cooling (Thomas and Baird, 2006).

Figure 3-10: The Torrent Research Centre (Worldarchitecture, 2018)

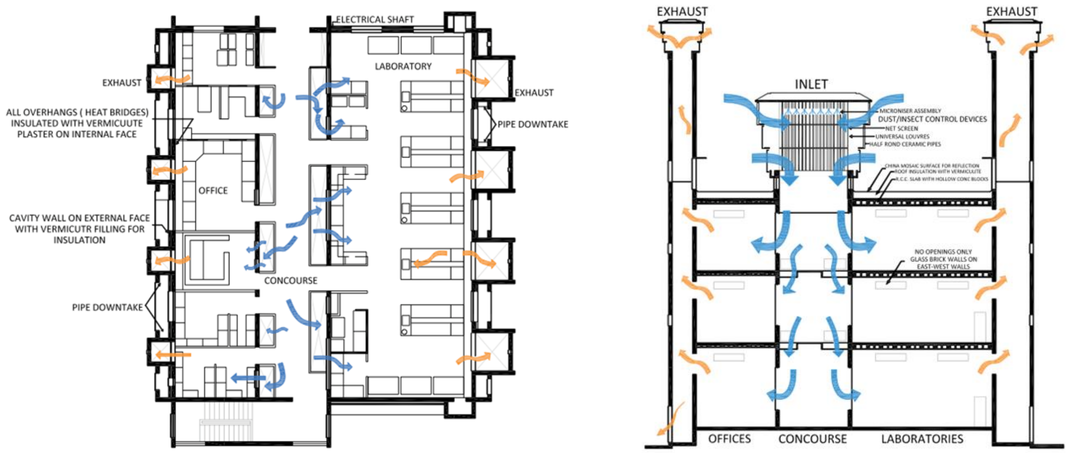


Figure 3-11: Floor plan of one of the PDEC buildings in the TRC (left), and section through the PDEC (right) showing the airflow strategy within the building (Thomas and Baird, 2006).

Following the successful application of the spray PDEC in the TRC buildings, this method was used in several other projects around the world. A further case of a spray PDEC system is provided by the Malta Stock Exchange (2001) which commissioned a PDEC system comprising misting nozzles, actively chilled water pipes and convective night ventilation for the central atrium space as presented in Figure 3-12. The design avoided the need for ductwork and fan coil units within the central 14m high atrium. The same approach is not applicable to cellular offices and lower ground-floor conference rooms. Under dry ambient conditions, the design of PDEC via high-performance hydraulic nozzles within the atrium is used, whereas, under humid conditions, direct cooling is facilitated via chilled water coils, placed at a high level next to the misting spray nozzles and beneath the ridge windows. The airflow path is reversed at night to expel any residual daytime heat gains, again via the central atrium, to attain a highly significant level of convective cooling at night. This PDEC installation is capable of matching around 25% of the entire cooling requirement. The combined application of both passive and low-energy cooling technologies (PDEC and cooling coils) led to a total energy reduction of around 48% (Ford and Diaz, 2003; Ford, Schiano-Phan and Francis, 2010).

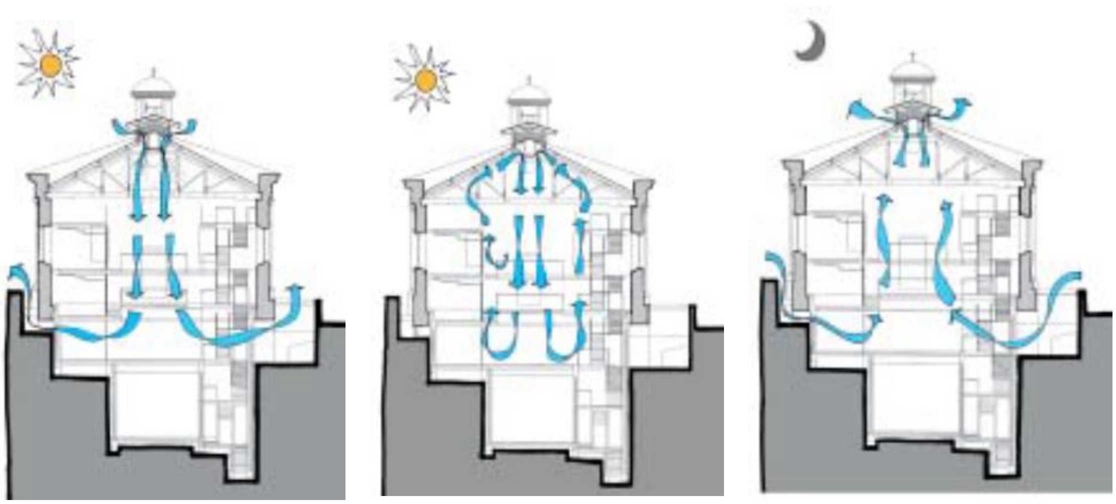


Figure 3-12: Passive cooling strategies applied in the Malta Stock Exchange from left to right: spray PDEC, downdraught cooling with chilled water pipes, and night ventilation (Ford, Schiano-Phan and Francis, 2010)

The PDEC tower, known as the katabatic cool tower, at the Global Ecology Research Centre (GERC) in Stanford University, California, shown in Figure 3-13 and Figure 3-14 represents another recent application of this mechanism. The 10m spray perimeter PDEC tower is integrated to cool the lobby space. Additional passive strategies were incorporated in the building, including enhanced daylighting, night sky evaporation/radiation, natural ventilation, and radiant slab cooling and heating. Although there is an absence of data relating to system output, the centre website reports that the katabatic cooling tower is capable of generating a temperature reduction of 14.4°C when external temperatures are as high as 29.4°C (CBE, 2020).

The "Night Sky" radiant cooling system represents the same concept of radiant heat loss to the night sky. A thin water film is applied to the roof at night; this is subsequently cooled via the radiation of heat to the surrounding cold, deep space and then stored overnight. Cool water is then recirculated to the radiant slabs through the building during the day at 13-15.5^{o}C, using 90% less energy than a chiller (Ford, Schiano-Phan and Francis, 2010; CBE, 2020). The integration of these passive techniques achieves a predicted total energy savings of 50%. The perception of occupants regarding thermal comfort conditions in summer is significantly positive indicating that the applied passive cooling techniques work well (Ford, Schiano-Phan and Francis, 2010).

Figure 3-13: External view of the GERC showing the PDEC tower (CBE, 2020)

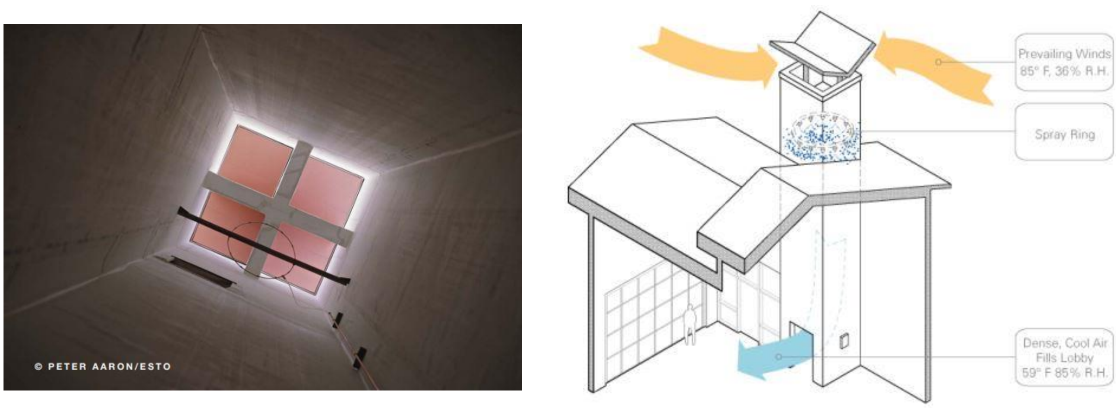


Figure 3-14: Internal view and a 3D schematic drawing showing the PDEC airflow strategy of the GERC (CBE, 2020)

Several other projects around the world have incorporated this system in their building such as the Federal Courthouse in Phoenix, Arizona, the Confederation of Indian Industries (CII), Bangalore, India, and the free-standing PDECT in Masdar Institute central courtyard in Abu Dhabi (Ford, Schiano-Phan and Francis, 2010; Al-Hassawi, 2017). The recent development, successful applications, and high cooling efficiency achieved from the fine water droplet size makes the spray PDEC the most efficient and cost-effective direct evaporative cooling system (Ford, Schiano-Phan and Francis, 2010).

3.5 DESIGN GEOMETRY AND AIRFLOW STRATEGIES

The design of a downdraught cooling mainly relies on gravity as the density of the cooling air increases causing it to fall through the tower/atrium and ultimately into the occupied space. As seen in the case studies described previously, the incoming air can be supplied centrally or via a perimeter shaft. As shown in Figure 3-15, Ford et al., (2010, 2019) classified the airflow strategies of downdraught cooling, depending on the geometric design of the building and integrated PDEC, into three main types: a central atrium, a central shaft, and a perimeter tower (Ford, Schiano-Phan and Francis, 2010; Ford, Schiano-Phan and Vallejo, 2019). A variety of air paths are possible depending upon the geometric design selected. The description of these three airflow patterns is discussed below.

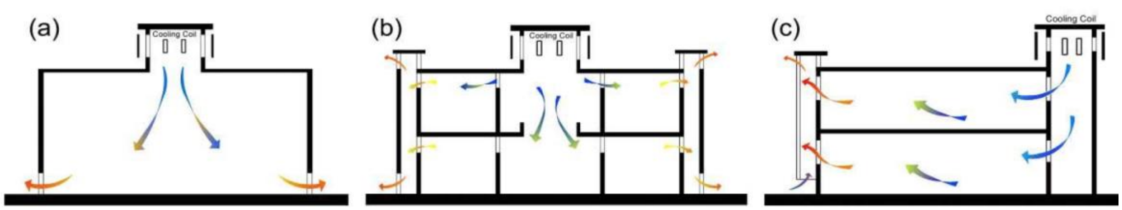


Figure 3-15: a geometric design for downdraught cooling: (a) central atrium, (b) central shaft, and (c) perimeter tower (Ford, Schiano-Phan and Vallejo, 2019)

- **Central atrium:** For this option, the atrium may be viewed as a single cell, comprising both a supply and delivery zone, and where the adjacent areas are excluded from the downdraught cooling provision. The Federal Courthouse in Phoenix and the Malta Stock Exchange in Malta (as described above) are two examples of this type of design. In this strategy, temperatures within the central atrium space may be highly variable.

- **Central shaft:** For this option, an enclosed central shaft functions to supply several nearby spaces. Exhaust air from separate spaces (which may include different floors) is expelled via specialist perimeter shafts or ventilated double facades designed for this purpose. These may be essential to guarantee successful expulsion of exhaust air from the building under all scenarios. The Torrent Research Centre in Ahmadabad is an example of this type of design.
- **Perimeter tower:** This option is the airflow method, where a perimeter tower is connected directly to single or multiple areas. The Global Ecology Research Centre in California is an example of this type of design.

PDEC with misting nozzles can be used in all the geometric designs described above, due to the complete evaporation of water. In the case of the PDEC towers with pads and shower PDEC towers, cooled air is supplied at the base of the tower, while in misting PDEC towers, cooled air can be directed over the entire height of the space. As mentioned previously, shower towers are typically enclosed due to the collection of the unevaporated water at the bottom of the tower. The case of the PDEC with porous ceramic slightly differs. This technique can be integrated within a tower or other airflow paths such as a double envelope.

3.6 SYSTEM EFFECTIVENESS AND OPPORTUNITIES FOR FURTHER DEVELOPMENTS

The performance of PDEC systems has significantly developed in the last decades (Givoni, 1995; Ford, Schiano-Phan and Francis, 2010). Moreover, several experimental and computational studies investigated the applicability and opportunity for further developments of the system in different parts of the world.

Al-hemiddi (1995) studied the application of three passive cooling systems for the hot and arid climate of Riyadh, Saudi Arabia: shower cooling tower; roof pond and a green roof. This investigation was conducted as part of his PhD research, supervised by Givoni, at the University of California, Los Angeles. A three-step methodological approach was taken, encompassing experimental testing on these three options to identify the one with the greatest cooling potential. In the first phase of the investigation methodology, the three systems were installed on a full-scale building with five equally-sized rooms that were located within the King Saud University campus. The second phase involved data collation over ten measurement periods: four over the summer of 1993 and six over the summer of 1994. This phase of the study led to the conclusion that a direct correlation existed between temperature drop and both shower head height and water flow rate as the tower configuration offering the greatest height and flow rate led to 80% evaporative efficiency. Another conclusion resulting from the study overall was that shower tower installations outperformed both roof ponds and green roofs, according to data collated during periods of simultaneous operation. Using the shower tower, the results revealed that when outdoor temperatures exceeded 40°C, the indoor temperatures were below 28°C. (Givoni, 1994; Al-hemiddi, 1995).

Pearlmutter *et al.* (1996) indicated that the majority of designs attain the greatest drop in temperature at the top of the tower as a consequence of direct contact here between the air and water. In the experimental study, different PDEC configurations were investigated, including fan assisted designs. This experiment was conducted in a reduced-scale tower of the Blaustein International Center, mentioned previously in section 3.4.2, in order to investigate the possibility of increasing its performance. The results revealed a capability of achieving cooling efficiency of up to 90-95% (reduction in WBD) (Pearlmutter *et al.*, 1996). In 2008, Pearlmutter, Erell and Etzion (2008) investigated the potential for a reduction in water consumption from conventional PDEC towers without a deleterious impact on cooling efficiency by altering the structure of the enclosure from the typical constant cross-section and individual set of misting nozzles to systems involving varying cross-section with multiple misting nozzle sets. They hypothesized that a secondary inlet with an additional set of misting nozzles installed at the part of the tower situated within the actual space being cooled would permit recirculation of relatively cooler and more humid air (in comparison with ambient air) back to the tower, to enable target temperatures to be achieved with reduced water consumption. Their results confirmed this hypothesis, demonstrating that a secondary inlet is highly advantageous with respect to cooling efficiency and water consumption for conditions when recirculated air has lower enthalpy than ambient air. However, where this is not the case, the cooling efficiency of conventional PDEC designs is greater (Pearlmutter, Erell and Etzion, 2008).

Ford et al. (2012) discussed the performance of a PDEC in a small experimental prototype house. This is considered the initial European application and performance analysis of this type of cooling technology for a housing case. The PDEC system was integrated as part of a house designed and built by students of the University of Nottingham for the 2010 Solar Decathlon Europe in Madrid, Spain. The PDEC system was situated at the top of a central light-well. Monitoring of the house's thermal efficiency took place for a restricted time over June 2010. The resulting data showed that a high-performance building envelope, in conjunction with a PDEC system, provided a comfortable ambient environment within the house over a timeframe involving increasingly warm temperatures. The data obtained indicated that PDEC is capable of offering significant energy savings with the attainment of satisfactory thermal conditions without the requirement for additional mechanical cooling. The researchers concluded that such a technique might be of potential benefit to housing projects in hot arid regions across the globe (Ford *et al.*, 2012).

Al-Hassawi (2017) investigated the development of a single-stage PDEC tower to expand its application to different climates rather than only the hot, arid conditions under which it is normally utilised. The research involved the development of a design for a multi-stage passive and hybrid downdraft cooling tower (PHDCT) and comparing it with a similar design, but a single-stage tower PDEC tower. The design offered a two-stage process for lowering the temperature of the air entering the tower shaft: (i) employing a sensible cooling stage (heat exchanger) and then (ii) employing a direct evaporative cooling stage (spray system). The multi-stage PHDC tower included electric fans to increase the airflow. Prototypes of the towers were constructed at half scale and tested in Tempe, Arizona over the summer of 2017. Data were collected simultaneously from both towers to assess efficiency under similar conditions. The findings demonstrated that the hybrid tower performed better than the single-stage tower under hot arid conditions only when sensible cooling was taking place simultaneously with evaporative cooling and a fan. Furthermore, this approach widened the application of downdraught cooling to hot and humid conditions when sensible cooling and fan were used without evaporative cooling. However, this improvement increased the energy used due to the fans and active cooling (Al-Hassawi, 2017, 2020).

A number of investigations have examined the possibility of further enhancing PDEC systems. Mathematical models have been constructed to comprehend aerodynamic performance and assess the thermal levels potentially attainable by PDEC systems utilising direct evaporative cooling.

Belarbi, Ghias and Allard (2006) have examined the cooling ability of the PDEC system by investigating the effect of water droplet size and distance between nozzles. They have developed a model that could be used to estimate the sizing of the water spray system (Belarbi, Ghiaus and Allard, 2006).

Kang and Strand have conducted several studies using a computational parametric analysis approach to maximize the PDEC performance by the manipulation of water system components and the tower (Kang and Strand, 2009, 2013, 2016). They have developed a computational model for EnergyPlus to predict the cooling performance of a spray PDEC (Kang and Strand, 2009). The authors investigated a set of parameters within the tower and water system, including tower geometry, inlet openings, water flow, and water droplet size. Their analysis produced a set of effective guidelines for the system to enhance the efficiency and performance of the PDEC tower. They concluded that the effective tower height is between double and triple the width of the tower. Additionally, finer droplet size (between 30μm to 100μm) showed better cooling performance (Kang and Strand, 2016).

Other studies performed by **Alaidaroos and Kararti** followed a similar approach to optimize a ventilated wall cavity in terms of energy, water use and thermal comfort. The study focused on the effect of the water droplet size to achieve maximum performance and maintain comfort (Alaidroos and Krarti, 2016a, 2016b, 2017). All these studies have concluded that smaller droplet sizes provided higher evaporation rates and better PDEC efficiency.

As discussed previously, most of the previous studies significantly focused on the development of this passive cooling technique in terms of its engineering aspects. These include the tower geometry, aerodynamic design of the system, nozzles size and their distribution, water flow and its distribution, and tower height. Mathematical modelling was carried out to comprehend aerodynamic performance and assess thermal levels attainable by PDEC systems utilising direct evaporative cooling. This was generally followed up by the design of computer software permitting designers to specify PDEC design parameters and predict associated system performance at an early stage in the design process (Cook *et al.*, 2000; Robinson *et al.*, 2004; Belarbi, Ghiaus and Allard, 2006; Ford, Schiano-Phan and Francis, 2010; Kang, 2011; Alaidroos and Krarti, 2016b). Whilst such calculations and modelling strategies abound, only a few complete monitoring datasets for PDEC systems are reported in the literature; the dataset collated by Cunnigham & Thompson in 1986 at Tucson, Arizona, and that reported for the experimental building in Catania being notable in this respect (Ford, Schiano-Phan and Francis, 2010).

Other research studies have been carried out by monitoring and analyzing existing PDEC buildings, namely by (Ford *et al.*, 1998; Thomas and Baird, 2006; Schiano-Phan and Ford, 2008; Schiano-Phan, 2012). The monitored buildings found in the literature were conducted in different parts of the world, including Europe, USA, and Asia. Assessing and reviewing the cooling performance of buildings where downdraught cooling has been introduced is essential in order to understand if the energy efficiency and thermal comfort of these building are achievable. The Torrent Research Centre study report by Ford et al., (1998), and Thomas and Baird, (2006) demonstrated that a high degree of occupant satisfaction combined with substantial energy reductions is possible by the employment of downdraught cooling in large commercial buildings. However, the report on five buildings in the south-west USA by Schiano-Phan, (2012) indicated a less robust outcome. While several monitoring studies have shown the optimistic performance of the PDEC system, there is still a lack of such types of study in the Middle East, which is ironic considering that, historically, the basic concept of this system initiated there.

Furthermore, there is a shortage of investigation about the significance of proper integration between the PDEC tower and the coupled building. A successfully integrated design of a PDEC building requires a multidisciplinary design team, including architects and engineers. Appropriate consideration of building / architectural design and air inlets and outlets position is as crucial as engineering for a successful building project. The proper integration between a PDEC tower and a building to be cooled offers a great potential for maximising cooling efficiency by this type of passive cooling approach.

In addition, most of the previous research concentrated on the use of the PDEC system in non-domestic buildings. PDEC has demonstrated its viability, both technically and commercially, with respect to non-domestic buildings. However, there is lack of research that assesses the potential applicability of such passive cooling technique in domestic buildings. According to the researcher's best knowledge, there is little reported in the literature relevant to residential buildings (Ford, 2012). Perhaps the difficulty of integrating a PDEC tower in a multi-space building with different design characteristics for each space, like houses, could be the reason to reduce the opportunity of successful integration. Among all the analyzed case studies found in the literature which employed PDEC as a cooling system, only a few of them were discussing the incorporation of such system in residential buildings. Indeed, Chiesa et al., (2017) reported on merely the PDEC system integration in residential buildings, omitting to discuss actual applicability (Chiesa *et al.*, 2017). Another research conducted by Ford et al., (2012) reviewed the efficiency of the first PDEC system for housing in Europe. However, it was conducted on a small experimental prototype house rather than a full-scale occupied house.

Based on the literature, the monitoring and analysis of an existing PDEC performance in a building in the hot arid climate of Saudi Arabia will be an added value to the literature in this field. In addition, further investigation on the applicability of the PDEC towers for existing residential buildings in the extremely hot Saudi climate will be another important research opportunity. As a result, this study finds it a valuable opportunity to: first, investigate the actual performance of PDEC in an existing building in the Kingdom of Saudi Arabia; second, model and analyze the applicability and performance of PDEC tower in a typical Saudi house. A residential building would be an ideal option to study the integration of a PDEC tower in this type of buildings and to analyze the effect of architectural design on the PDEC performance. The successful performance of such a system could be introduced as a viable solution to tackle the high energy demand required for cooling in the Saudi residential sector.

3.7 ADVANTAGES AND DISADVANTAGES OF THE PDEC SYSTEM

The primary advantage of these systems is the potential for substantial energy reductions to be achieved (Givoni, 1994; Santamouris and Asimakopolous, 1996; Ford, 2002). The intake of external air and the circulation of this air throughout the internal space vastly enhance thermal comfort and air quality of the space (Givoni, 1994; Bowman *et al.*, 2000; Cook *et al.*, 2000; Ford, 2002). Furthermore, the possibility of ventilation at night via the PDEC towers is viable, and this leads to a lowered demand for cooling during the day and also minimises the necessary operational time of the main cooling systems (Bowman *et al.*, 2000). In addition, the air intake is cleansed by the water employed for the evaporative cooling process (Etzion *et al.*, 1997). A further significant benefit arises from the fact that these systems are capable of attaining the significant amount of cooling in the afternoon, coinciding with the greatest cooling requirement of the day, as the WBD increases, leading to a significant reduction of peak electricity demand. These systems are also capable of operating in areas with no wind, as airflow is facilitated by density differences and momentum transfer between water droplets and the incoming air (Bowman *et al.*, 2000; Pearlmutter, Etzion and Erell, 2006; Ford, Schiano-Phan and Francis, 2010). Furthermore, PDEC towers can be integrated within new constructions or retrofitted into existing buildings using only basic construction techniques and at relatively minimal expense (De Melo and Guedes, 2006; Ford, Schiano-Phan and Francis, 2010).

Climatic dependency is the primary drawback associated with PDEC towers (due to their dependence upon evaporation), as it is for many other similar passive cooling techniques (Bowman *et al.*, 2000; Ford, 2002). Where PDEC systems, under certain ambient conditions, offer insufficient cooling capacity, a conventional cooling system may be additionally required. A further disadvantage is the lack of review in the literature, which might permit a more thorough comprehension of the impact of a building's design on the efficiency of a PDEC (Bowman *et al.*, 1997). Studies also observe that water hardness and microbiological contamination may present challenges to the successful operation of PDEC systems (Ford, 2002; Alaidroos and Krarti, 2017). For PDEC systems utilising pads, high-pressure reductions and limited life span of pads presented other potential drawbacks (Lewis Thompson, Chalfoun and Yoklic, 1994; Ford, Schiano-Phan and Francis, 2010).

3.8 CONCLUSION

Over the past few years, many buildings integrated PDEC around the world as a primary cooling system. However, despite the fact that all surveyed buildings exhibited energy efficiency and cost-effectiveness, and most demonstrated satisfactory thermal comfort level, it is surprising that traditional evaporative cooling techniques, specifically PDEC, are not more common. Investigative approaches employed over the studies involved the generation of theoretical models, investigation and assessment of an existing PDEC system, an experimental investigation of a novel PDEC system, or a combination of both experimental research and theoretical study. Investigations were performed in closed as well as open spaces, and all that was performed on downsized-scale models had the cooling mechanism located within a tower type structure. For all investigations, data were evaluated by means of statistical procedures and results validated via comparative analyses. Studies in this field have led to significantly developed PDEC systems that can be an alternative to conventional air-conditioner if the PDEC and the building are coupled as one integrated design.

Recent studies conducted in this field have revealed a great opportunity for the successful applicability of the PDEC system in hot, dry climates. Due to the lack of studied PDEC buildings in the Middle East region, the researcher, in the beginning, considered the importance of monitoring and assessing an existing PDEC building in the Saudi climate before investigating its applicability to residential buildings. The next chapter will discuss in detail the monitoring and investigation of a PDEC case study in Saudi Arabia.

CHAPTER 4. DAR ALRAHMANIAH LIBRARY: THE PDEC CASE STUDY IN SAUDI ARABIA

4.1 INTRODUCTION

This chapter presents the field measurements, analysis, and assessment of the performance of an existing Passive Downdraught Evaporative Cooling (PDEC) building in Saudi Arabia. The case study building, Dar Al-Rahmaniah, is a small public library located in the central region of Saudi Arabia. The library consists of three main sections: men, women and children, and auditorium. Only the men's building was investigated and assessed for reasons discussed later in this chapter. The purpose was to investigate the applicability of the PDEC system in the extremely hot, dry climate of Saudi Arabia, and the factors affecting its performance. For more than 70 days during the summer of 2018, several data loggers were installed in the Dar Al-Rahmaniah Library to monitor and collect data from the building and two PDEC towers. Different types of data loggers were used to record various parameters inside and outside the towers and the building. The primary objective of analysing this case study was to conduct a full-scale PDEC assessment in Saudi Arabia. Two PDEC towers are used to cool the main and largest section of the library. The case study provided detailed information about the applicability of the PDEC tower in the climate of Saudi Arabia. A parametric analysis of the wind effects was conducted by correlating different wind speeds and directions against environmental conditions in the library. The results indicated that the PDEC towers could deliver significant cooling for library users. However, the towers' effectiveness was influenced by changes in wind speed and, in a counter-intuitive way, stronger wind speeds tended to reduce the towers' cooling efficiency. Moreover, thermal comfort analysis investigated the acceptability limits of indoor temperature using two different thermal comfort models. Details descriptions of the analysis and assessment are discussed in this chapter.

4.2 SELECTION OF THE CASE STUDY

Very few PDEC buildings were found in Saudi Arabia that are still relying on PDEC towers as their main cooling system. A literature review, as well as personal communications with experts in the field, such as Dr. Al-Hemiddi, led to two possible PDEC case study buildings - Al-Rahmania mosque and Dar Al-Rahmaniah Library. Both buildings belong to Abdulrahman Al-Sudairy Cultural Centre. The two buildings were visited by the author at an earlier stage of the research to find out if they could make an appropriate case study to investigate. Initial information and spot measurements were collected during the first visit to both buildings in 2017 as part of the process to decide the appropriate case study for investigation. Eventually, Dar Al-Rahmaniah Library was chosen for the four reasons listed below:

(1) The library building operates for most of the day while the mosque building was operating only during prayer times, which are only five short times a day every couple of hours. Although the PDEC towers in both buildings were running continuously during the summer, the closure of the mosque during unoccupied hours during most parts of the day, especially peak hours, would not provide the adequate data for the purpose of this research.

(2) In addition to the long closure time for the mosque, the only exhaust openings were the main entrances of the mosque. This will minimise the cooling performance of the PDEC towers during unoccupied times as the towers will not be operating appropriately as discussed in section 3.4.1 previously (Al-Saud, K. A. M., & Al-Hemiddi, 1999). In contrast, the airflow in the library was designed in a better way, which will be further explained in this chapter.

(3) Furthermore, the library is located in a relatively hotter region (Riyadh) in Saudi Arabia compared to the region of the mosque (Al-Jouf).

(4) Al-Rahmania mosque was previously investigated by Al-Saud, K. A. M., & Al-Hemiddi, (1999) while there are no reported studies found in the literature about the Dar Al-Rahmaniah Library

These four reasons have led to the selection of Dar Al-Rahmaniah Library as a case study to examine the cooling performance of the PDEC tower in the extremely hot arid climate of SA. Figure 4-1 below shows the library and the two PDEC towers.

Figure 4-1: The main entrance of Dar Al-rhmaniah Library and the two cooling towers

4.3 LOCATION AND CLIMATE

The PDEC building assessed in this study is the Dar Al-Rahmaniah library. The library is situated in Alghat city, latitude 26.03°N, in the central region of Saudi Arabia. The city is located in the north-western part of Riyadh province (see Figure 4-2). The dense sandy dunes, highlands, plains, and valleys shape the general landscape of the area. According to the Koppen-Geiger climate type map, Saudi Arabia is located in the BWh zone, which is classified as a hot and arid climate (Peel, Finlayson and McMahon, 2007). Despite the cold winter in the region, the overall weather is considered very hot and dry. External dry bulb temperatures (DBT) in summer exceed 45°C, and the summer average DBT and wet bulb temperatures (WBT) are 36.5°C and 18.8°C, respectively. Figure 4-3 shows the prevailing climatic conditions of the area, displaying that the daytime relative humidity is typically below 20% during the summer and the average wind speed is around 3m/s, with peak wind velocity reaching up to 12m/s. The prevailing wind directions are north and north-west, particularly during the summer season (see Figure 4-4).

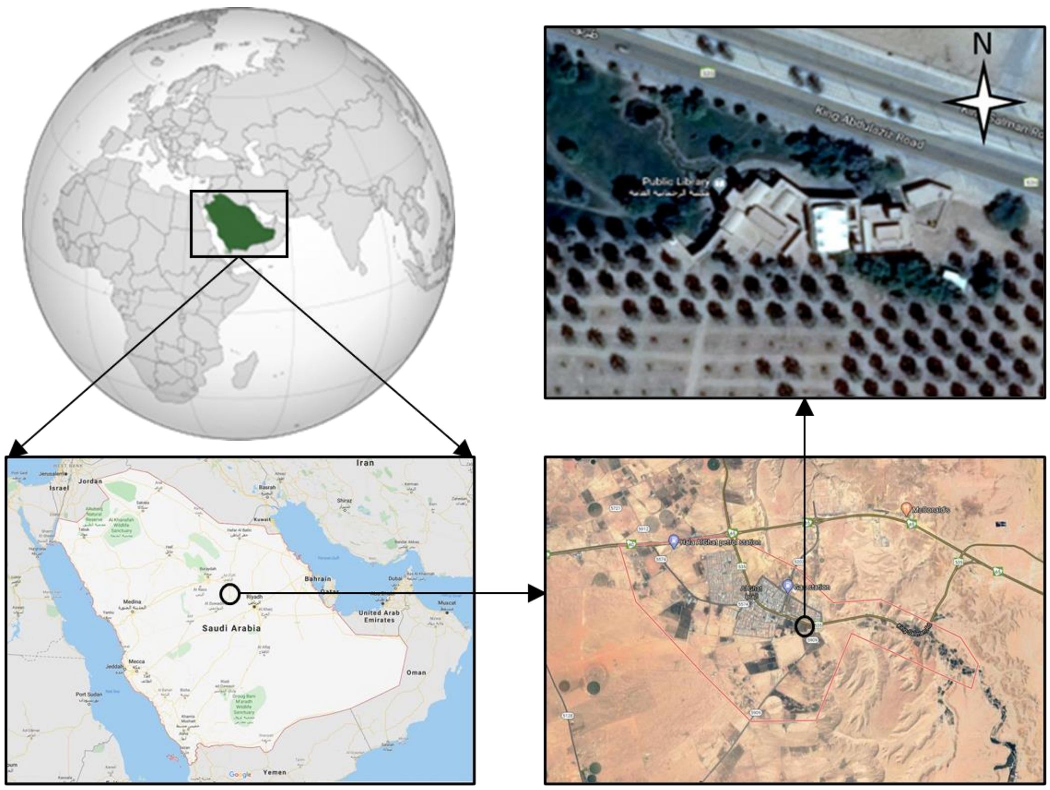


Figure 4-2: The location and orientation of the case study

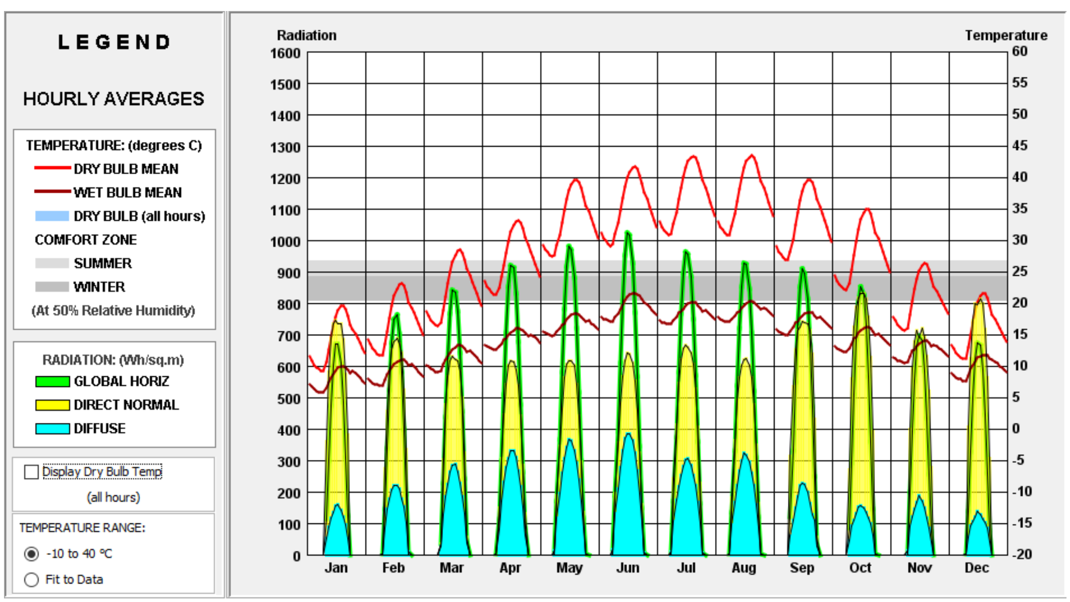


Figure 4-3: Monthly diurnal averages for Riyadh (Climate Consultant, 2019a)

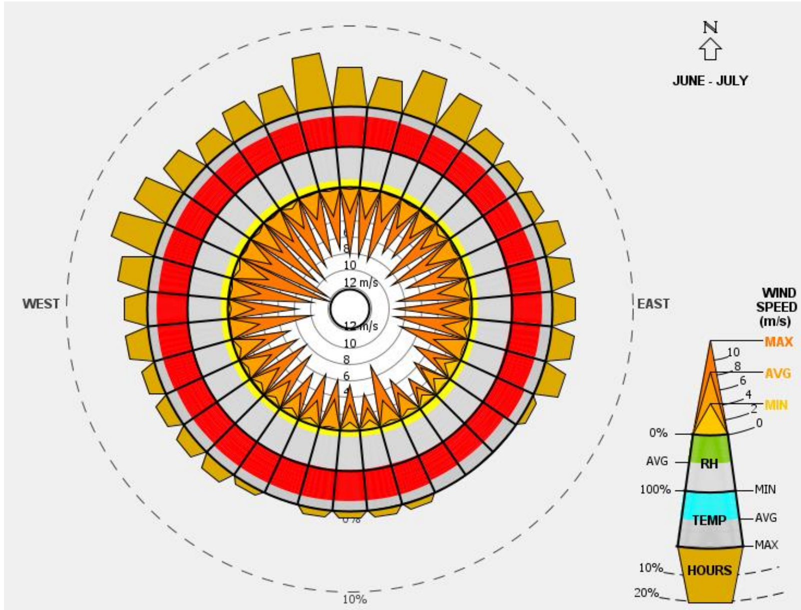


Figure 4-4: Wind rose for Riyadh during the summer (Climate Consultant, 2019a)

4.4 THE STUDIED BUILDING AND PDEC TOWERS CHARACTERISTICS

The purpose of this section is to describe the design and characteristics of the case study building and PDEC towers. The library is built within an open landscape area and surrounded by trees, and a body of water to the north-west side. It consists of three main parts, including a men's section, a women and children's' section, and an auditorium section. The men's building, which is the studied building, represents the main and largest part of the library, where two PDEC towers are used to cool the open space. It is apparent that the designer of the library tried to reflect the surrounding environment when designing the building. The use of construction materials from the same environment, such as straw bale walls covered with earthen plaster and wooden roof structure, gives a clear expression of how the building belongs to its land. The high thermal mass of the used material could provide a cooler internal temperature of the occupied spaces.

As shown in Figure 4-1 above, the main entrance is located on the north-west side of the men's building between two PDEC towers, with the left-hand tower named as Tower A in this study and B on the right side of the entrance. The floor plan and sections drawings of the library are shown in Figure 4-10, Figure 4-11 and Figure 4-12 in the On-site

Monitoring section below. The library is mainly a large open space with a total floor area of approximately 443m^2. Open-plan offices for the workers are located in the west corner by the large open space, and adjacent to tower B's supply opening. Other service spaces such as toilets and storages are located in the NE and SW perimeter of the library. The two PDEC towers use the wetted pads approach to cool the open space of the library. It is apparent from the location of the towers that the design concept was to capture the prevailing summer winds and direct them into the building after evaporatively cooling the air. The two towers are approximately 10m high with four openings on the top. At the bottom of each tower, there is one large opening to deliver the cool air to the occupied space. Long and leeward clerestories openings are placed in the centre of the roof facing north-eastern and south-western side. The leeward clerestory openings in the roof were designed to assure the circulation of the air inside the building. Table 4-1 and Table 4-2 and Figure 4-5 to Figure 4-7 below show the architectural details and construction specifications for the building and the Towers.

The library working time is divided into two shifts from Sunday to Thursday. The first shift starts from 09:00 to 12:00, while the second shift is from 16:00 to 20:00. However, the PDEC towers were set to work for 24 hours each day during the entire summer season.

Table 4-1: Building and construction specifications of the men section

	Building & construction details
Orientation	North-West
Number of storeys	1
Space height	4.4m
Library floor area	443 m^2
External walls	112cm total thickness: earthen plaster finish + straw bales (average size: 95 x 48 x 30cm) + earthen plaster finish
Roof	10cm light clay straw plaster + 7cm heavy clay plaster + 2cm lime plaster finish
column	Cast in place concrete column
Roof leeward openings	In the centre of the library roof (0.9m(H) x 14m(W))

Table 4-2: PDEC Tower specifications and details for Tower A and B.

	PDEC tower specifications
Tower height	10m
Tower dimensions	3.7m x 3.4m (narrows to nearly 3.2m x 2.9m at the top)
Windcatcher	Four sides openings at the top (1.5m height x 2m width each)
Supply openings	One supply opening at the bottom of each tower (2m width x 1.8m height)
walls	46cm total thickness (20cm concrete masonry + 20cm stone block)

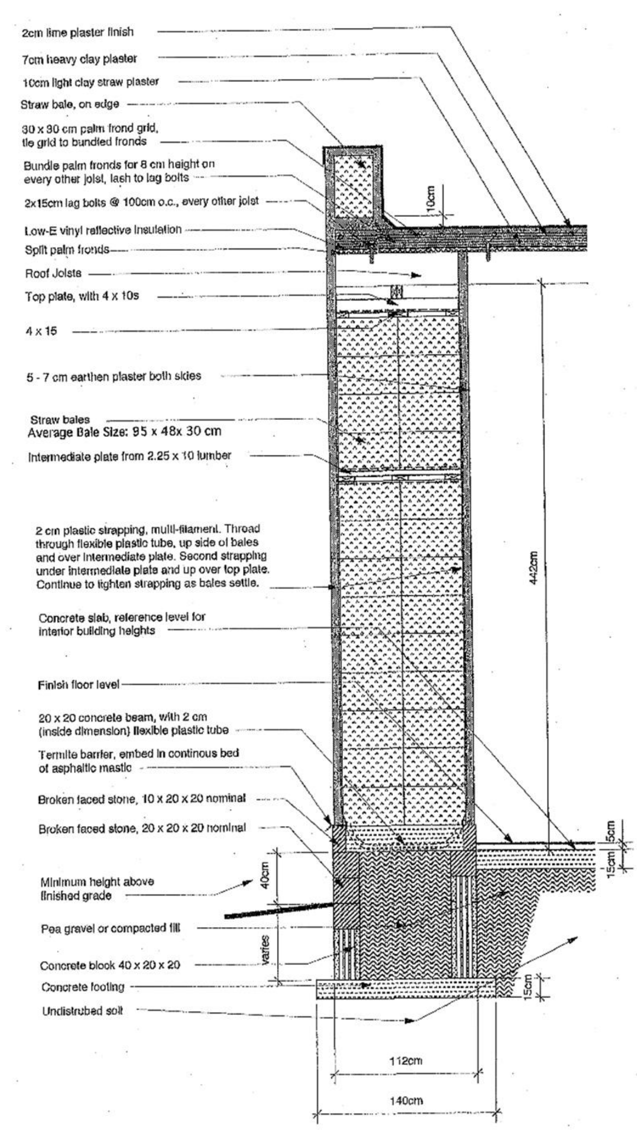


Figure 4-5: Section of a typical library straw bale wall

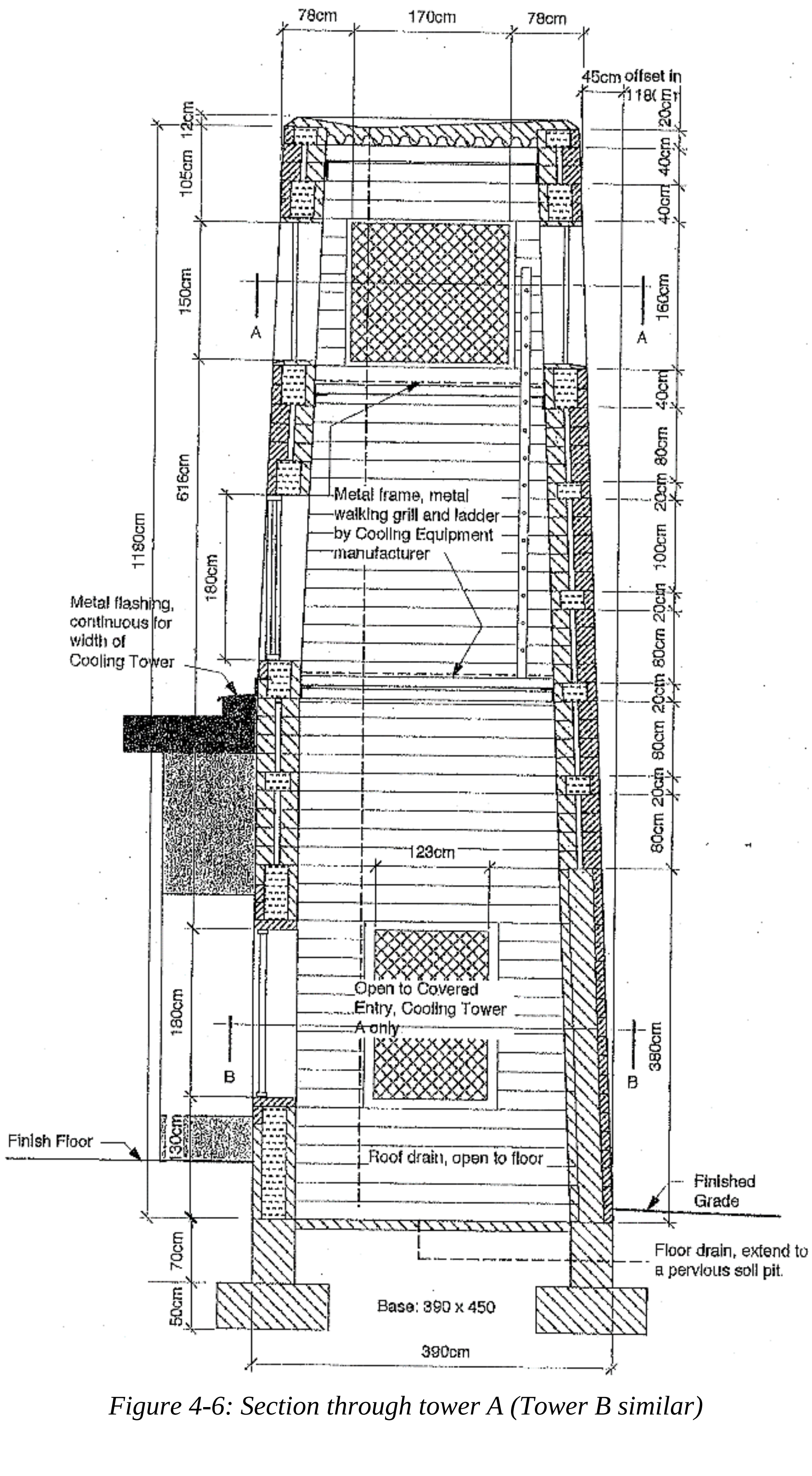


Figure 4-6: Section through tower A (Tower B similar)

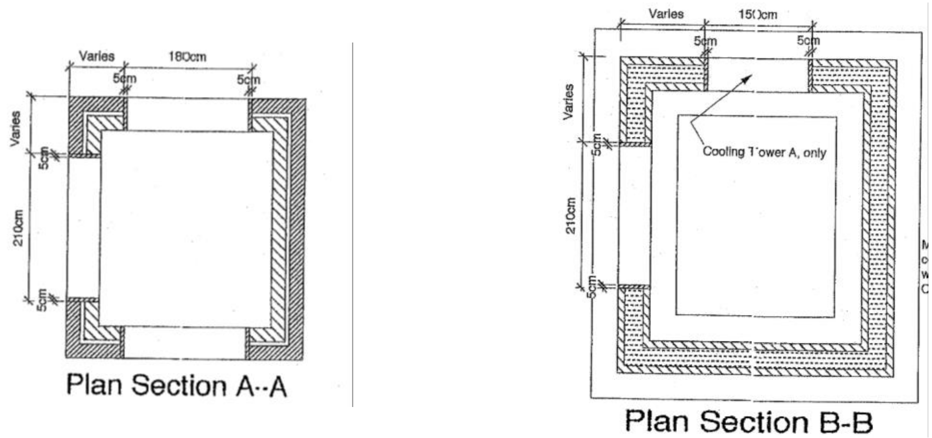


Figure 4-7: Plan views of tower A at different height level (Tower B similar)

4.5 ON-SITE MONITORING

To date, various methods have been developed and introduced to conduct building monitoring. Guerra-Santin and Tweed have recently reviewed and presented a number of building monitoring methods (Guerra-Santin and Tweed, 2015). The study classified building monitoring into three main categories, including energy, comfort and outdoor/indoor environment, and building operation.

In terms of comfort and environment monitoring, two different data collection methods could be employed to perform the monitoring. The first method provides objective data and involves the monitoring of indoor and outdoor parameters, including temperature, relative humidity, CO2 levels, solar radiation, wind speed, wind direction, and precipitation. The other method is based on field surveys that aim to collect subjective data regarding thermal comfort based on occupants' responses. The monitoring could be conducted in two different ways: long-term measurements and spot measurements. The long-term measures are considered when the purpose of the monitoring is to investigate a building performance for a long period of time. This method is useful when access to a building is granted to install monitoring devices. On the other hand, the spot measurements are usually used when investigating the expression of thermal comfort for occupants at a specific time. So, their responses are then linked to recorded indoor and outdoor parameters at the same moment of occupant responses. Spot measurements are usually necessary when recording and gathering specific details, or when long term measurements are not possible. Indoor and outdoor climates could be utilised to evaluate thermal comfort using thermal comfort models such as the PMV and adaptive model (Guerra-Santin and Tweed, 2015).

Energy consumption is the second monitoring category. Energy can be measured using existing meters or installed sub-meters. The energy meters provide data about the overall consumption of a building while the sub-meters can be used to categorise the energy use within the building. The energy consumption data can be collected in three different methods. Meter readings are the first, easiest, and cheapest way. The energy data can be obtained directly from the energy meters in a building at the beginning and the end of the monitoring period or the utility bills when on-site meters are not available or accessible. High-frequency data loggers provide another option for energy data collection. The advantage of this method is that it provides detailed information about energy usage in a building. The third method is the use of an existing Building Management System (BMS)(Guerra-Santin and Tweed, 2015). Like high-frequently energy logging, BMS can provide detailed information about a building. However, the BMS is suitable when it is already installed in a building; otherwise, it would be expensive (Guerra-Santin and Tweed, 2015).

The third monitoring category is building operation. Occupants' behaviour and lifestyle affect the building operation and, ultimately, energy consumption. Building operation monitoring can be performed by either physical monitoring or occupant investigation. Physical monitoring provides measured data that indicates the operation of a building like heat and water usage, doors and windows opening, lighting, noise, and occupants existence in space. In the other hand, occupants' investigation involves observation, interviews, and questioner surveys with occupants about their lifestyle in the building. The disadvantage of this technique is the difficulty to carry out such monitoring process because of the privacy of users and accessibility to the building (Guerra-Santin and Tweed, 2015).

For the research purposes, environment parameter monitoring (indoor and outdoor) is considered as well as site visits to collect possible data about the building and PDEC details. Indoor and outdoor parameters encompassing external and internal DBT, WBT external and interior relative humidity, external wind speed and wind direction, and internal air velocity were monitored during the summer of 2018 using data loggers that were installed outside and inside the library and towers.

In the early stage of the research, electricity monitoring was considered. However, as mentioned previously, the building is divided into three main parts, including separate sections for men, women and children, and an auditorium. Two main limitations were faced when investigating the chosen building. First, it was not possible to monitor the women's section as it was not accessible for the author for religious and privacy reasons. Hence, the men's building was chosen for the monitoring process as it was fully accessible and represented the largest part of the library where two PDEC towers were used to cool the building. Second, the energy consumption monitoring and analysis was not conducted as the entire library with its three sections was run and monitored by just one electricity meter. In addition, it was difficult to install submetering loggers for electricity due to the high cost of purchasing and installing such devices as well as their need for professionals to install and monitor such devices. As a result, it was not possible to acquire and analyse the energy use for the investigated building only. The studied building and its two PDEC towers were monitored for over 70, days, from the 21 June to the 31 August, during the summer of 2018. Before instaling the devices, full permission was granted from Abdulrahman Al-Sudairy Cultural Centre (see Appendix B).

4.5.1 Monitoring Equipment

Four different data-logging equipment were used for the monitoring of the building (Figure 4-8). The recorded parameters included external and internal dry-bulb and wet-bulb temperature, external and interior relative humidity, external wind speed and wind direction, and internal air velocity. The data logger types used in the monitoring process are explained as follows:

- **Kestrel 5500:** The Kestrel 5500 is a weather meter that can read and record a wide range of parameters. These parameters include wind speed, wind direction, dry-bulb temperature, RH and wet-bulb temperature. The meter is easy to set up and install. This mini weather station was installed on the library roof to record different weather parameters. The mini weather station was installed on a tripod to move with the wind and measure wind direction and speed. It was also shaded to protect the sensors from direct radiations (as recommended by the manufacturer).

- **Kestrel 5200:** The Kestrel 5200 is like the Kestrel 5500. The most apparent difference is that the 5200 meter does not contain a compass, so it cannot read and record wind direction. However, it can record extra parameters such as evaporation rate and moisture content. The Kestrel 5200 could be used to measure external weather parameters and indoor environmental parameters. Two Kestrel 5200 were installed at the Tower supply openings to collect the supply air conditions.
- **EXTECH SDL350 Thermo-Anemometer:** The EXTECH SDL350 consists of two parts - the meter and a probe that contains the sensors. The meter is featured by its sensitive sensors, which can record temperature and air velocity readings at low values. The EXTECH SDL350 was chosen to record air velocity readings from within the PDEC tower B.
- **Rotronic HL-1D:** The Rotronic HL-1D is a compact and easy to install data logger. It can record air temperature and relative humidity for a long period. Seven data loggers of this type were installed in different locations within the PDEC tower B and the occupied space.

Kestrel 5500 | Kestrel 5200 | EXTECH SDL350 | Rotronic HL-1D

Figure 4-8: The data loggers used for the monitoring of the PDEC case study

4.5.1.1 Data-loggers Details and Accuracy

The specifications of the sensors are summarised in Table 4-3. All the loggers were new and unused. Factory calibrations were checked by running the loggers in a controlled space for 12 hours with 30 minutes reporting interval to ensure consistent readings. Note that the minimum starting speed for the Kestrel loggers is 0.6m/s, which meant that external wind speeds below 0.6m/s would be recorded as zero. The validation results for the data loggers are shown in Figure 4-9 below.

Table 4-3: Data loggers and sensors specifications

	Measurement range	Accuracy	Reporting interval
Kestrel 5500	Temp: -29 to 70°C RH: 10 to 90% WS: 0.6 to 40m/s	Temp: ±0.5°C RH: ±2% WS: ±3%, compass: ±5°	10 minutes
Kestrel 5200	Temp: -29 to 70°C RH: 10 to 90% Air speed: 0.6 to 40m/s	Temp: ±0.5°C RH: ±2% Air speed: ±3%	10 minutes
EXTECH SDL350	Temp: 0 to 50°C Velocity: 0.2 to 25m/s	Temp: ±0.8°C V: ±5%	10 minutes
Rotronic HL-1D	Temp: -20 to 70°C RH: 0 to 100%	Temp: ±0.3°C RH: ±3.0%	10 minutes

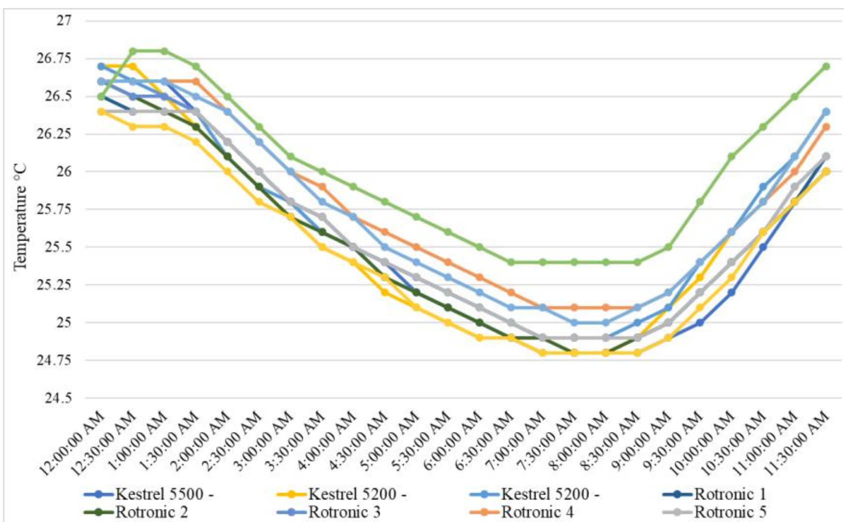


Figure 4-9 Reading results of the data loggers for 12 hour

4.5.2 Data-loggers Installation

The data loggers mentioned above were installed in the library for more than 70 days from 21st June to the 30th Aug 2018. The recordings were set for 24 hours continuous logging each day with a logging interval of 10 minutes. The data loggers were installed in different locations in the library and the PDEC towers, as well as the mini weather station installed outside (Figure 4-10, Figure 4-11, and Figure 4-12). All the data loggers were labelled and numbered prior to their installation to organise the process of installation, and eventually simplify the process of sorting and arranging the collected data. The schematic drawings show the position of the sensors. The mini weather station (Kestrel 5500) was installed on a tripod centrally above the roof of the library. As shown in Figure 4-13, the meter was raised above the roof by approximately 1.2m. The meter was shaded as recommended by the manufacturer. Two Kestrel 5200 were installed in a fixed position at the supply openings of Tower A and B at a height of roughly 1.4m from the floor. Four temperature and humidity data loggers (H1-1D) were positioned on walls in different locations within the library. These locations included spots near the supply opening of Tower A (computer zone), near the supply opening of Tower B (administration zone), the middle of the library, and the back of the library. The height of the sensors was 1.6m, which provided an ideal position within the occupied spaces. One more H1-1D meter was installed near the supply opening of an AC unit to collect data of the working hours of the mechanical cooling units. Two H1-1D meters were also installed within Tower B - one was at the top of the Tower, located 2.3m below the pads, while the other was located on the back wall at the bottom of the Tower, at a 1.6m height above the floor. The thermo-anemometer was installed inside Tower B. The probe sensors were positioned in a fixed position centrally inside the Tower at 2.9m above the floor. The small opening within the probe, where the sensors located, was positioned vertically to allow the air within the tower to pass through it to accurately measure the temperature and air velocity within the tower. Figure 4-13 shows pictures of the library and data-loggers during the installation.

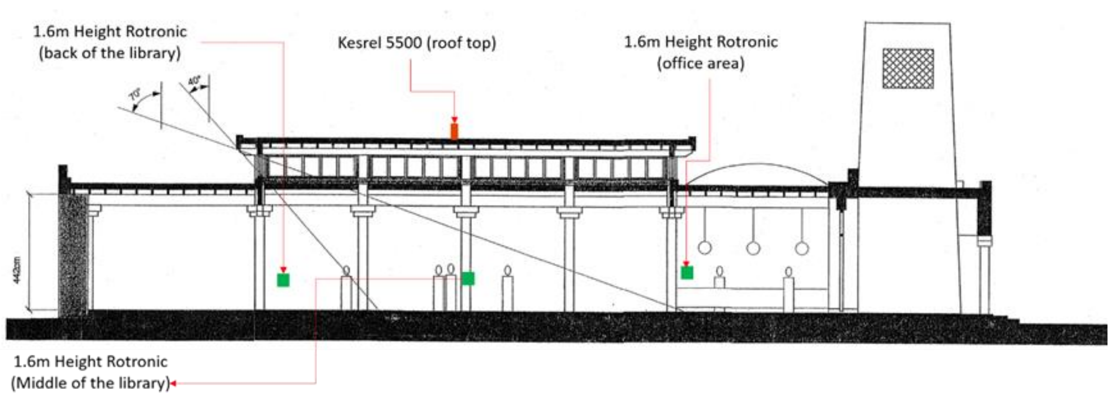


Figure 4-10: Section A-A showing the location of some data-loggers

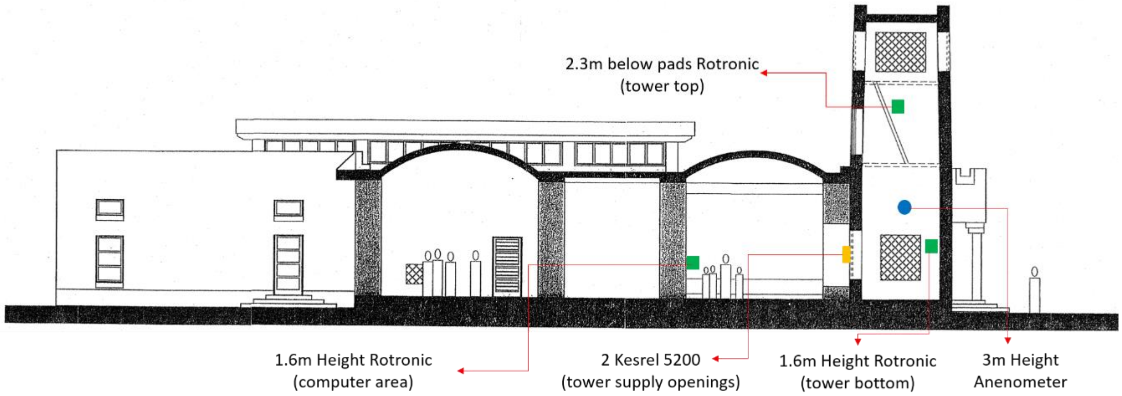


Figure 4-11: Section B-B showing the location of some data-loggers

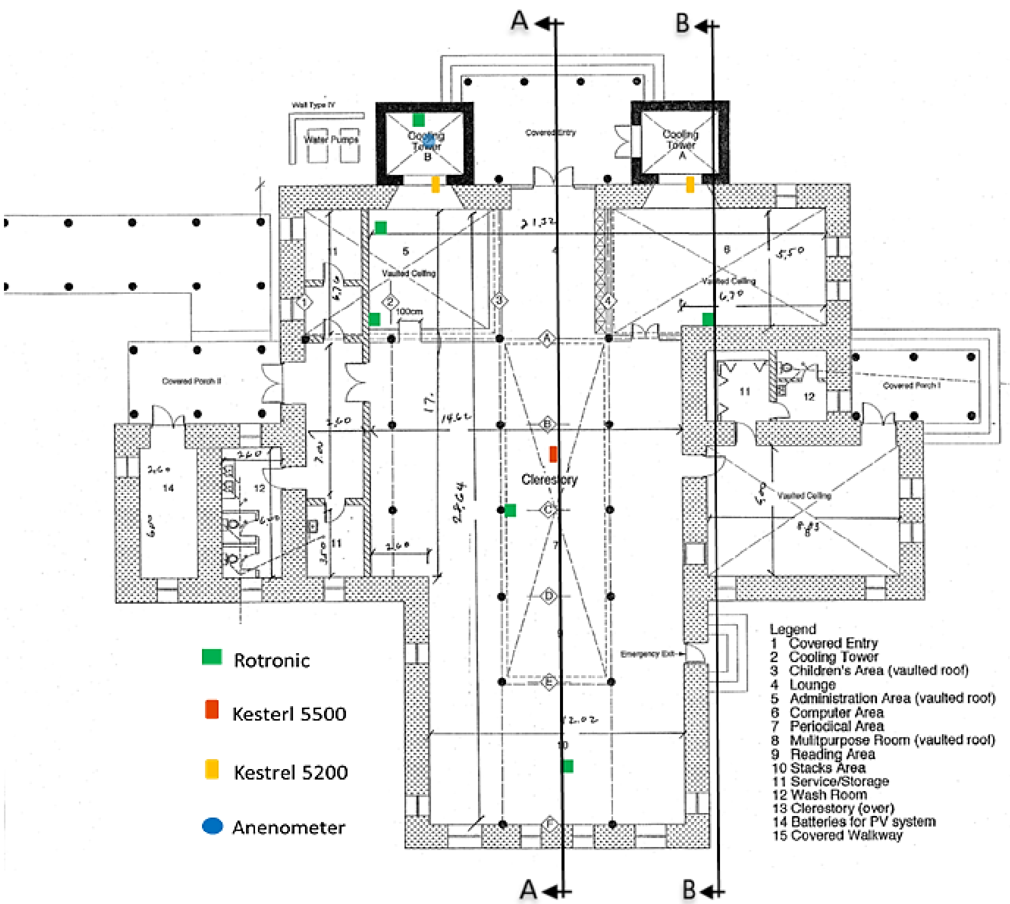


Figure 4-12: Library floor plan showing the location of the data loggers installed

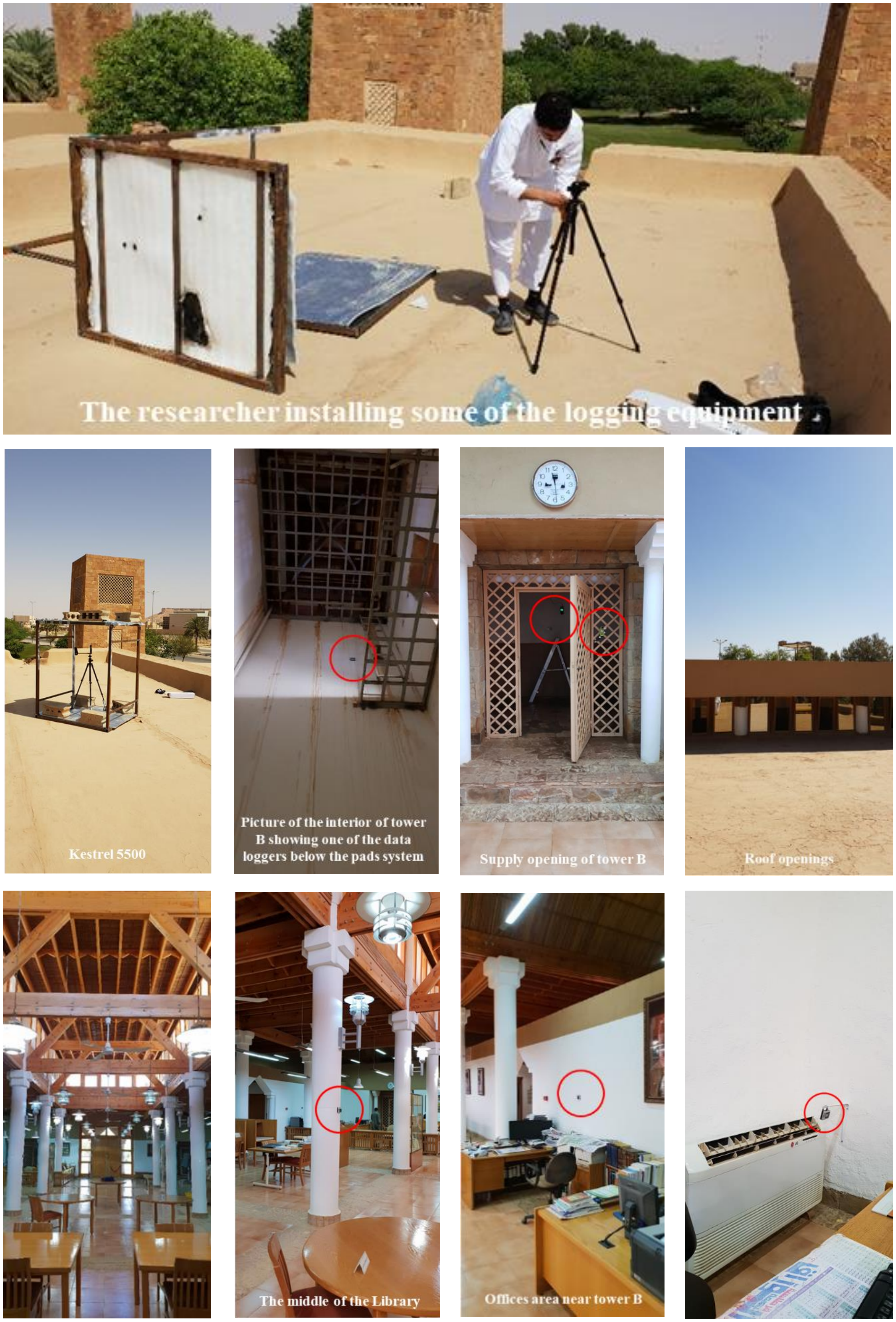


Figure 4-13: Pictures taken during the installation of the data loggers

4.6 **RESULTS AND ANALYSES**

4.6.1 Cooling Impact

For the hot, dry climate of Saudi Arabia, the monitored performance demonstrated the ability of the PDEC system to cool the incoming air. The temperature difference between the external DBT and that delivered at the bottom of the PDEC towers ranged from 6°C in the early morning to 22.5°C during the hottest parts of the days (~3.00pm). The minimum and maximum measured indoor temperatures were 23.0°C and 29.5°C, respectively. The hottest recorded period, represented in 10 days from 5th to 15th of July, is presented in Figure 4-14 below. The recording for the entire measured period is shown in Appendix C. The graph below describes the measured hourly external dry-bulb temperature (DBT), external wet-bulb temperature (WBT), and the indoor temperature observed by a Rotronic HL-1D data logger placed in the middle of the library. The explanation for presenting the temperature readings from the middle of the library was for two main reasons. Firstly, this location was almost at the central location of the open-plan, as shown in Figure 4-12 and Figure 4-13 above. Secondly, it is within the reading and setting area for occupants and visitors to the library. Consequently, the measured temperatures will provide an indication of the temperature felt by most users as it is neither too close (cooler) nor too far (warmer) from the tower supply openings.

The PDEC towers provided a significant amount of cooling to the space, considering that the mechanical air conditioning was on for only 4 hours from 16:00 to 20:00 on the 11th July. On July 14th, the maximum external DBT peaked around 46°C mid-afternoon while the WBT was around 20°C. The supply air temperature for tower A (Ta) and B (Tb) was recorded at 24.2°C and 23.5°C respectively at the same time while the internal temperature was around 25.8°C. At the same peak hour, the indoor relative humidity (RH) increased rapidly when compared to the external RH due to the evaporation process occurred within the PDEC tower. The recorded external RH was around 8% while the internal RH was approximately 65% at Tower A (RHa), 70% at Tower B (RHb), and 61% in the middle of the library.

Despite the PDEC towers providing cooling for most of the time, there was still a need for mechanical cooling as the PDEC towers could not provide enough cooling all the time.

For instance, the maximum DBT reached around 43°C on July 11th. The WBT was recorded around 18°C while the external RH was recorded at 7% during the same time. Given these suitable conditions for such a passive cooling system, the result, however, shows a higher indoor temperature although with the relatively lower DBT compared to the previous case. The indoor temperature was observed around 28°C at 15:00 while the indoor RH was about 43%. The total reduction from the DBT to delivered temperatures was around 16°C, while it was around 22.5°C in the first case, leading to the mechanical cooling being used after 16:00 when the building was occupied in line with the PDEC towers. To further investigate that, the cooling efficiency will be calculated and analysed for the entire monitored period in the following section.

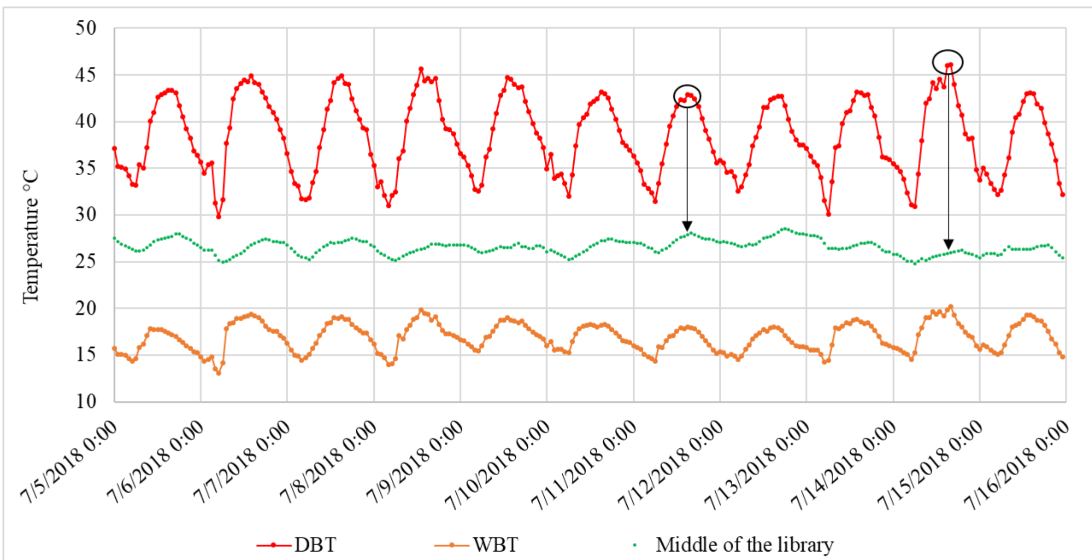


Figure 4-14: 10 days from 5th to 15th July, representing the hottest recorded period

4.6.1.1 PDEC cooling efficiency

The cooling efficiency for both towers was calculated using Equation 3.1 mentioned in section 3.3 of the previous chapter. Figure 4-15 shows the calculated hourly cooling efficiency for the entire recorded period. The overall evaporative cooling efficiency for each tower is good, as shown in the graph below. However, high fluctuations in both towers' efficiency was observed. The maximum and minimum efficiency achieved by Tower A was approximately 91% and 2%, respectively, while it was around 94% and

16.5% for Tower B. The very low cooling efficiencies were observed only during the night hours when the library was closed. By analysing the data, it was found that the minimum efficiencies for both towers were not happening simultaneously. In fact, when one tower's performance was poor, the other tower performed well. This opposite performance was observed after midnight until early morning (when the library was closed). This could be attributed to the closure of exhaust openings during this time, which makes one tower acts as a stack tower to exhaust the air coming from the other tower. This finding is supported by the fact that the temperature and RH of the less efficient tower are close to the occupied space condition (indoor temperature and RH), which indicates that the tower is affected by the condition of the surrounding space. Otherwise, both towers showed approximately similar performance during occupied hours. The average cooling efficiency was found to be roughly 66% and 71% for tower A and B, respectively.

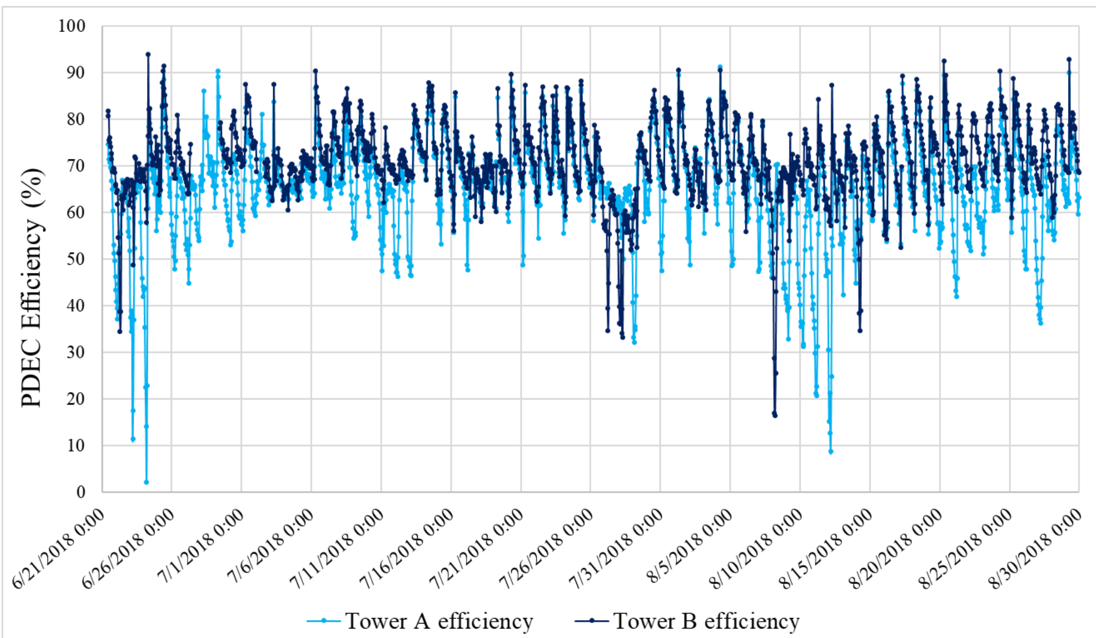


Figure 4-15: PDEC efficiency of tower A and B during the whole measured period

During working hours, the minimum cooling efficiency for Tower A increased to nearly 44% while the maximum was around 89%. For Tower B, the minimum cooling efficiency was approximately 54%, and the maximum was around 91%. The average cooling efficiencies during the occupied hours for towers A and B were around 70% and 75%, respectively. The better stability of the towers' performance and higher values of minimum efficiency levels is linked to the better air circulation within the building during these hours as the roof's leeward openings were opened to enhance the cooling performance.

It was also noted that under certain weather conditions, the PDEC performance was less effective. Changes in wind conditions played significant roles in the overall performance of the PDEC towers. As a result, analysis of wind direction and wind speed effect was carried out.

4.6.2 Wind Direction Effect

In this case study, it was observed that the wind direction has a minimal impact on PDEC performance. Figure 4-16 and Figure 4-17 show the recorded supply temperatures for both towers correlated against different wind directions. The correlation was performed by sorting down the recorded wind directions from 0^o to 360^o, where north is (0^o), East (90^o), south (180^o), West (270^o), and 360^o return to the north. The results clearly illustrate the minimal effect of changes in wind directions on supply temperatures of the PDEC towers. In fact, higher supply temperatures were measured during north and north-western wind directions, which is towards the PDEC towers directly. This was mostly occurring during either higher outdoor DBT or higher wind speeds. This will be further discussed in the following section. The minimal impact of wind direction could be attributed to four main reasons. First, the building was oriented in a way that placed the two cooling towers towards the prevailing wind direction, which was north-west. This minimised the effect of wind direction for most of the time. Secondly, it is strongly expected that the design and placement of the leeward clerestory openings within the roof significantly minimised the effect of other wind directions. Third, the windcatcher, at the top of each tower, was designed with four openings facing each direction. Then, an X-shaped wind barrier was placed inside the windcatcher directing the coming winds from any direction towards the airstream within the tower. Last, most of the collected data were at low wind speed while the data that was during higher wind speed was mostly coming from the prevailing wind direction. As a result, the impact of wind direction was neglected when investigating the wind speed effect.

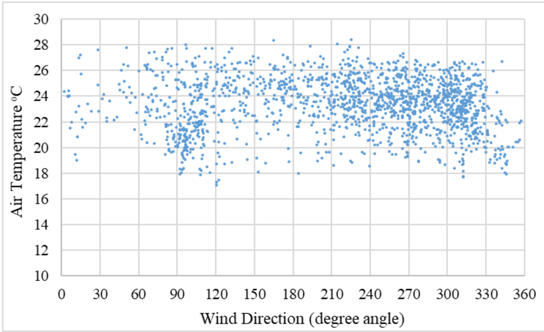


Figure 4-16: Hourly recorded Ta correlated against different wind directions (all readings)

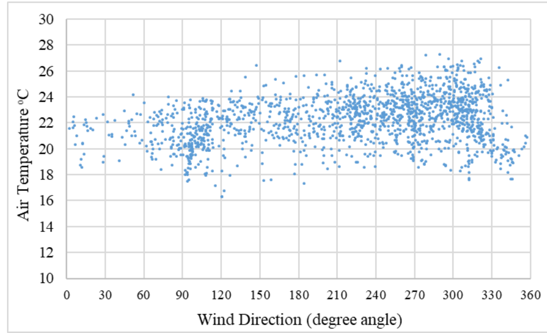


Figure 4-17: Hourly recorded Tb correlated against different wind directions (all readings)

4.6.3 Wind Speed Effect

Referring to the initial analysis, it was apparent from the collected data that the wind speed had a direct influence on the performance of the PDEC towers. Initially, two days were selected representing low cooling performance of the PDEC towers. Figure 4-18, Figure 4-19, and Figure 4-20 show wind, humidity, and temperature conditions on the 8th and 9th of August. The selected dates represent the lowest recorded internal RH and highest indoor temperatures despite the running of the PDEC towers in a very hot and dry weather with low WBT and RH level. The results indicate that the lower the wind speed then the higher the humidity levels and the greater the temperature reductions achieved. On 8th and 9th August, and during a time when the wind speed went above 4m/s, the performance of the two PDEC towers became unstable, leading to fluctuations in the supply air temperature, higher internal air temperatures, and lower humidity levels. Because of that, the indoor temperatures reached around 30°C while the relative humidity went below 30%. As a result, the loss of PDEC cooling had to be offset by mechanical air conditioning, which was running during work hours. This scenario frequently happened in several other days. Hence, a parametric analysis of the wind speed effect will be conducted in the following section.

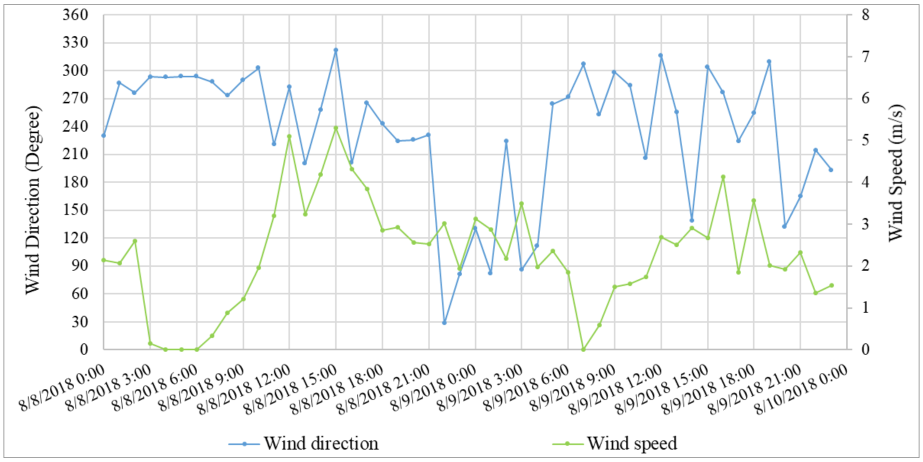


Figure 4-18: Wind speed and wind direction for the 8th and 9th August.

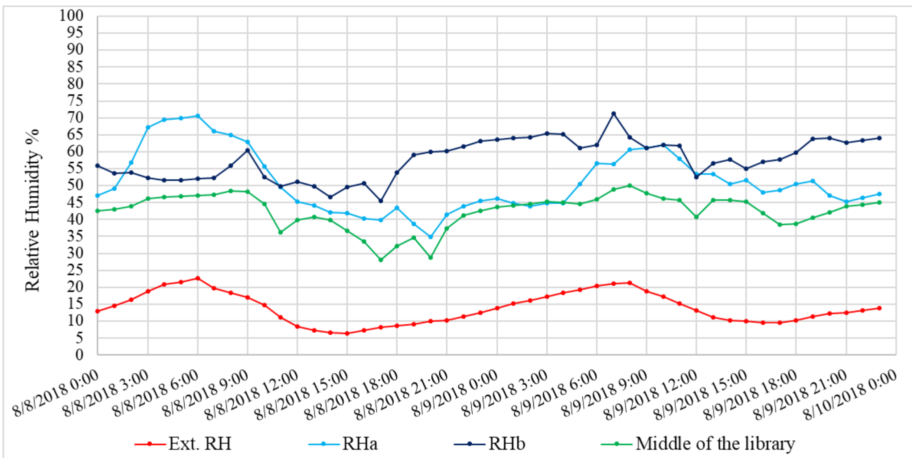


Figure 4-19: External and internal relative humidity during the 8th and 9th August

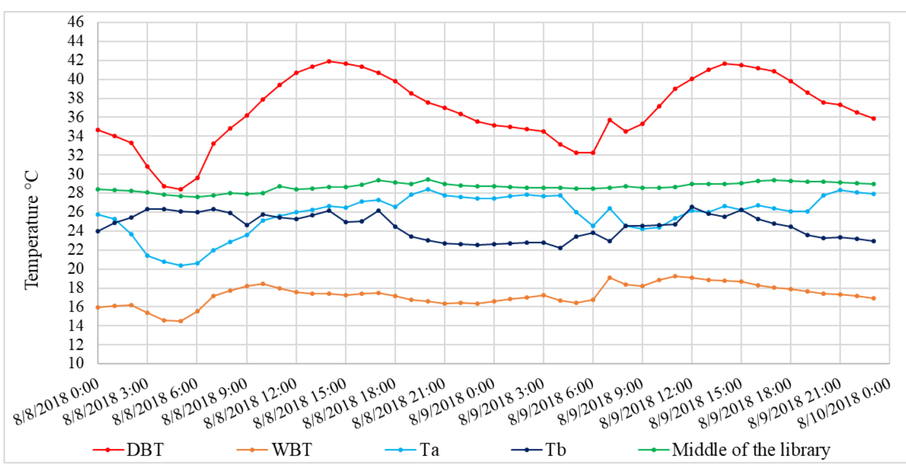


Figure 4-20: External DBT, WBT, and internal temperatures for the 8th and 9th August

4.6.4 Analysis of the Effect of Wind Speed

This section discusses in detail the effect of external wind speed on the performance of the PDEC towers in the library. The parametric analysis of the effect of wind speed was conducted in two steps. The first step aimed to study the relationship between wind speed and the values achieved by the PDEC towers in terms of supply temperature and cooling efficiency. Similarly, the second step discusses the relationship between the external wind speed, but with the tower air velocity. This analysis is discussed in the following two subsections.

4.6.4.1 Wind speed vs cooling performance

A parametric analysis of the wind speed was conducted by correlating different wind speeds (from low to high) against the hourly supply temperatures, and the calculated cooling efficiency (see Figure 4-21 to Figure 4-28). The left column of the graphs show observed hourly supply temperatures plotted against wind speed for the PDEC towers (A and B). In a similar way, the right side represents the effect of wind speed on the cooling efficiency of the PDEC towers. In the beginning, the investigation was performed for the whole recorded period, as shown in Figure 4-21 to Figure 4-24.

The results indicated that the PDEC towers' effectiveness was influenced by changes in wind speed, but in a counter-intuitive way as stronger wind speeds tended to reduce the efficiency of the towers and increase the supply temperature. The graphs below clearly show how the increase in wind speed increased the supply temperatures from as low as 17°C to as high as approximately 29°C. Hence, the maximum cooling efficiency reduced from 90% to nearly 60%. This correlation analysis between the wind speed, on the one hand, and the supply temperatures and cooling efficiency, on the other hand, showed a strong negative relationship. However, it can be noted that higher supply temperatures and lower cooling efficiency were measured at lower wind speed. This was mostly occurring after work hours when the library was closed. To clarify that, the same analysis process was repeated, but during working hours from 9:00 to 20:00 daily. This was the time of the day representing the higher DBT when there was a large difference between the DBT and WBT, known as wet-bulb depression (WBD). Another justification was that the higher wind speeds were recorded during daytime while nighttime was mostly calm.

Furthermore, the library exhaust openings are open during this time, which would minimise the uncertainty of the data due to closed openings. Figure 4-25 to Figure 4-28 confirm how the wind speed has a negative influence on the cooling performance of both towers. A possible explanation for this is that turbulence increased around the tower inlet (windcatcher) at the top and roof exhaust openings due to the higher wind speeds, as discussed by (Kang and Strand, 2016). This situation can be seen, as well, in the supply air velocity and air velocity measured by the thermo-anemometer located inside Tower B, which will be further discussed below.

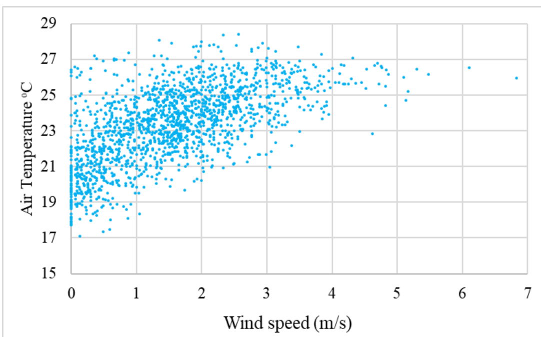


Figure 4-21: Hourly recorded Ta correlated against different wind speeds (all readings)

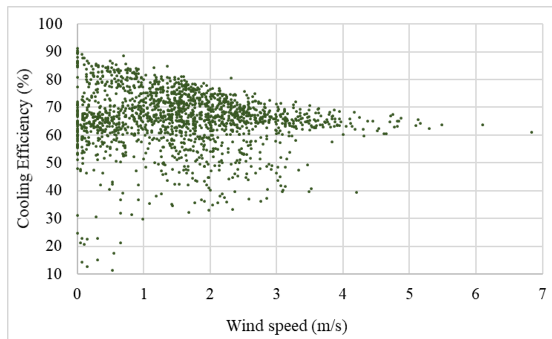


Figure 4-22: Hourly cooling efficiency for tower A against wind speed (all readings)

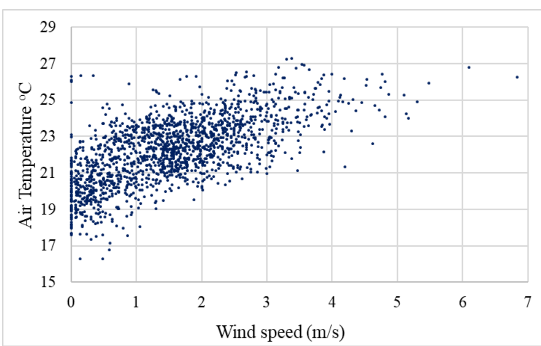


Figure 4-23: Hourly recorded Tb correlated against different wind speeds (all readings)

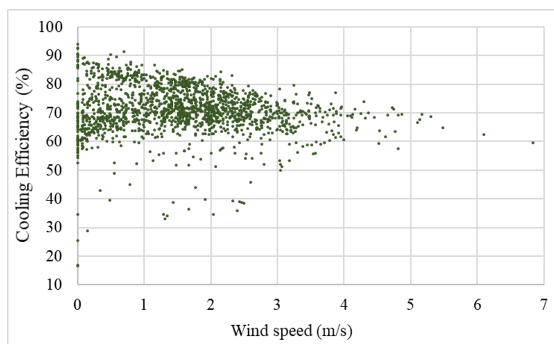


Figure 4-24: Hourly cooling efficiency for tower B against wind speed (all readings)

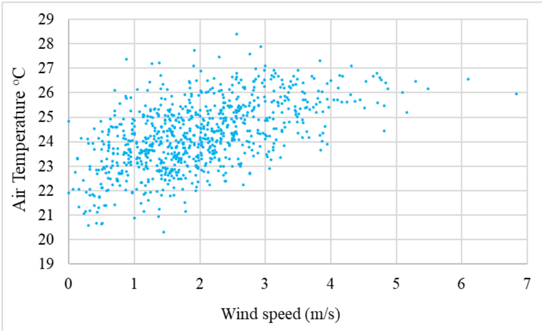


Figure 4-25: Hourly recorded Ta correlated against different wind speeds (work hours)

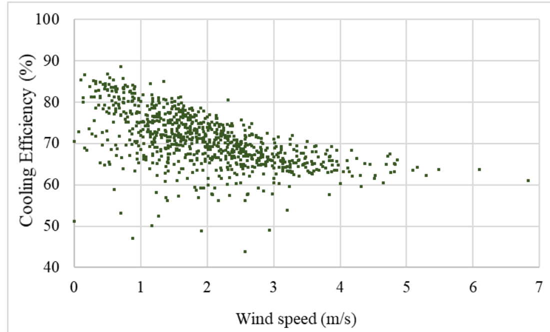


Figure 4-26: Hourly cooling efficiency for tower A against wind speed (work hours)

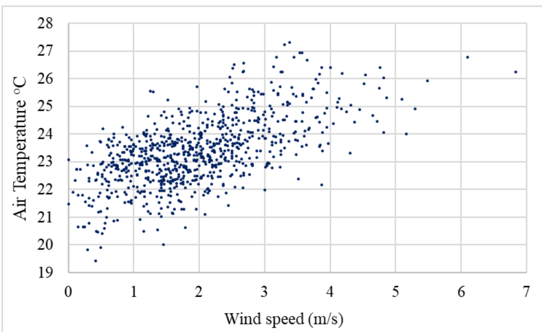


Figure 4-27: Hourly recorded Tb correlated against different wind speeds (work hours)

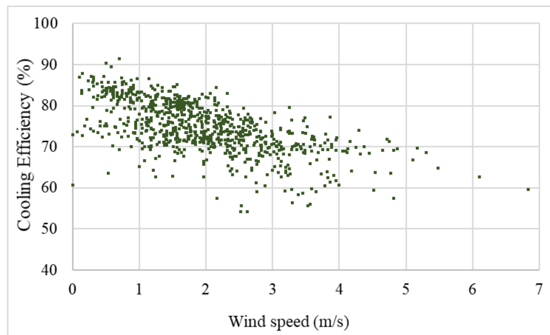


Figure 4-28: Hourly cooling efficiency for tower B against wind speed (work hours)

4.6.4.2 Wind speed vs air velocity

Following the findings in the previous section, it was observed that air velocity within the tower decreased to below 0.15m/s during the periods of higher external wind speeds. In contrast, during calm or low wind speed conditions, the acquired air velocity data of the towers were mainly above 0.5m/s, with air velocity readings exceeding 1m/s at specific points. To illustrate that, a parametric analysis of the relationship between the wind speed on one side and Tower B air velocity on the other side was performed. The analysis was performed by sorting the recorded wind speeds from low to high and then correlating them against the air velocity measured by the thermo-anemometer within Tower B. The correlation of the wind speed and air velocity shown in Figure 4-29 gives an explicit indication of how the higher wind speed decreases the air velocity within the tower.

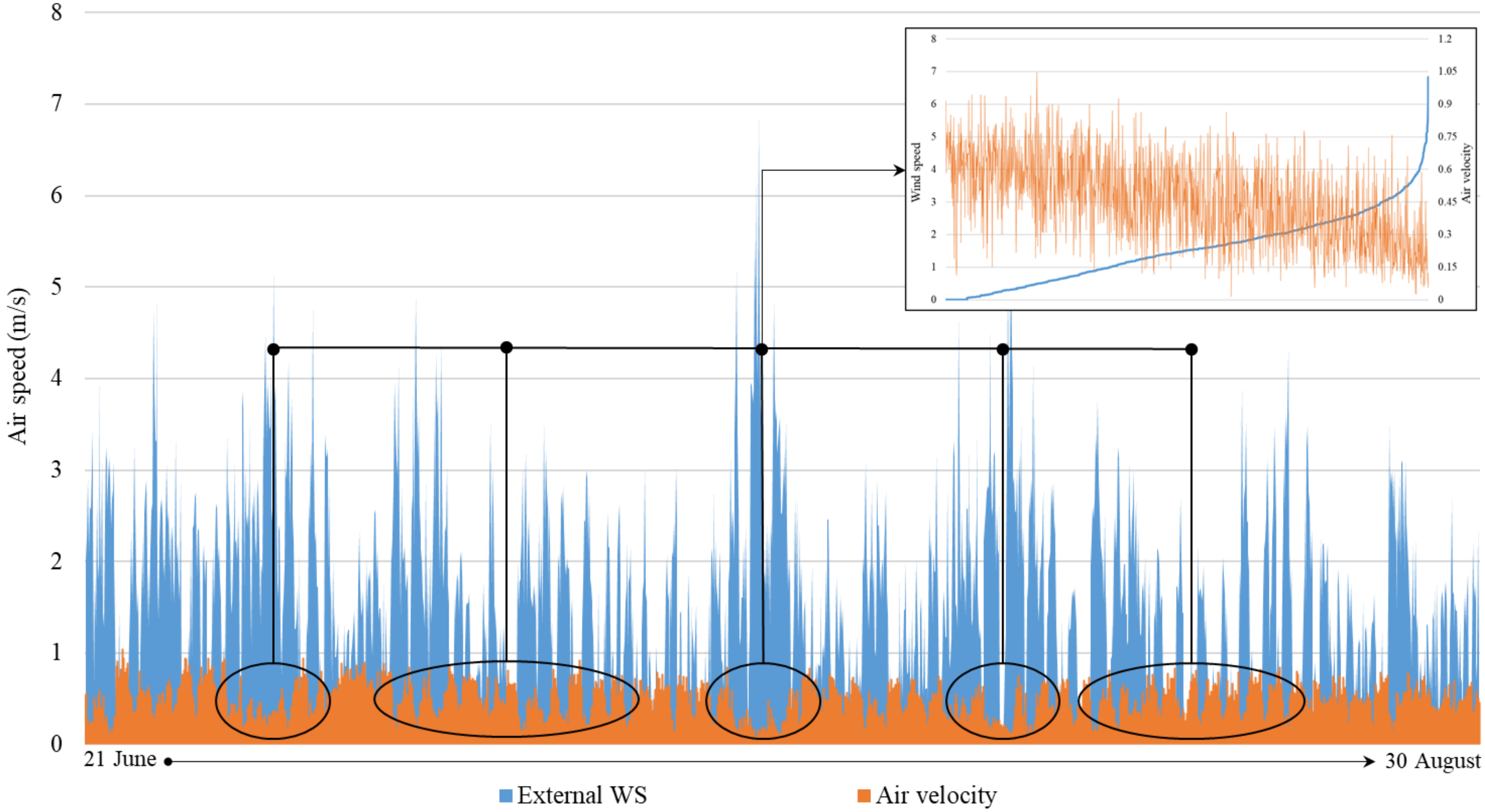


Figure 4-29: The influence of wind speed on the air velocity within the tower

4.6.5 Tower Depth

Readings from the data logger that was installed on the back wall at the bottom of Tower B (tower bottom) showed higher temperature than the supply temperature of the same tower, although both devices were at the same level. It was observed that there was a temperature difference of 2°C to 4°C for most of the time between the supply and the tower bottom temperatures. Figure 4-30 clearly illustrates this difference in four days during the hottest period. It can also be seen that the temperatures recorded by the anemometer, located at 2.9m height within the tower air stream, show approximately similar temperatures of the supply air. This indicates that there is a quiet zone where air does not move at the back of the tower bottom as the air is pulled by the supply opening on the opposite side. This suggests that a smaller tower depth could be enough to allow the air to move easily and directly to the supply opening.

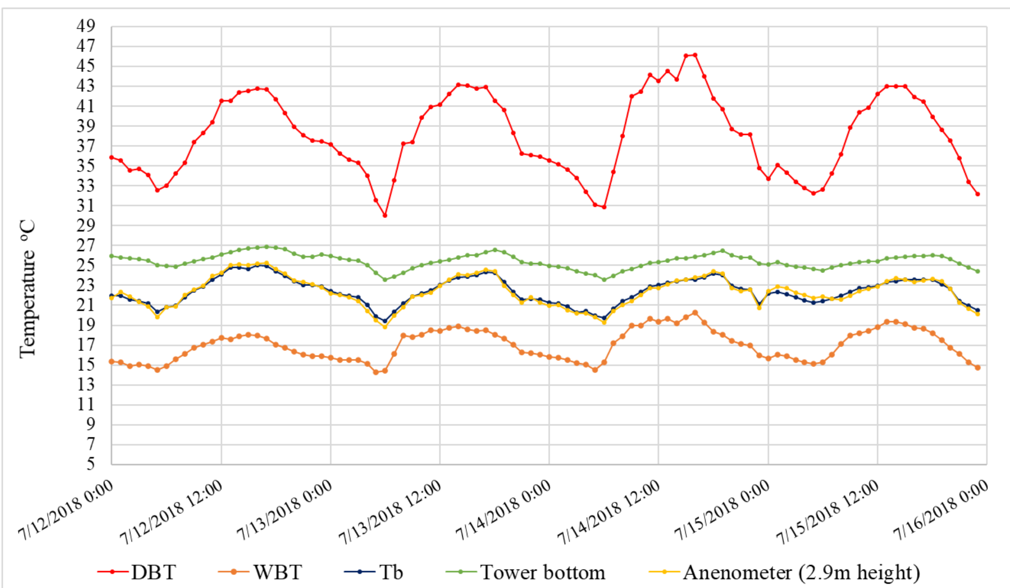


Figure 4-30: Temperature readings for the data loggers places at the bottom of tower B

4.6.6 Overall Performance

The overall cooling capacity of the PDEC towers to provide useful levels of cooling performance in the hot, arid climate of Saudi Arabia was demonstrated. Although both towers performed well most of the time, Tower B, in some cases, was more effective than Tower A. This finding could be linked to the pads' quality as the pads in Tower B were replaced prior to installing the data-loggers in the towers. In addition, the temperature in the areas close to the PDEC towers, like the office and computer lab areas, were found to be relatively cooler than the further areas such as the middle of the library (Figure 4-31). This was expected as the evaporatively cooled air will lose some of its coolness while passing through the occupied space.

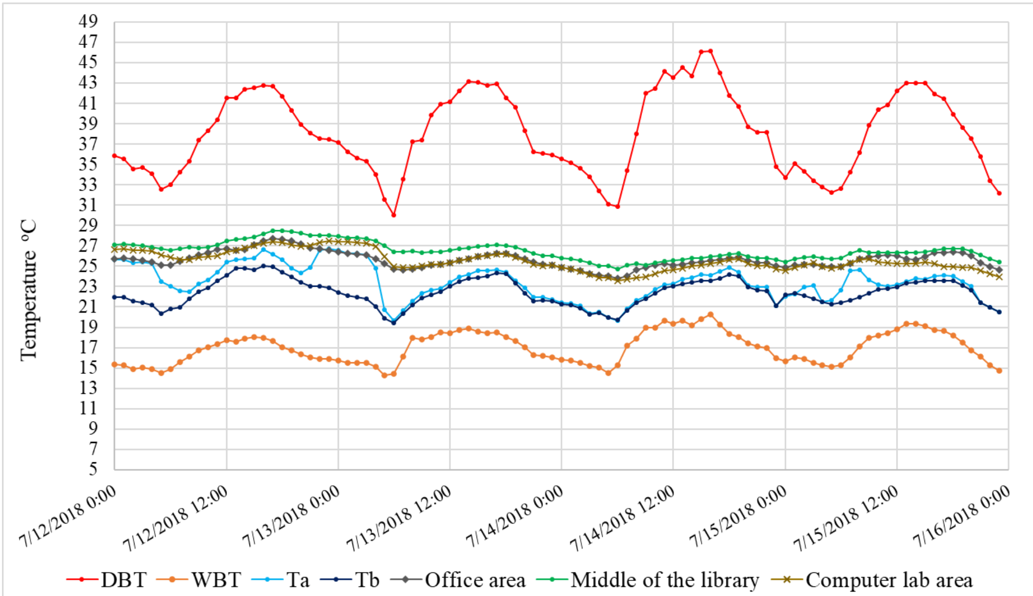


Figure 4-31: Temperature readings of the towers and different areas in the library

4.7 THERMAL COMFORT

It is very difficult to achieve thermal satisfaction for every occupant in a space as humans do not require the same environmental conditions. ASHRAE defines thermal comfort as "*the condition of mind which expresses satisfaction with the thermal environment*" (ASHRAE, 2010). So, thermal comfort ranges can be determined when the majority of space users are feeling satisfied with the thermal space environment. Two main thermal comfort models have been developed from the research of the last fifty years. One model, the heat balance PMV model, considers occupants as passive recipients of thermal stimuli. On the other side, the adaptive model recognises occupants as active users interacting with their environment. Different major comfort standards around the world, including ASHRAE 55, and CIBSE, have incorporated these two models, which are discussed below.

4.7.1 Predicted Mean Vote (PMV) – Fanger Model

The expression of thermal comfort in Fanger's (PMV) model is based on heat balance principles that are defined by six factors: (1) air temperature, (2) mean radiant temperature, (3) relative humidity, (4) air movement, (5) metabolic rate, and (6) clothing level (ASHRAE, 2010). The calculation of mean comfort vote was derived from people involved in climate chamber experiments (ASHRAE, 2010; CIBSE, 2013).

The PMV has been developed to predict the percentage of dissatisfaction of occupants that are involved in the same environment, which is known as the Predicted Percentage of Dissatisfied (PPD). The thermal sensation scale is developed to predict occupants' response (vote) to thermal conditions in a 7-point scale: (-3) cold, (-2) cool, (-1) slightly cool, (0) neutral, (+1.0) slightly warm, (+2.0) warm and (+3.0) hot. Voting within -0.5 and +0.5 represent a PPD of 10% while the dissatisfactory environment is considered when people are voting outside the central three scaling points +3, +2, -2, and -3 on the PMV/PPD scale (ASHRAE, 2010; CIBSE, 2013). The range of comfort zone and PPD distribution is based on the steady-state conditions in the climate chamber experiments (ASHRAE, 2010; CIBSE, 2013). Hence, other models have developed for naturally ventilated buildings where indoor conditions changed continuously throughout the day based on the external weather conditions and occupants' control.

4.7.2 Adaptive Thermal Comfort Model (ATC)

According to ASHRAE 55, adaptive thermal comfort (ATC) is defined as "*a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters*" (ASHRAE, 2010). Recent studies revealed that occupants showed a higher level of thermal comfort satisfaction in naturally conditioned spaces and extreme climates (Dear, Dear and Ph, 1998; Dear, 2001; Dear, Dear and Brager, 2002; Paul, John and Dear, 2012; Humphreys, 2015). This model was developed by conducting field-studies in 160 buildings from nine countries (Dear, 2001). To apply the ATC model, the investigated building (occupied space) must be exposed to the outdoors and conditioned naturally, and mechanical cooling/heating must be avoided. Besides, outdoor climate plays an important role in specifying preferred indoor comfort levels. Clothing values, humidity, and airspeed limits are not required when applying this option. It should be mentioned that indoor comfort temperatures in naturally ventilated buildings tend to be significantly higher in warmer climates.

ASHRAE Standard 55 has included this model since 2004 to define the acceptable thermal comfort limits, as shown in Figure 4-32, in naturally conditioned buildings dependent on the monthly mean outdoor temperature (ASHRAE, 2010). The ATC model used was initially developed by De Dear and Barger in 2001 and expressed in the Equation 4.1 (Dear, 2001):

Adaptive thermal comfort model

$$T_{comf} = 0.31\ Tm + 17.8 \tag{4.1}$$

where T_{comf} is the comfort temperature, and Tm is the monthly mean outdoor temperature. The model represents two comfort zones. The first (narrower range) expects that 90% of occupants feel comfort while the second wider range expects 80% acceptability. These two ranges can be defined by adding 2.5°C to both sides of the optimum comfort temperature to determine the 90% acceptability and 3.5°C for the 80% acceptability (De Dear, 2001). However, ASHRAE Standard 55 states that there is no specific standard if the mean monthly external temperature is less than 10°C or greater than 33.5°C, as this model may not be used, while the only other option is the PMV (ASHRAE, 2010).

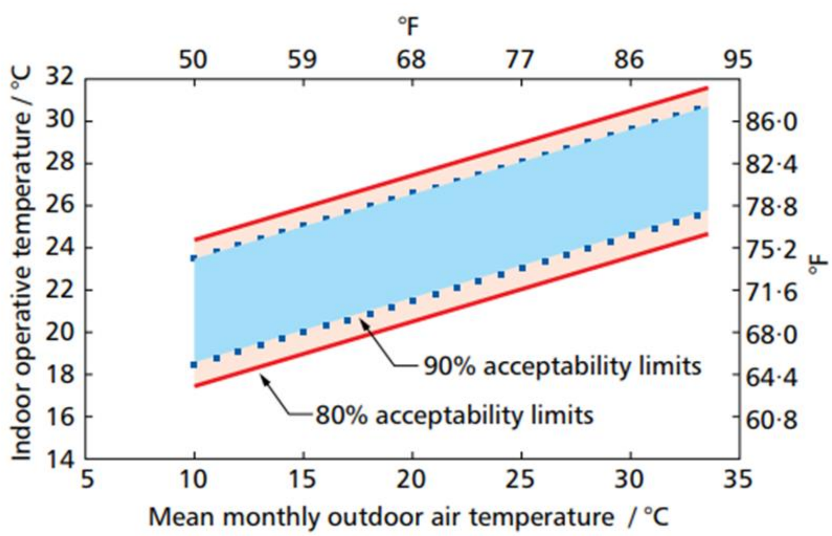


Figure 4-32: Acceptable operative temperature ranges for naturally conditioned spaces

4.7.3 Mixed-mode Buildings.

There is still a lack of definitive comfort models, as discussed earlier, to predict a thermal comfort zone in some situations. For instance, mixed-mode buildings, such as the case study presented in this research, where both passive and active cooling systems exist, are difficult to categorise. Temperature variations within spaces make it difficult to predict occupant's sensations. Researchers have suggested using the adaptive model in mixed-mode, supporting their argument by saying that the occupants have some control over some local thermal conditions (Dear, Dear and Brager, 2002; Paul, John and Dear, 2012). People with control over their building conditions have been found to tolerate a wider comfort temperature range, which is similar to the adaptive model range in naturally ventilated buildings (Dear, Dear and Brager, 2002). A study conducted by Paul and de Dear encourages the use of the ATC model in mixed-mode buildings as a guideline for passive cooling mode (Paul, John and Dear, 2012). The observation in their study supported the applicability of the adaptive model in mixed-mode buildings.

4.8 **THERMAL COMFORT ANALYSIS**

The middle of the library temperature readings was considered when conducting the thermal comfort analysis. Brief thinking might conclude that the PMV approach could be used when the building is mechanically cooled while the ATC method is used during the passive cooling mode. However, the different comfort ranges between the two models do not give similar results, which makes it difficult to apply such methods. For example, the maximum comfort level in the ATC model could be out of the comfort range of the PMV model in such an extreme climate. (CIBSE, 2013). As a result, both models were considered separately in different scenarios when conducting a thermal comfort analysis. At the beginning of the analysis, the ATC model was used to predict periods of thermal comfort during passive cooling mode only. Then, the PMV model is used for the same purpose during the mixed-mode cooling case. At this stage, the building was analysed during both work hours only, and then, during the entire monitoring period when applying the ATC model. The PMV model was used during work hours only as active cooling was used during these periods of the day. Ultimately, the ATC model and PMV model were then applied to predict the comfort level during the entire monitored period, including both passive mode and mixed-mode cooling of the building. The aim for that is to provide analysis by applying the two comfort ranges as, on the one hand, the adaptive model is not recommended by standards like ASHRAE when mean monthly outdoor temperatures exceed 33.5^{o}C, which is the case of the climate in this study, and the only other option is the PMV model. On the other hand, the adaptive model is recommended by previous research in the literature (Dear, 2001; Dear, Dear and Brager, 2002; Paul, John and Dear, 2012). Furthermore, PDEC towers were the dominant cooling system used in the building, providing cooling during approximately 95% of the total monitored period. This analysis would ultimately lead to determining the model that would be more suitable for providing a comfort zone as there is no clear guidance for such an extreme climate.

4.8.1 Passive Cooling Mode - Adaptive Model

Of the 1688 recorded hours, 410 hours were during the work (occupied) hours. The mechanical cooling was working in line with the PDEC towers (mixed-mode) for about 19% of the total occupied hours while the rest (81%) was on passive cooling mode only. In terms of the total monitoring period, the mixed-mode case represents only 5% during the whole period. This is attributed to the system were working 24 hours, including weekends and holidays. Hence, the monitored hours during the mixed-mode case were neglected in this approach to assure that the building was passively cooled. Following the adaptive comfort model limits stated in ASHRAE 55 (ASHRAE, 2010), the higher endpoint of the mean monthly outdoor temperature (33.5°C) was considered in Equation 4.1 above. Consequently, the narrower 90% acceptability limits were 25.6°C and 30.6°C while the wider 80% acceptability comfort level was between 24.6°C and 31.6°C. Using these comfort levels, detailed analysis of thermal comfort hours are explained below.

4.8.1.1 Work hours only.

Using the adaptive model, the building was analysed during working hours (332 hours) when the building was on passive cooling mode only. The number of comfort hours within the wider thermal comfort range was 325 hours, representing approximately 98% of the total period, while the remaining 2% were below the comfort zone. In detailed representation for each month, the percentage of comfort hours for June, July, and August were approximately 92%, 99% and 99% respectively. In terms of the narrower comfort zone, approximately 84.5% of the total work hours fall within the comfort zone while the rest of the hours were below the lower limit of the comfort zone. On a monthly basis, approximately 88.5% of hours are within the narrower thermal comfort zone in June, 83.5% in July, and 84% in August.

4.8.1.2 Entire monitoring period.

During the whole monitoring period, 1606 hours were recorded during passive cooling mode only, including work and no-work hours. Approximately 92% of the recorded indoor temperatures fall within the expanded thermal comfort limits where 80% of occupants are expected to feel comfortable. Within the 90% acceptability range, 70% of the monitored period is considered comfort thermally. The rest of the measurements were recorded below this limit.

4.8.2 Mixed-mode – PMV Model

Active cooling was used during occupied hours only. So, the building was on mixed-mode cooling for about 78 hours during work hours. Using the Climate Consultant weather tool, the PMV model was used to calculate the zone in which most people would feel thermally comfortable. The lowest level of thermal comfort, in the summer, calculated by the PMV model was 23°C while the highest comfort level was 26.7°C. The predicted percentage of people satisfied with this comfort zone is 80%. Using this thermal comfort range, of the occupied period, only 24% (19h) of the recorded temperatures were within the comfort zone. The rest of the resadings were above the maximum comfort level.

4.8.3 Passive and Mixed-mode

4.8.3.1 Adaptive thermal comfort model.

The adaptive model was used to predict thermal comfort hours during both work hours (410h) and total recorded hours (1688h). The results are illustrated in Figure 4-33 and Table 4-4 below. It can be seen that the majority of recorded indoor temperatures were falling within the comfort zone, ranging between 71% of acceptable temperatures within the narrower range of the total monitored period, to 98% within the wider range during work hours only. During the occupied period, 401 hours, which account for approximately 98% of the period, were recorded within the comfort 80% wider comfort zone. In the narrower zone, almost 357 hours were falling within the comfort zone representing nearly 87% of the work hours. For the total period, 1565 hours of the recorded 1688 hours were falling within the 80% acceptability limits, accounting for roughly 93% of the hours. In the 90% acceptability zone, almost 70% (1203 hours) of the hours were measured within the zone. The discomfort temperatures were all recorded below the minimum comfort level.

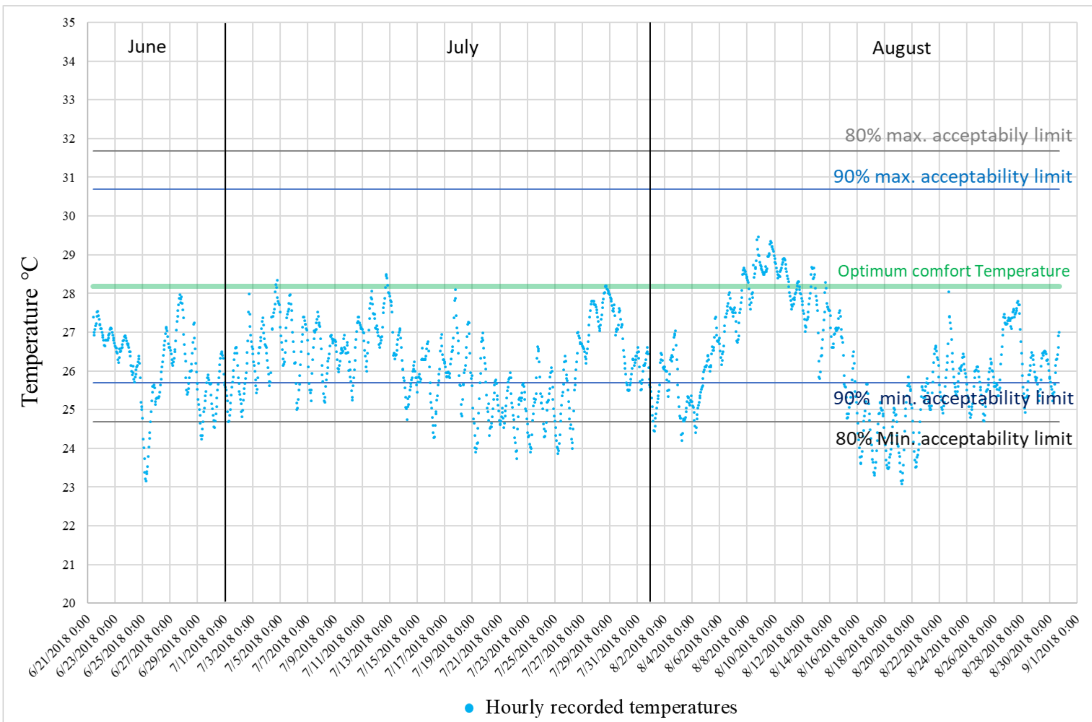


Figure 4-33: Total recorded temperatures in the middle of the library and the adaptive thermal comfort model limits

Table 4-4: Summary of the thermal comfort analysis using the adaptive comfort model during both occupied hours only and the total monitoring period

	No. of hours	comfort hours (80% acceptability)	% of comfort hours (80% acceptability)	comfort hours (90% acceptability)	% of comfort hours (90% acceptability)
occupied hours	410	401	97.8	357	87
total period	1688	1565	92.7	1203	71.3

4.8.3.2 PMV model.

Similar to the previous section, the PMV model comfort range was the guide to predict comfort temperature in this section. The results show that the percentage of thermal comfort hours decreased dramatically, as shown in Figure 4-34 and Table 4-5. This is attributed to the narrower thermal comfort zone. Of the total occupied hours, only 219 hours were recorded within the PMV comfort zone, representing approximately 53.5%. However, this percentage increased to almost 67% of the total monitored period. This increase is attributed to the temperature readings during the night time, which were cooler compared to the day hours.

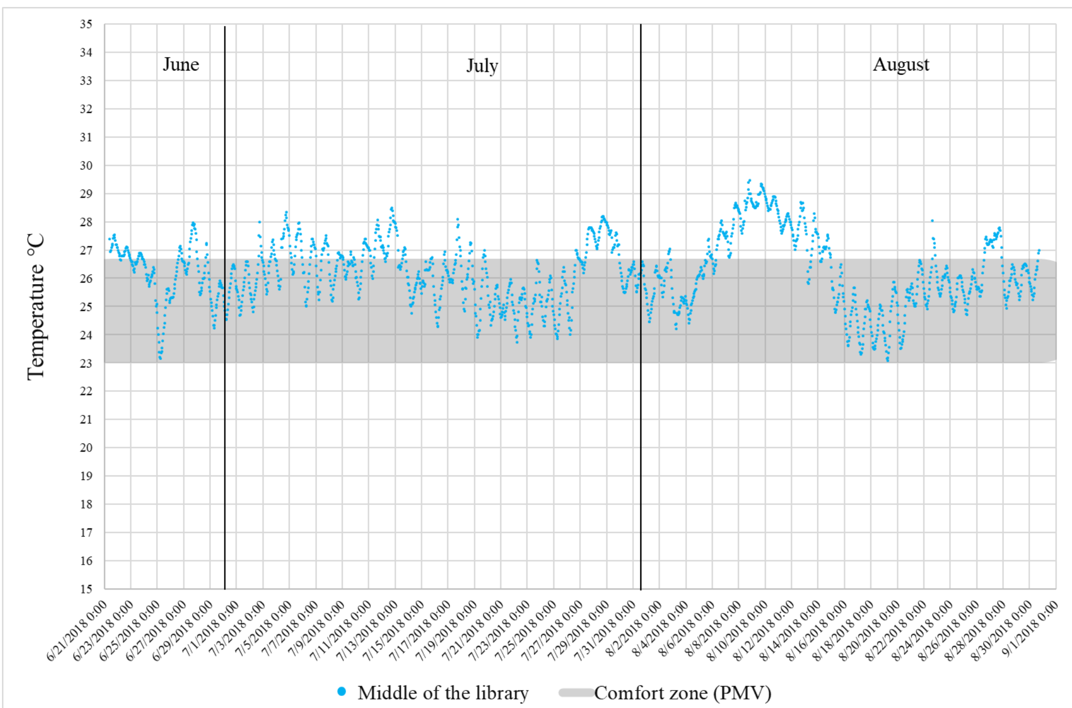


Figure 4-34: Total recorded temperatures in the middle of the library and the PMV comfort model limits

Table 4-5: Summary of the thermal comfort analysis using the PMV model during both occupied hours only and the total monitoring period

	No. of hours	**comfort hours**	**% of comfort hours**
work (occupied) hours	410	219	53.4
total period	1688	1133	67.1

4.8.4 Comparison of the Two Comfort Models

By comparing the results with the use of mechanical cooling, the PMV comfort range does not seem to be logical as higher temperatures were recorded during occupied hours (exceeding PMV comfort zone) without using mechanical cooling. This would indicate that occupants were feeling comfort at higher indoor temperatures, which makes the adaptive thermal comfort model appear to be more suitable compared to the PMV model. However, it was mentioned that the mechanical air-conditioning was working for approximately 19% of the work (occupied) hours even though the recorded temperatures did not exceed even the narrower (90% acceptability) limits of the ATC. This indicates that the occupants were feeling less comfort (warmer) within the specified ATC comfort level discussed in this study. This finding indicates the need for more appropriate thermal comfort limits for such an extreme climate.

4.9 **CONCLUSION**

This chapter analysed and assessed the performance of an existing PDEC building – the Dar Al-Rahmaniah Library in Saudi Arabia. The case study provided detailed information about the ability of the PDEC towers to provide effective passive cooling, although the degree of cooling was affected by prevailing wind speeds. It was apparent from the finding that higher wind speeds had a negative impact on the performance of the towers. The parametric analysis of the influence of wind speed on the cooling performance and air velocity apparently illustrated the negative effect of higher wind speed, leading to higher supply air temperatures. This finding must be taken into account when designing a PDEC building in order to minimise the negative effect of wind speed, negatively pressurise an occupied space to allow proper air circulation with space, and ultimately increase the cooling capacity of a PDEC tower. The effect of wind direction was found to be minimised by the overall design and form of the library. An effort has been made during the site visits and monitoring of building to find out if the building and PDEC system has met the design aspiration. However, it was not possible to get this type of data. The architectural drawings were the only accessible and available source of data. Nevertheless, it can be said that, and based on the performance analysis of the PDEC towers, the overall cooling capacity of the two towers was impressive and provided a significant amount of cooling for the buildings. This finding might give an implication of a successful design and implementation of the system.

The second part of the analysis used two different comfort models, the adaptive comfort approach (ATC), and PMV model to determine levels of thermal comfort in the library. Results indicated that the thermal comfort assessment obtained by using the ATC model seemed to be more relative. High levels of comfort could be delivered by the PDEC towers for most of the occupied time

Limitations of the study in this chapter include the fact that very low wind speeds could not be measured as the weather logger only recorded speeds above 0.6 m/s. Furthermore, not all the library sections were accessible while all the library was operated on one electricity meter, which led to neglecting the analysis of energy performance.

Based on the optimal performance and applicability of the PDEC towers, the next chapter will discuss the computational modelling and validation of a PDEC tower prior to studying its virtual integration into a typical Saudi villa.

CHAPTER 5. DEVELOPMENT AND VALIDATION OF A PDEC MODEL

5.1 INTRODUCTION

Having assessed the performance of an actual PDEC tower in the Saudi hot arid climate, this chapter aimed to model and validate a computational PDEC system before considering integrating it to a Saudi house. A single-story open plan room with a PDEC tower was digitally modelled, and then changes in wind speed and direction and window architectural form were simulated to see the effect on the PDEC performance. The purpose was to examine the possibility of improving the performance of the PDEC tower by the architectural design of the coupled building to act as one integrated design.

IES-VE software was selected for the simulations as it can conduct a dynamic thermal simulation for PDEC systems (IES, 2016). Riyadh, latitude 24.65°N, in the central region of Saudi Arabia, was the chosen site for this digital study. The current weather file for Riyadh was obtained from the software Meteonorm. As expected, the results demonstrated that PDEC towers could achieve significant cooling, but that their effectiveness was greatly reduced by changes in wind speed and direction linked to opening distributions in the room attached to the PDEC tower. Ultimately, a number of developed window design configurations were tested to improve the cooling performance of the PDEC tower.

5.2 PDEC COMPUTATIONAL MODELLING

5.2.1 Simulation Software

The high energy consumption of buildings and their negative impact on the global climate demonstrates the importance of the need for more energy-conscious buildings. The increasing interest in building energy efficiency has led to the emergence and development of Building Performance Simulation (BPS) tools (Nadarajan and Kirubakaran, 2016). Nowadays, many research studies associated with building performance have used BPS tools. In many developed countries, BPS tool has been integrated as an essential stage during the design process of buildings to predict building performance (Nadarajan and

Kirubakaran, 2016). Various BPS tools have been developed and used during the last six decades (Crawley *et al.*, 2008). During the design process, BPS tools are used by designers and engineers to assist in understanding expected building performance, as well as to aid decision-making during the initial and final design stages. Several outcomes can be obtained from BPS tools, such as energy performance, thermal comfort, CO2 emissions, energy costs, and building life cycle (Maile, Fischer and Bazjanac, 2007). Moreover, they can be used to develop the performance of a single project by assessing different design alternatives.

Nowadays, the selection of a BPS tool has become more difficult as there are almost 400 BPS tool available (Attia, Gratia, *et al.*, 2012). Effective use of a BPS tool is another challenge following the selection of the software. They are sophisticated systems requiring learning and training, at the beginning, which is sometimes time-consuming, in order to ensure the validity of the model and outcomes.

Integrated Environmental Solutions – Virtual Environment (IES-VE) was selected for this research to create virtual models (IES, 2020). At the early stage of the study, it was essential to decide the appropriate BPS tool as a significant part of the research relies heavily on that. In order to make an informed decision, the process of selecting a BPS software involved a literature review, self-training, personal communications with experts in the field, and direct contact with software companies. Several research studies were reviewed to develop a background and knowledge about a possible BPS tool for the study (Maile, Fischer and Bazjanac, 2007; Crawley *et al.*, 2008; Weytjens *et al.*, 2011; Attia, Gratia, *et al.*, 2012; Attia, Hensen, *et al.*, 2012; Nadarajan and Kirubakaran, 2016). The choice of a BPS tool was then limited to two options, DesignBuilder and IES-VE, as they are providing a user-friendly graphical interface. DesignBuilder was initially used as it is the user-friendly three-dimensional interface of the highly recognized software entitled EnergyPlus. The spray PDEC tower empirical model developed by Givoni in 1994 was employed in EnergyPlus by Daeho Kang (Kang and Strand, 2009). The advantage of this model is that it can predict the air conditioning and power consumption of the PDEC. Moreover, the software is fully available and supported by the University of Liverpool, which makes it widely used amongst researchers. Hence, full license access was available through the University. However, it was then recognized that the PDEC model was not available within DesignBuilder and was limited only to EnergyPlus. EnergyPlus, on the other hand, does not provide a three-dimensional model and deals with the model as written inputs and outputs. As a result, it was excluded as it can limit the ability to improve the PDEC performance through the architectural elements of the coupled spaces as one integrated design. The decision was then changed to IES-VE as it can conduct a dynamic thermal simulation for PDEC systems. As discussed previously in CHAPTER 2, the adiabatic cooling process governs the wide majority of the direct evaporative air cooling processes (Kang, 2011). This process is followed in a spray/evaporative tool in IES-VE (IES, 2016).

To develop the personal knowledge, extensive self-training using online tutorials and IES-VE forum was performed, followed by two face-to-face training courses led by experts from the software company were attended at the early stage of the research. Moreover, improving the personal knowledge involved direct personal communication with the vice president of IES West Coast, USA, Liam Buckley, who had developed a PDEC model in IES. The communication has clarified several important aspects regarding the simulation process of the system. Additionally, having a working PDEC model file initially developed and provided by IES-VE provided a good start, making the software the best selection.

IES-VE has a friendly graphical interface with multiple tools/software, which provided a comprehensive modelling and simulation environment suitable for assessment and further development. Dynamic simulation using the ApacheSim engine within IES-VE can capture all the thermodynamics, controls, and heat/mass balances at sub-hourly time-steps, taking into account the effect of every internal and external surface temperature. IES-VE advances the simulation options by integrating ApacheSim with other tools within the VE such as the system simulation program ApacheHVAC and the bulk airflow simulation program MacroFlo creating an integrated simulation environment (IES, 2015b, 2020). This integration provides an appropriate and flexible performance environment when running a PDEC simulation. IES has been validated and tested under several standards, including ASHRAE 140, CIBSE TM33, and BEST TEST (IES, 2019). The required inputs in IES-VE include: (1) a weather file based on the project's location (APLocate), (2) the geometrical model and orientation (ModelIT), (3) the construction details and thermophysical properties (ApcheSim), (4) HVAC system (ApachiSim & ApachiHVAC), (5) occupancy schedules and profiles, and (6) opening schedules and profiles (MacroFlo).

5.2.2 Weather Data File

Like much other software, IES-VE requires an hourly weather file in order to perform the analysis of the required location. Weather files provide annual climatic information, at hourly bases, encompassing DBT, WBT, RH, solar radiation, wind speed, and wind directions etc. Weather files that use synthetic years based on a long-time recording period are more appropriate for simulation to predict performance for long-term averages. EnergyPlus Weather (EPW) file is one of the most commonly used formats using the previously mentioned calculation process (EnergyPlus, 2020). EPW file format can be read and employed in IES-VE. EPW file is easily available for download through several websites such as EnergyPlus website. Other commercial websites like Meteonorm can generate weather files for the locations that are not readily available (Meteonorm, 2019a). For the purpose of the study, the current hourly EPW file for Riyadh was produced from Meteonorm and used in the analysis process.

5.2.3 Model Creation

As previously discussed, IES VE software was selected for the study as it can simulate spray PDEC systems with changeable cooling efficiency rates (Buckley, 2014). Based on the findings in the previous chapter, a computational model was created to virtually evaluate wind effects and the possibility of improving the cooling performance by the addition of buffer space to a room impacted on PDEC performance. A PDEC tower was located centrally and internally against the rear north wall of a single-story room connected to the tower, facing the prevailing wind direction (Figure 5-1). The developed computer model applied the typical construction/material details of a Saudi Arabia building. The model construction specification is described in Table 5-1, and the tower specifications in Table 5-2. Most of the literature considers either 4:3 or 3:2 as a suitable depth-to-width plan aspect ratio for a rectangular tower. The dimensions of this study's tower cross-section were 1.6m x 2.5m, following the 3:2 aspect ratio. The width of the tower was parallel to the direction of the prevailing wind direction.

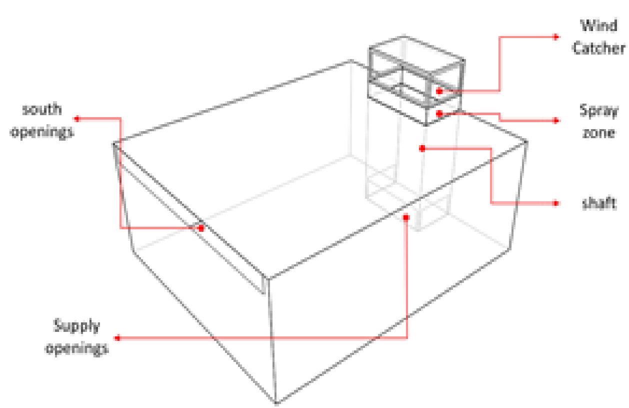


Figure 5-1 Base case building model and PDEC tower geometry

Table 5-1: Construction specifications for the building

	Construction Specifications
Building Height	3.5m
Floor dimensions	7.5m x 9m
Floor area	63.75 m2
External walls	25mm external cement plaster + 100mm hollow concrete block + 50mm expanded polystyrene + 150mm hollow concrete block + 25mm internal cement plaster
Roof	gravel + 100mm expanded polystyrene + membrane+ 200mm concrete slab
Glazing	6mm outer pane + 12mm cavity + 6mm inner pane
South opening area	3.55 m2

Table 5-2: PDEC tower parameters and specifications

	PDEC tower specifications
Assumed cooling efficiency	80%
Tower Height	5m
Tower cross-section dimensions	1.6m x 2.5m
Wind Catcher	Four sides louvres with 80% openable area (total area: 5.76 m^2)
Supply openings	Three openings facing the room (total area: 3.43 m^2)

A previous study recommended a tower height of double to triple the width of the tower (Kang and Strand, 2016). As a result, a tower height of 5m was set for this study. At the base of the tower, three openings faced the room and had a total opening area of 3.43 m^2. On the opposite side of the space, a horizontal clerestory window was placed in the room's south façade with an opening area of 3.55m^2 (i.e. slightly larger than the tower's supply openings). This model was used as the base case design for the computer study. Other opening configurations were also tested (Figure 5-7).

5.3 PDEC MODEL VALIDATION

Since the spray PDEC system technique was considered in this study, it was not possible to use the library's PDEC towers, discussed in Chapter 4, for the model validation as the library building employed a PDEC tower with pads system. Hence, to check that the IES-VE model had been configured correctly, the PDEC model was tested against experimental data derived from a European Union (EU) PDEC project. All the data regarding the construction datils and operation schedules were obtained from Ford et al., (2010); and Galatà and Sciuto (1997). The experimental building, shown in Figure 5-2, was built in Catania, Italy, and consisted of a tower with two rooms attached to the north and south sides of the tower. The PDEC tower dimensions were 4.1m x 4.4m x 10.7m. The windcatcher had two openings, each measuring 1.7m x 3.7m, and facing the east and west, which represented the prevailing wind direction. The tower was set to operate from 10:00 to 18:00. Data loggers were placed outside and within the building. The outdoor data recorded included solar radiation, air temperature, relative humidity, wind direction, and wind speed. Air temperatures and relative humidity were measured at different locations within the tower and the north room.

Figure 5-2 Experimental PDEC tower built in Catania (Galatà and Sciuto, 1997)

A model of the Catania tower was created in IES-VE. All the building details and opening profiles were considered when running the simulation. The simulation was run for 24 hours for the 30th July at a two-minute time step.

Because a number of data-loggers were installed in the tower and north room, the hourly average temperature and relative humidity (RH) of the different data-loggers in each space (tower and room) were considered when compared to the simulated results in IES-VE. Figure 5-3 to Figure 5-6 shows a good agreement between the measured and predicted data for the internal DBT and RH in the PDEC tower and north room, which gave them confidence to develop an IES model for the Riyadh tower and room. In Figure 5-4, it should be noted that the modelled indoor RH in the tower only shows a steep increase at 09:30 when the spray system starts operating and then drops to nearly the outdoor RH level. This shift is expected to be attributed to the fact that the internal parts of the actual walls of the tower stay wet in real conditions even when the PDEC system stops working, which makes the indoor RH in the real measured data higher. However, this was not the case in the modelled data, which was showing the increase in RH only when the spray system was working. To justify that, This was not happening in the room attached to the tower (see Figure 5-6), as it was not affected directly by the spray of the PDEC tower, which makes a constant agreement of both the modelled and measured data during all times.

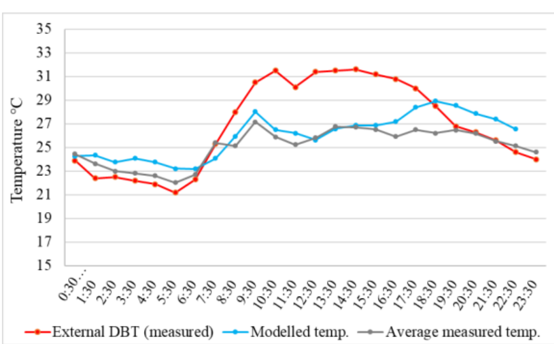


Figure 5-3: Measured vs predicted internal temperatures in the PDEC tower

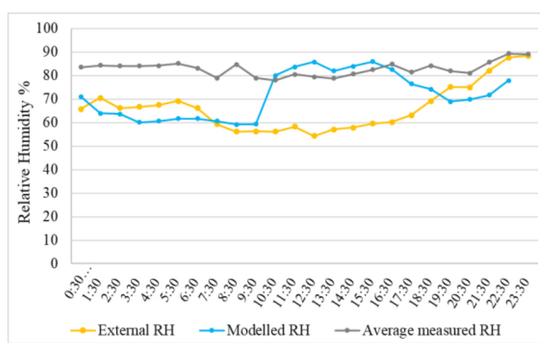


Figure 5-4: Measured vs predicted internal RH in the PDEC tower

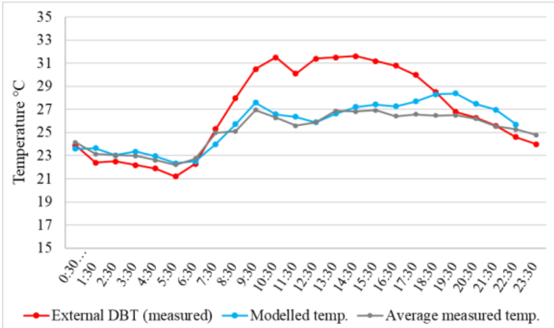


Figure 5-5: Measured vs predicted internal temperatures in the north room

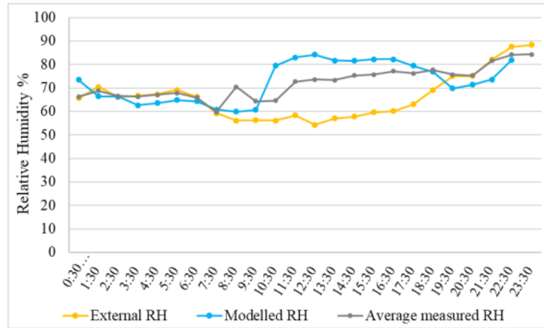


Figure 5-6: Measured vs predicted internal RH in the north room

5.4 SIMULATION PROCESS

For the Riyadh tower, the efficiency of the PDEC system was set in the IES model to be approximately 80% of the dry bulb to wet bulb temperature (wet-bulb depression) as this efficiency rate was easily achievable referring to the PDEC analysis in Dar Al-Rahmaniah Library. Moreover, this is considered the accepted average efficiency for a direct evaporative cooling system (Salmerón *et al.*, 2012). Two different weather scenarios were tested in the simulations – (i) a very hot July day with northerly winds and (ii) slightly cooler August day with some southerly winds. The results show that the PDEC tower could achieve a significant amount of cooling. However, the tower effectiveness was highly influenced by changes in external wind conditions, which agrees with the case study analysis in CHAPTER 4. As a result, a double-skin type buffer zone corridor was then created on the south façade to test if the window could be protected and the tower performance improved for southerly winds. The buffer zone and the further improvements were developed based on recommendations from the literature (Gratia and De Herde, 2007). The parameters that have been considered included buffer depth, buffer height, opening sizes, and opening placement. The investigation included many different configurations to improve the air movement of the PDEC within the space. Several cavity depths were tested, and it was found out that this parameter had no large influence on the overall performance of the PDEC tower. So, a cavity depth of 0.4m was chosen for this study. Three configurations were chosen for this study in addition to the base case, as shown in Figure 5-7. These three configurations represented the major changes that have been discovered during the research modelling process. The first configuration had two louvres openings located along the floor and ceiling of the buffer zone that covered the exhaust window on the south façade of the space attached to the tower. These louvre openings were located to exhaust the air that is coming through space south opening while minimizing the unwanted wind pressure from the south side by the addition of the buffer zone. The second configuration had two horizontal louvre openings along the top North and south side of the buffer zone in addition to the floor opening mentioned in the first configuration. The floor opening was then removed for the third configuration.

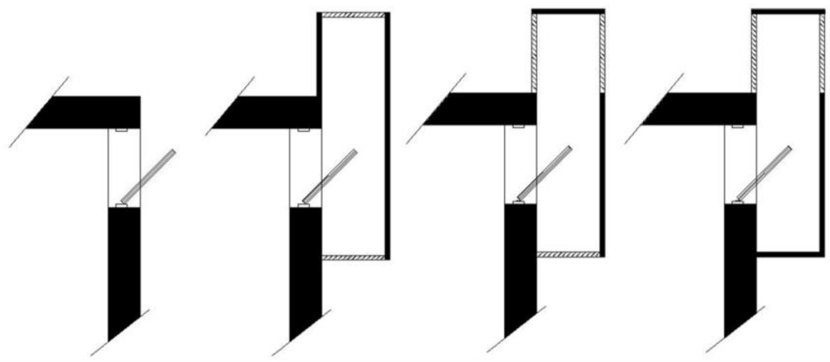


Figure 5-7: Section through the exhaust openings for the base case and the developed three different configurations of the buffer zone

5.5 RESULTS AND DISCUSSION

5.5.1 Baseline Case

As mentioned previously, two days (scenarios) were considered. For scenario (i) on 29th July the maximum external air temperature peaked around 46°C mid-afternoon while the maximum external wet-bulb temperature was around 21.5°C. The average external relative humidity was 14%.

Figure 5-8 shows the wind speed, and wind direction for 29th July generated from the weather file using IES software. The right vertical line represents the wind speed. The left vertical line refers to the wind direction, with the convention that a wind direction from the North is 0°, East 90°, South 180° and West 270° (Table 5-3).

Table 5-3: orientation and corresponding degree value base on software setting

Orientation	**North (N)**	**North east (NE)**	**East (E)**	**South east (S)**	**South (S)**	**South west (SW)**	**West (W)**	**North west (NW)**
Degree	0^o or 360^o	45^o	90^o	135^o	180^o	225^o	270^o	315^o

The sharp fluctuation in the wind direction line does not necessarily mean a big change in the wind direction. For instance, in Figure 5-8, the wind direction was approximately between 250° and 325° (WNW) for most of the day, and then suddenly swung around to 15° (NNE) at 14:00. This means the wind direction has only moved from WNW to NNE although the change looks more dramatic on the graph. Thus, for scenario (i), the winds were mostly from the north (i.e. directly on to the tower) with a maximum wind speed of 4.6m/s (Figure 5-8). Figure 5-10 shows the hourly external dry bulb and wet bulb air temperatures and the PDEC-generated internal air temperatures in the room. Figure 5-10 shows how effective the PDEC system was, with a peak internal temperature around 27.2°C compared to an outdoor peak around 46°C. The internal relative humidity dramatically increased to around 60% during the day (Figure 5-12). This is attributed to the stable weather conditions and lower humidity levels during the day (Figure 5-8 and Figure 5-12).

For scenario (ii) on 2nd August the day was slightly cooler, with a maximum external DBT and WBT of around 40°C and 18.7°C respectively, and a mean relative humidity around 15%. The wind direction was mostly from the north-west but changed to the south and south-east from 14.30 to 16.30 and 20.00 to 21.00 and so struck the building before reaching the tower (Figure 5-9). The wind speed was higher compared to scenario (i), increasing through the day and reaching 9.2m/s around 16.00 (Figure 5-9).

The results for scenario (ii) were not as expected when compared to those from the scenario (i), with a reduction in the PDEC effectiveness being observed that was related to the unstable weather conditions. Figure 5-9 and Figure 5-11 show how the change in wind direction greatly reduced the effectiveness of the PDEC tower between 14.30 and 16.30 and between 20.00 and 21.00, when the wind direction became southerly. Internal temperatures peaked around 35.5°C and stayed higher than in the July scenario. The internal relative humidity had dramatically decreased when the winds were southerly (Figure 5-13). This suggests that the clerestory window opening in the south façade was allowing positive pressure to be generated in the room that acted against the ingress of cool air from the tower. As a result, improving the design of the south exhaust window was considered to minimize the unwanted positive wind pressure on the opening. This development is discussed in the following section.

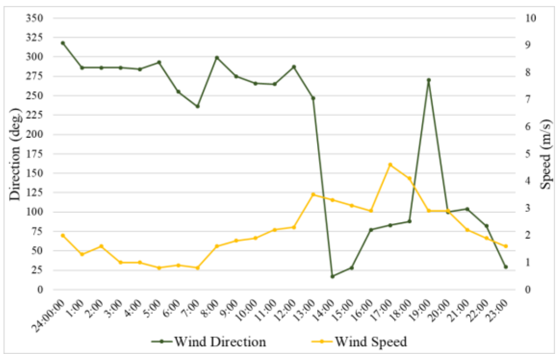


Figure 5-8: Wind speed and wind direction, 29th July

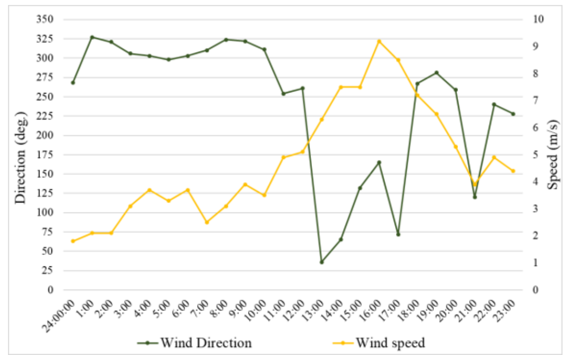


Figure 5-9: Wind speed and wind direction, 2nd August

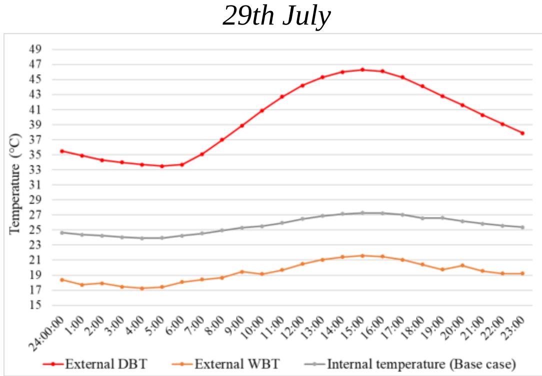


Figure 5-10: External and internal air temperatures, 29th July

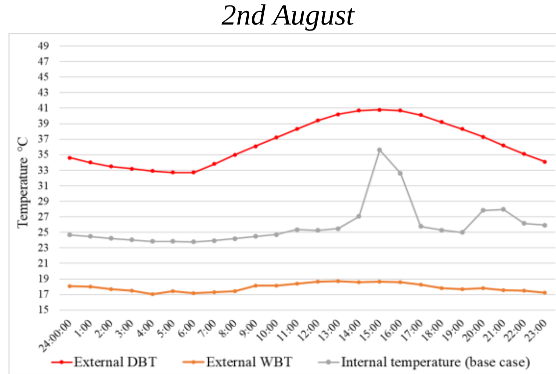


Figure 5-11: External and internal air temperatures, 2nd August

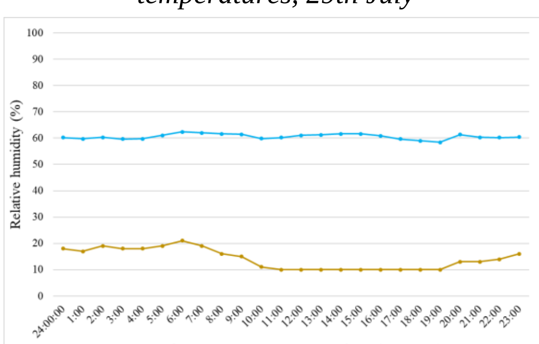


Figure 5-12: External and internal relative humidity, 29th July

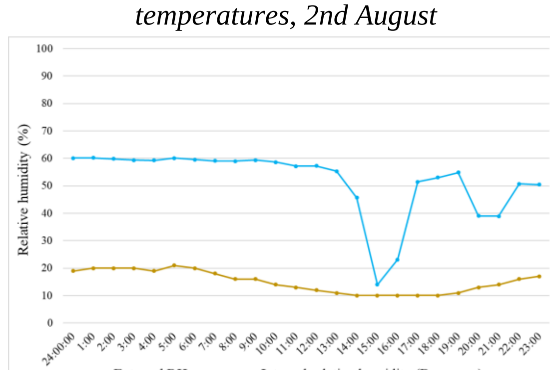


Figure 5-13: External and internal relative humidity, 2nd August

5.5.2 Developed Cases

Figure 5-14 shows the internal air temperatures for the 29th July (northerly wind) conditions for the base case without the buffer zone and the three different zoned configurations. The addition of the buffer zone had little impact on the July tower performance, which might be expected for northerly low-speed winds. However, Figure 5-15 shows the positive impact of the buffer zones on the August tower performance during southerly wind conditions between 14.30 and 16.30 and between 20.00 and 21.00, but there was a negative impact after the wind changed direction. An interesting finding was that the internal temperature went up between 12.00 and 14.00, and between 16.30 and 18.30 when winds were blowing from north. The only logical explanation for this change was the higher wind speed as this scenario was working properly during steady wind conditions. By comparing this finding to the analysis of Dar Al-Rahmaniah Library, it is evident that the wind speed was the reason behind the lower cooling efficiency. The pressure increases on the tower, and buffer openings due to higher wind speeds have affected the performance negatively. So, the first configuration would provide better results only for southerly winds and lower wind speed conditions; otherwise, the base case performed better most of the time as the prevailing wind direction was northerly.

For the second configuration, the top opening was replaced with two leeward openings at the top North and south sides of the buffer zone. This was developed to minimize the positive pressure of the wind speed, so the leeward side opening could negatively pressurize the buffer zone. Although the results showed that the situation had improved, the negative effect of the wind speed still had an impact on this configuration (Figure 5-15).

The bottom opening was then eliminated for the third configuration. The purpose behind this was to create a stack effect within the buffer zone. The results showed that significant improvement was achieved during this scenario (Figure 5-15). This configuration gave the best results compared with the other scenarios for most of the time and during different weather conditions. The two upper openings had decreased the pressure within the buffer zone cavity while the elimination of the bottom opening helped to create a stack effect.

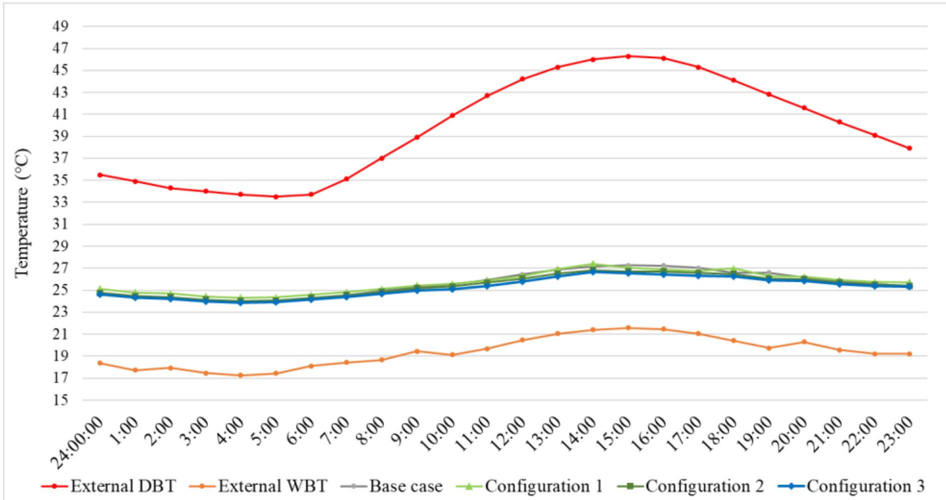


Figure 5-14: Comparison between results of the base case and the three buffer zone configurations, 29th July

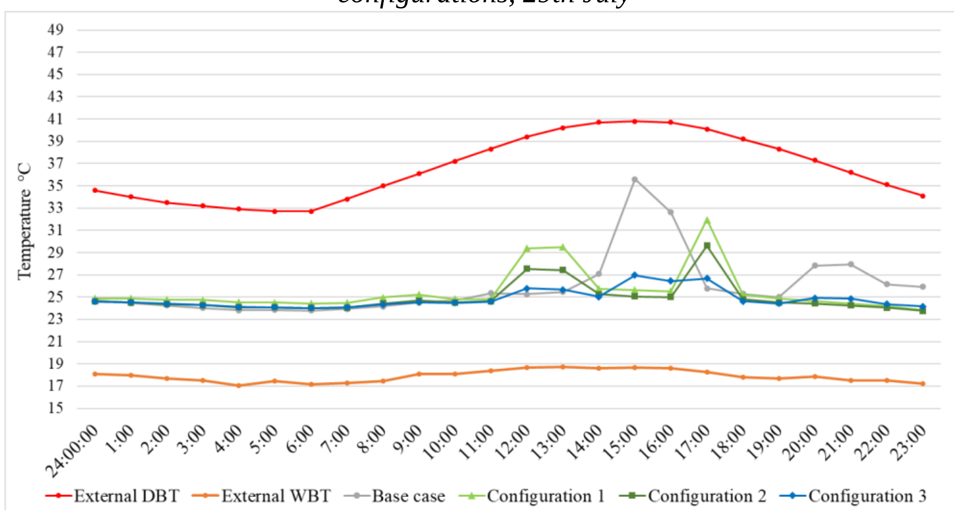


Figure 5-15: Comparison between results of the base case and the three buffer zone configurations, 2nd August

Although many summertime simulations have been made, the two scenarios presented here give a good initial representation of how the PDEC system performed for a range of summer wind speeds and wind directions prior to considering the PDEC integration to a typical Saudi villa. It should be mentioned that the findings that were observed in the second scenario (2nd August) occurred during many other days (e.g. 4th June, 6th June, 2nd July, 8th August etc.), and under similar weather conditions. Overall, the PDEC tower performed well as Riyadh has a climate that is generally dry and hot throughout the summer.

5.6 CONCLUSION

This chapter initially investigated the impact of the architectural design of window openings on the performance of a PDEC tower. The tower was virtually created and linked to a room. The software IES-VE was used to conduct the simulation of the PDEC system, and the tower’s predicted performance was impressive in Saudi Arabian climatic conditions. However, the performance was affected by changes in wind direction and wind speed. A buffer zone was added to the south side of the coupled space to minimize the negative effect of the winds. By assessing many configurations of the suggested solution, the performance was improved significantly. This chapter provided an initial computation analysis of a PDEC performance prior to considering it in a Saudi dwelling. Further detail analysis, involving monitoring and modelling of a typical Saudi house, will be conducted in the next chapter to better understand the relationships between the tower and different room factors. Moreover, full season analysis and representation will be considered to better comprehend the overall performance of the PDEC system under different weather condition in different spaces, as well as, assessing and predicting the impact on the energy consumption and thermal comfort.

CHAPTER 6. THE MONITORING AND MODELLING OF A TYPICAL SAUDI HOUSE

6.1 INTRODUCTION

In the previous two chapters, the PDEC performance has been studied and analysed in the hot arid climate of Saudi Arabia. CHAPTER 4 provided an analysis of an existing PDEC building, Dar Al-Rahmaniah Library. The findings offered base knowledge and a strong understanding of the applicability of an actual PDEC tower in such climate. In CHAPTER 5, a PDEC tower was virtually modelled in IES-VE and linked to an occupied space to study the possibilities of maximising its performance in terms of its relation to a coupled area.

In this chapter, the first part of stage three will be discussed, which includes the research inputs of the computaional analysis of an existing typical saudi house followed by the PDEC assessment results in the following chapter (outputs). This chapter presents the monitoring process, and computational modelling and validation of the Saudi house. The villa is located in Hail city between the north and middle region of Saudi Arabia. Its climate is characterised as hot and dry, which is approximately similar to Riyadh Province. The villa was monitored during the summer of 2018. The building details and monitoring data of the villa were then used to model and validate the villa in IES-VE.

Based on the monitored data, the modelling process is described in detail including weather file, architectural and construction details, systems, and profiles. The base case energy consumption of a typical Saudi villa is determined at the end of this chapter. The base case will then be used to study the integration and further investigations of the PDEC in the next chapter.

6.2 LOCATION AND CLIMATE ANALYSIS

Due to the climatic dependency of the PDEC system, it is significant to consider the location and climatic conditions to perform a proper performance and energy use analysis of a PDEC building. In the beginning, Riyadh was viewed as a location of the study villa as it represents the largest city in the country with a hot, dry climate. However, due to limitation of accessibility and difficulty to find a suitable case study, the city was excluded. Hail was later considered as the climate of the city is classified as hot and arid, which is similar to Riyadh. The city of Hail, Latitude 27.5N, is almost 600km North West of Riyadh, the capital city of Saudi Arabia (Figure 6-1).

The climate of the city is classified as hot and arid (BWh) according to Koppen-Geiger climate type map (Peel, Finlayson and McMahon, 2007). The winter season is considered cold. However, the overall weather is hot and dry most of the year.

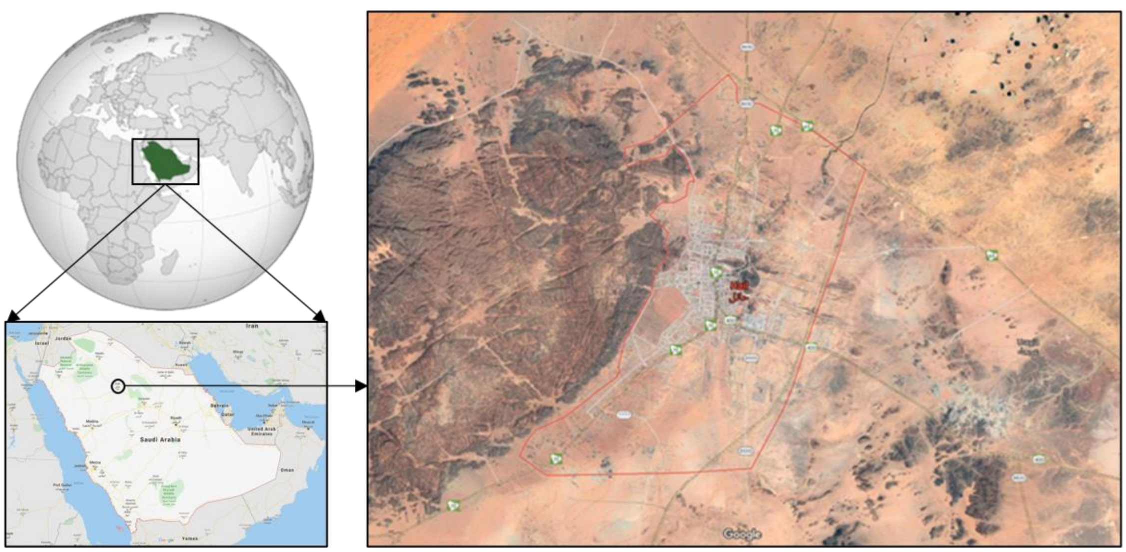


Figure 6-1: The location of the Hail case study (Google Maps, 2019a).

Climate Consultant 6.0 was initially used to conduct a climatic analysis of the region. The weather file for Hail was generated from Meteonorm (Meteonorm, 2019a). The analysed weather conditions include external DBT, WBT, relative humidity, wind velocity, and wind direction. Figure 6-2 shows the monthly average DBT throughout the year. The "Mean" demonstrates the average of hourly DBT for each month. The ''Average High'' represents the average of the daily maximum DBT for each month while the ''Average Low'' expresses the average of the daily minimum DBT for each month. The record high and low DBT are shown in small circles. During the summer, the weather is very hot and dry with DBT exceeding 43°C and the average maximum DBT of approximately 40°C. The monthly average DBT and WBT is 33°C and 16.5°C, respectively during the summer months (Figure 6-3). The low humidity levels justify the large difference between the DBT and WBT. The average relative humidity is roughly 19% during the hot season. Figure 6-4 shows monthly diurnal averages of external DBT (°C) and relative humidity (%) for each month during the whole year.

The wind velocity data are illustrated in Figure 6-5 and measured in (m/s). The "Average High" and "Average Low" represent the monthly average maximum and minimum wind velocity, respectively. The "Mean" value demonstrates the average wind velocity of all hours for each month. The peak values are illustrated in small circles for each month. In general, the weather can be categorized as a claim throughout the year with an annual mean wind speed of 3.39 m/s. The maximum wind speed value is about 11.9 m/s during the hot season. The prevailing wind directions are North and North-West during the summer and for most of the year as well (Figure 6-6).

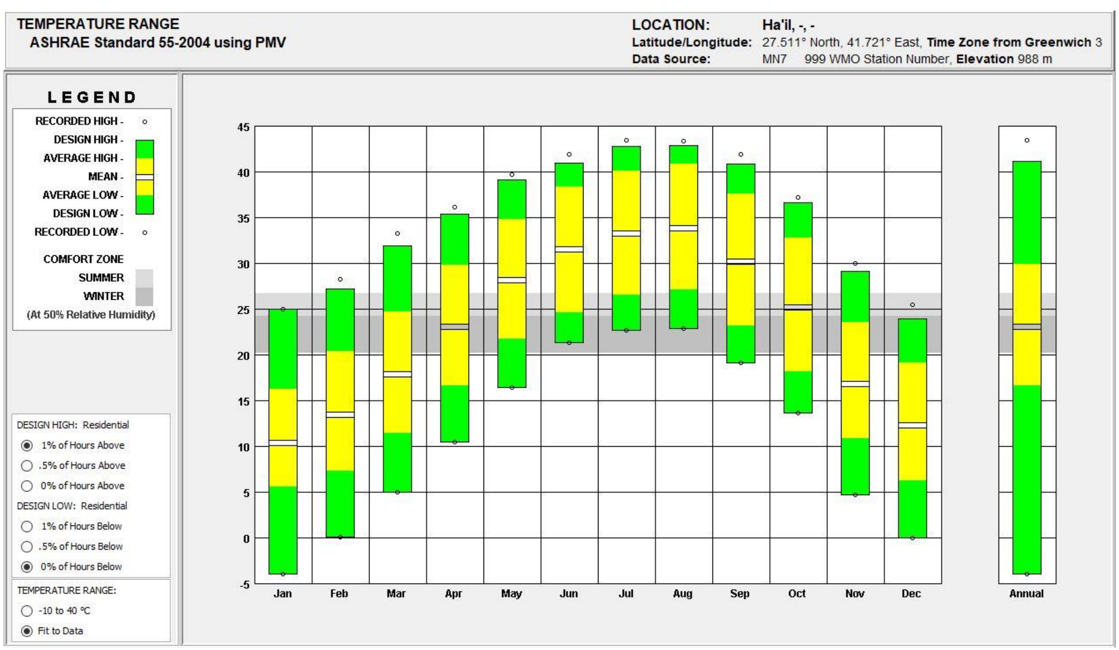


Figure 6-2: Monthly mean, average maximum, and average minimum temperature (Climate Consultant, 2019a).

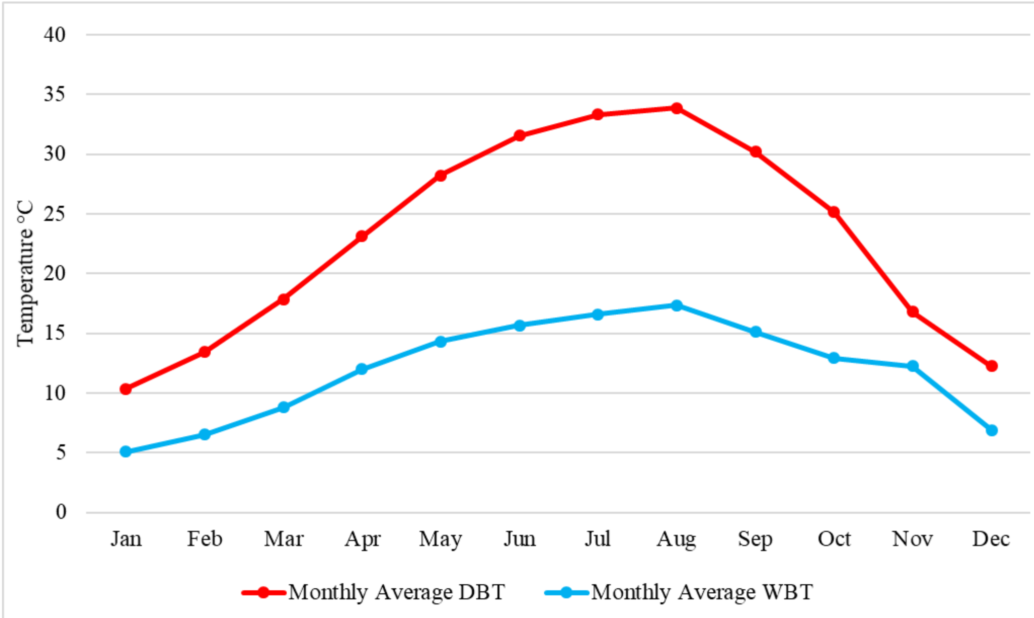


Figure 6-3: Monthly average DBT and WBT temperature (Meteonorm, 2019b).

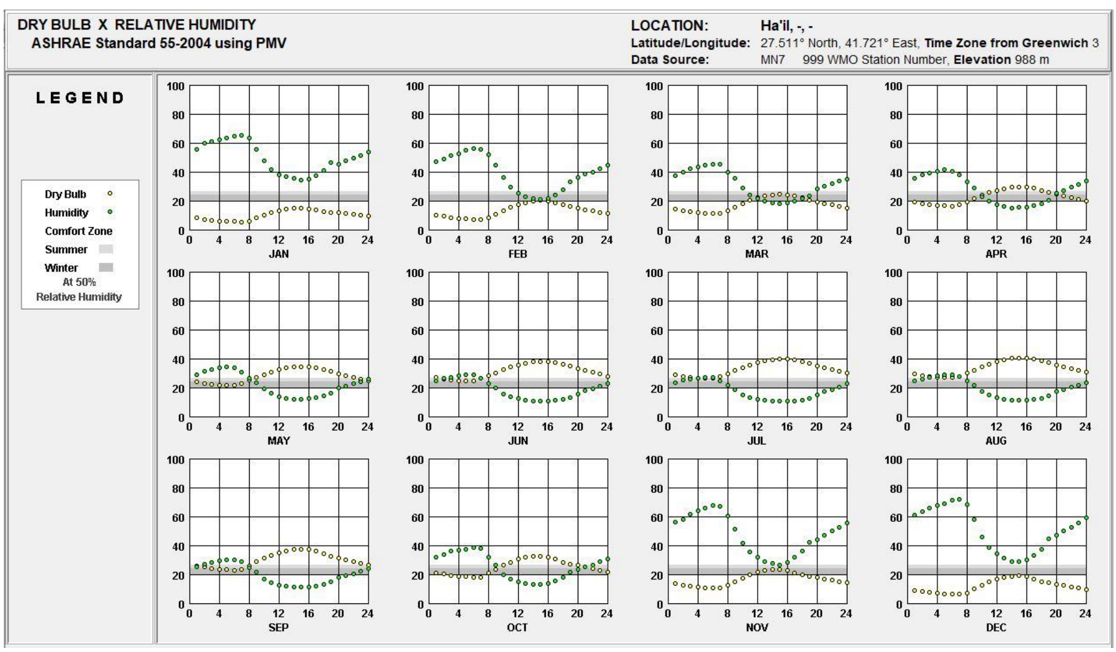


Figure 6-4: Monthly diurnal averages of external DBT and relative humidity (Climate Consultant, 2019b).

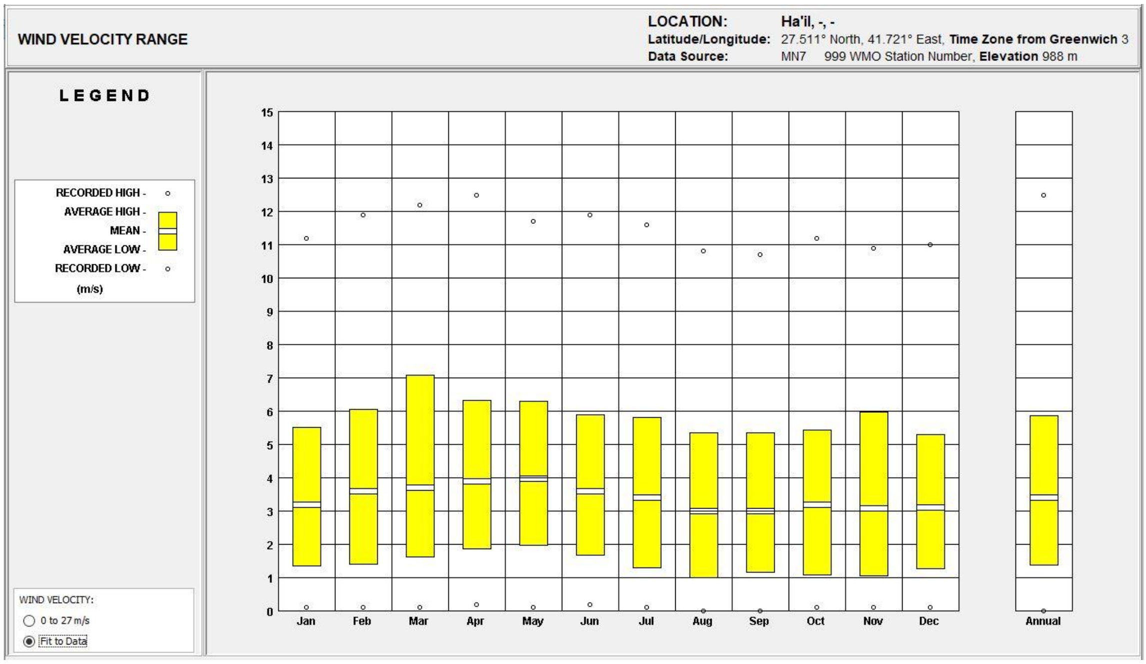


Figure 6-5: Monthly average, average maximum, and average minimum wind velocity (Climate Consultant, 2019b).

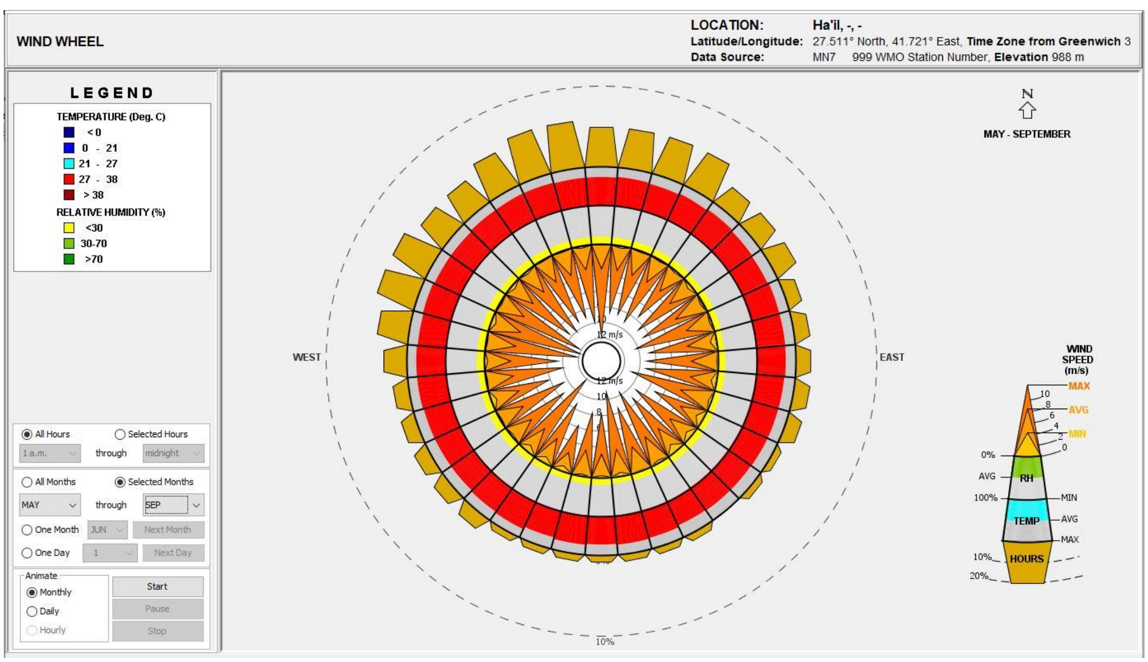


Figure 6-6: Windwheel during the summer season (Climate Consultant, 2019b).

6.2.1 *The Rationale for Selecting Hail as a Case Study*

Previously, the PDEC showed significant cooling performance under the extreme weather conditions of Riyadh during the summer. The high DBT, the considerable difference between DBT and WBT, the low humidity levels, and calm weather are all climatic characteristics that could provide high potential applicability of a PDEC tower. These conditions are nearly similar in both Hail and Riyadh (see Figure 6-7), where both cities have high DBT and low RH levels during the summer. Therefore, this would make this region a suitable selection for the further analysis of the case study and the integration of the PDEC system in such a climate.

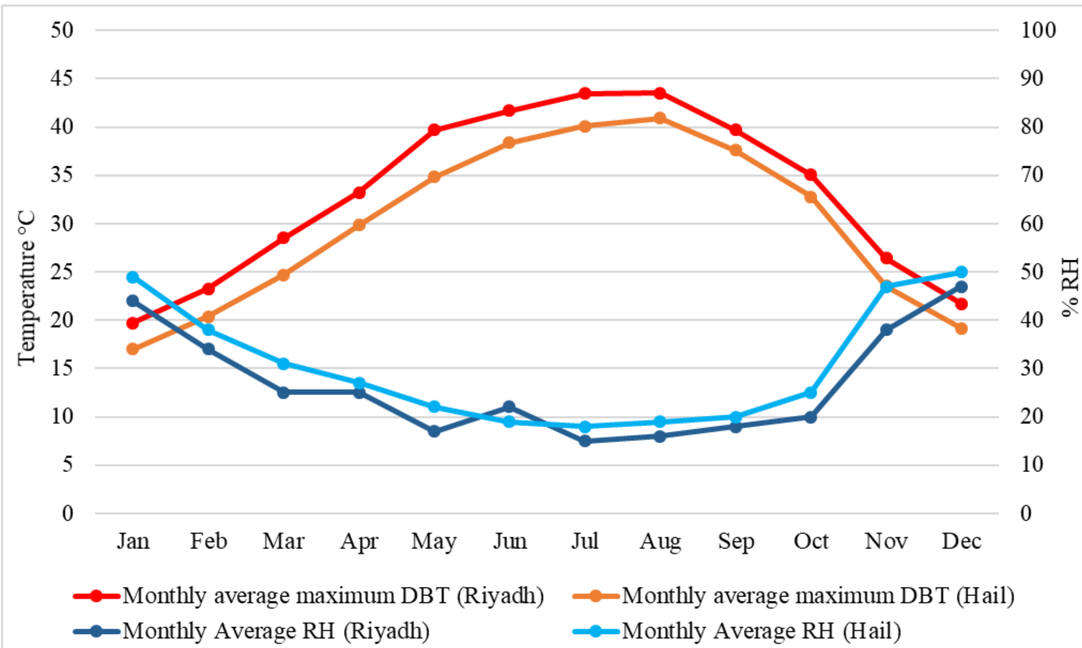


Figure 6-7: Monthly average maximum DBT and average RH levels for Riyadh and Hail (Meteonorm, 2019b).

6.3 SELECTION OF SAUDI TYPICAL VILLA

A typical Saudi detached family house (villa) located in the city of Hail was selected to investigate the effectiveness of a PDEC performance in a Saudi housing.

Several factors were taken into consideration in order to assure a proper selection of the case study villa. These factors include:

- Accessibility.
- Building age
- Building geometry and design
- Building size (area).

Two case study villas were found with access for data collection and data-loggers installation. One of the villas was excluded due to the size, while the selected house was within the size range of the average, typical Saudi dwelling (Alrashed, 2015).

In 2016, the selected villa was completed following the Saudi Building Code requirements at that time. The newly built villa would provide an up-to-date case study. The building geometry and design allows easier integration of a PDEC tower with access to most of the main spaces in the house. Moreover, the building is oriented to the North West, which is the prevailing wind direction. Six people occupy the house. The number of occupants was also taken into consideration when selecting the case study, as this number represents the average Saudi family size (GASTAT, 2019). All these factors make this case study a suitable selection for the research analysis and future improvement and virtual integration of a PDEC tower. The consideration of these factors during the selection and analysis process is explained in details in this chapter.

6.3.1 Description of the Case Study Villa

This section aims to describe the design of the selected case study villa. The case study represents a two-storey typical Saudi villa with an annexe built over part of the first-floor roof. The architectural drawings were collected from the owner of the house. A brief description of the villa is summarised in Table 6-1. The villa was built on a 340m^2 land area with a total built floor area of 463m^2. The shared spaces of the villa area placed on the ground floor while the second floor comprises the private spaces. Due to religious, cultural and privacy reasons, the villa has two different entrances and two guest rooms. The main entrance (family entrance), which is connected directly to the living room, is used by the occupants for daily circulation. The second entrance is used for guests, leading directly to the men’s guest room. The ground floor spaces include a central living room, male guest room, female guest room, and kitchen. The first floor comprises another living space, master bedroom, and three bedrooms. The annexe is located on a second-floor level containing the housekeeper room, and laundry room.

Table 6-1: Description of the case study villa

Year of completion	2016
Number of stories	2 + annexe
Total land area	340 m^2 (20m x 17m)
Total built area	463 m^2
Floor to floor height	3.5 m
Orientation	North-West
Ground floor	Living room, male guest room, female guest room, kitchen, storage, and two toilets
First floor	Living room, master bedroom, 3 bedrooms, and 3 bathrooms
Annexe (2nd floor)	Housekeeper room, laundry room, and bathroom
Number of occupants	6

The property entrances are from the north side. However, the villa is shifted and oriented towards the north-west (Figure 6-8). The layouts of the villa are shown in Figure 6-9 to Figure 6-12. The two central living spaces are aligned on top of each other, creating the main circulation points in the house, both horizontally and vertically. Horizontally, each living room is surrounded by all the different spaces on the same floor creating the main connection space. Vertically, both living areas are linked to an open stair zone that ends with a dome at the top roof (Figure 6-12).

Both the orientation of the villa and the layout design makes this case study a suitable selection for this study. The orientation towards the north-west, which is the prevailing wind direction, would enhance the integration of a PDEC tower. Furthermore, the open plan with central living spaces and open stair zone would provide easier integration of a PDEC system with access to different areas in the house.

Figure 6-8: External and satellite view of the case study villa and its urban context (Google Maps, 2019b).

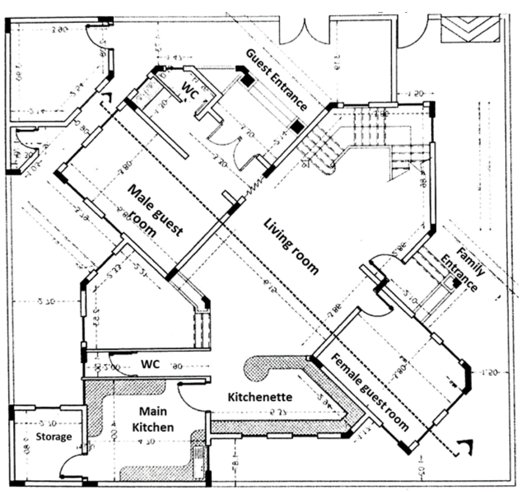


Figure 6-9: Ground floor plan

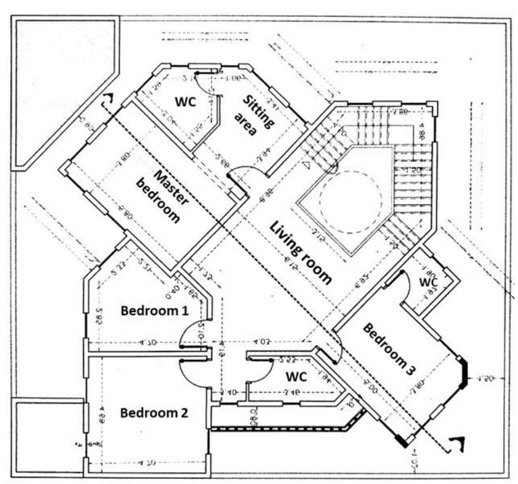


Figure 6-10: First floor plan

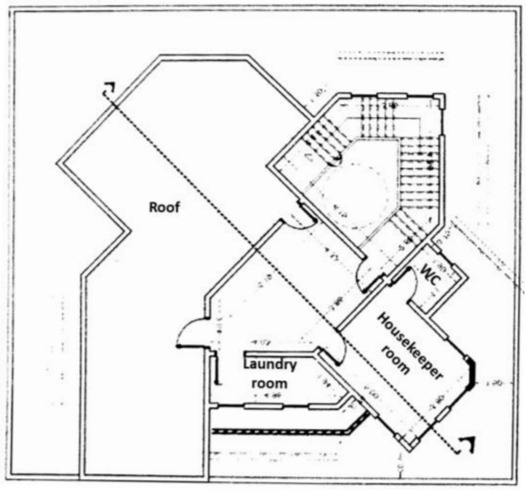


Figure 6-11: Second floor plan (Annexe)

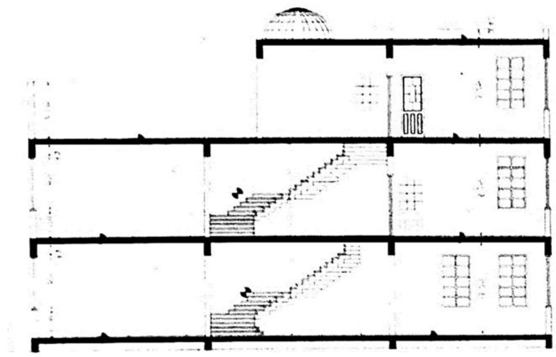


Figure 6-12: Section through the living spaces and the open stair zone.

6.4 BUILDING MONITORING AND DATA COLLECTION

Building performance simulation (BPS) tools have become a valuable mean to predict building performance. BPS tools have been increasingly used during the design or retrofitting stages of new or existing buildings in many countries (Nadarajan and Kirubakaran, 2016). However, differences between predicted and actual building performance have been observed in previous research (Hens, Parijs and Deurinck, 2010; Guerra-Santin and Tweed, 2015). The difference between the expected and actual performance of buildings is known as a performance gap. On-site monitoring for buildings can help to reduce the performance gap. Guerra-Santin and Tweed have recently reviewed and presented a number of building monitoring methods (Guerra-Santin and Tweed, 2015), and the different approaches were described in section (4.5).

For the purpose of this research, energy and environment parameters (indoor and outdoor) monitoring were considered as well as site visits to collect possible data about building operation such as HVAC and lighting fixtures audits. Energy consumption data were obtained from electricity bills provided by the Saudi Electricity Company (SEC, 2019). Indoor and outdoor parameters encompassing DBT, relative humidity, and external wind speed and wind direction were monitored during the summer of 2018 using data loggers that were installed outside and in the main spaces of the villa. The lighting fixtures and HVAC system details for each area were collected during the site visit.

The monitored data were then used to find out the existing occupants profiles based on the use of the HVAC system, which was reflected in the rooms' temperatures. Finally, the data were then used for the modelling and validation of the villa in IES-VE.

6.4.1 Monitoring Equipment

Two different data logging equipment, Kestrel 5500 and Rotronic HL-1D, were used for the monitoring of the building. The Kestrel 5500 is a mini weather station and was installed outside to record outdoor parameters including DBT, WBT, RH, wind speed, and wind direction. For indoor monitoring, four Rotronic HL-1D data loggers were installed in the main spaces of the house, excluding bedrooms, to record internal DBT and RH. The Rotronic HL-1D is a suitable monitoring device for the indoor environment as it is a compact, quiet, and easy to install data logger. The specifications of the data loggers used in the monitoring were explained previously in section (4.5.1).

6.4.1.1 Data-loggers Accuracy

All the loggers were new and unused. To ensure the constancy of the data loggers, factory calibrations were checked by running the loggers in a controlled space for 12 hours with 30 minutes reporting interval. Figure 6-13 and Figure 6-14 show a good agreement between the recorded temperatures and RH during the 24 readings..

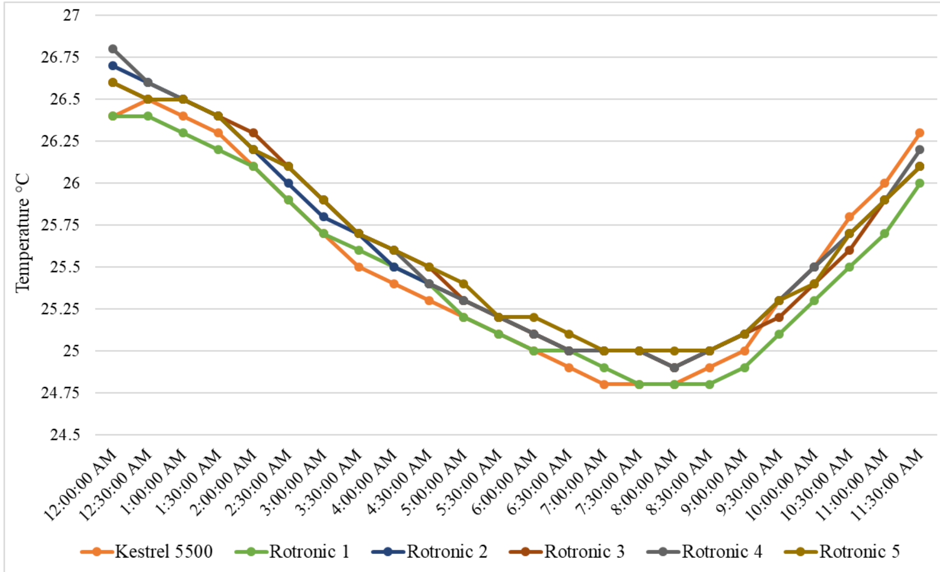


Figure 6-13: Data loggers temperature calibration

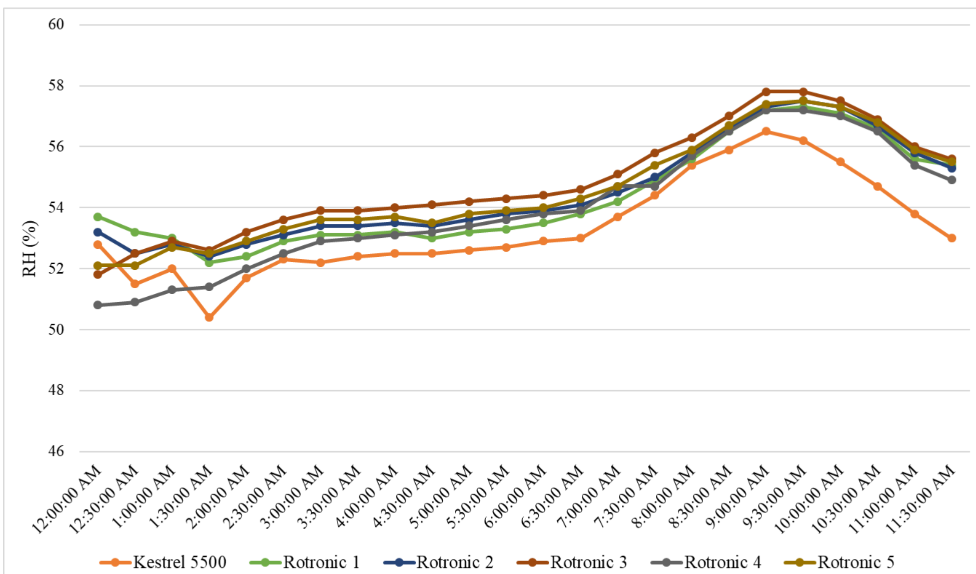


Figure 6-14: Data loggers RH calibration

6.4.2 Data-loggers Installation

The data loggers were installed during the peak hot months of the year, June, July, and August. The recordings were set for 24 hours continuous logging each day with a logging interval of 10 minutes. The data loggers were installed in different locations outside and within the house. All the data loggers were labelled and numbered to facilitate and organise the process of installation.

This mini weather station, a Kestrel 5500, was installed on the top roof. Following the manufacturer's recommendation to guarantee maximum accuracy, the data logger was shaded and raised above the roof parapet. Additionally, the floor and roof of the shading structure used for the mini weather station were covered with insulating material to prevent any excessive heat that could radiate back from the metal used to build the shading structure.

The four Rotronic data loggers were installed in the main spaces of the house including the ground and first-floor living room, men's guest room, and the stair zone. Furthermore, these spaces represent approximately 50% of the total functional areas in the house. The bedrooms were not accessible for monitoring due to cultural and privacy reasons. The data loggers were placed appropriately in locations that are away from any direct sunlight, windows, and cooling and heating sources. Moreover, and for safety reasons, all the loggers were installed at 1.7m from the floor to protect them from children. In the ground and first-floor living spaces the data loggers were installed on internal walls due to their central location in the villa. Further details during the installation process can be seen in Table 6-2, Figure 6-15, and Figure 6-16.

Table 6-2: Details and location of the data loggers installation

Name	Location	Height (meter)
Kestrel 5500	Roof top	2.1 (above the roof)
Rotonic 1	GF Living Room	1.7
Rotonic 2	FF Living Room	1.7
Rotonic 3	Stair zone	1.7
Rotonic 4	Male Guest Room (MGR)	1.7

Figure 6-15: pictures taken during the installation of the outdoor data loggers and shading structure

Figure 6-16: Locations of indoor data-loggers

6.4.3 Monitored Data Analysis

Each installed data-logger recorded over 10,900 readings. The collected data were then converted to hourly data by averaging the recorded data for each hour. The monitored outdoor data were then analysed and compared with the EPW file data from Meteonorm for a reason that will be discussed later in the validation section (6.6.1.1). The data are summarised in Table 6-3, which shows the minimum, maximum, and average outdoor DBT and RH for the monitored and EPW file data for June, July, and August.

Table 6-3: Maximum, minimum, and average DBT and RH for the measured and EPW data.

Criteria	**June**		**July**		**August**	
	Monitored data	**EPW data**	**Monitored data**	**EPW data**	**Monitore d data**	**EPW data**
Max DBT (°C)	43.6	41.9	**43.9**	**43.5**	43.3	43.4
Min DBT (°C)	26.8	**22.5**	27.7	22.7	**26.6**	22.9
Average DBT (°C)	34.3	32.2	35.1	33.3	34.7	33.9
Max RH (%)	23	35	26	41	33	41
Min RH (%)	5	10	6	10	7	10
Average RH (%)	13	18	13	18	15	20

6.5 VILLA MODELLING

Having selected and monitored the case study villa, this section will discuss one of the key research aspects, the modelling of the case study villa. As mentioned previously, IES-VE was chosen to model the villa. In this section, a detailed description of the villa characteristics, systems, and modelling process is discussed prior to the validation of the computational model. The input parameters that were taken into consideration when modelling the villa are the architectural and building construction details, building systems, occupancy profiles and schedules, and weather data file.

6.5.1 Architectural Details

During the monitoring process, the building was checked if it was built according to the architectural drawings. By confirming the accuracy of the drawings, the ModelIT tool within IES virtual environment was used to create the building geometry and functional spaces. The size, external wall area, windows sizes, the orientation of windows and window-to-wall ratio (WWR) of each functional space in the villa are shown in Table 6-4. The stair zone includes the details of all the three levels of the stair as it is open across the height of the villa.

It should be noted that the window details for the GF and FF living rooms are not presented in the table. This is because these spaces are open to the stair zone and kitchenette space. The villa has six toilets encompassing two on the ground floor, three in the first floor for bedrooms, and one in the annexe. The virtual model of the villa can be seen in Figure 6-17.

Table 6-4: Architectural details of internal spaces

Space	**Area (m^2)**	**External wall area (m^2)**	**size of windows**	**Number & orientation of windows**	**WWR (%)**
GF living room	36	-	-	-	-
FF living room	36	-	-	-	-
Stair zone	28.5	139.5	(1mx7m)	2 N + 1 E	15
Male guest room (MGR)	25.5	27.7	(1mx1.5m)	2 NW + 2 SW	21
Female guest room	23	40.8	(1mx1.5m)	2 NE + 2 SE + 1 SW	18
Kitchen	25	31	(1mx1.5m)	1 E +1 W	
Kitchenette	17	23.7	(1mx1.5m)	2 S	12
Master Bedroom (MB)	25.5	27.7	(1mx1.5m)	2 NW + 2 SW	21
MB Sitting area	14.2	17	(1mx1.5m)	2 NE	17
Room 1	17.3	18.7	(1mx1.5m)	1 NW + 1 W	16
Room 2	25	45	(1mx1.5m)	1 E +2 W	10
Room 3	23	36.8	(1mx1.5m)	1 NE + 2 SE + 1 SW	16
Housekeeper room	23	36.8	(1mx1.5m)	2 NE + 2 SE + 1 SW	16
Laundry room	10.6	28	(0.5mx0.5m)	2 S	2

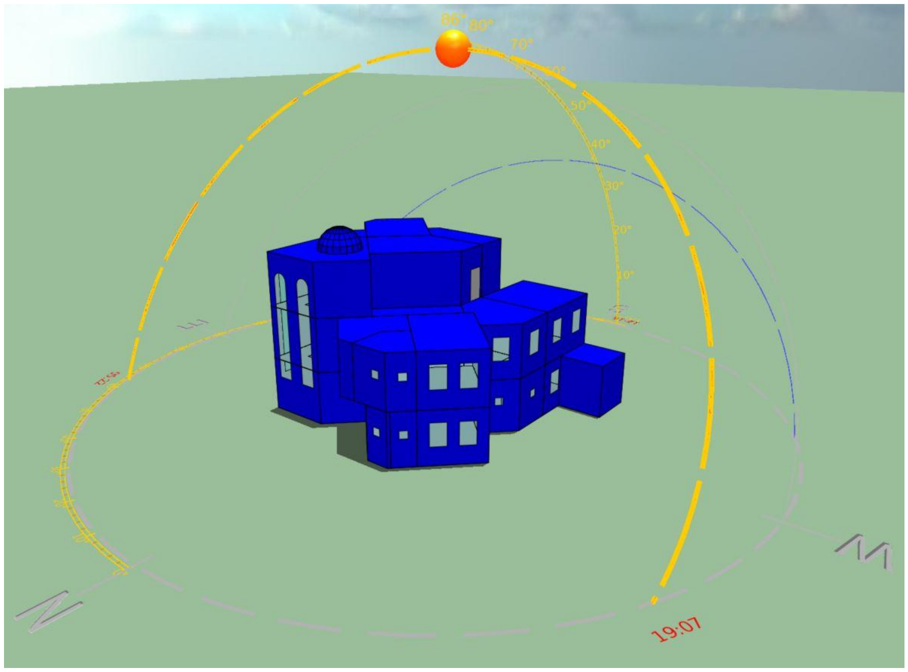


Figure 6-17: The virtual model of the villa in IES.

6.5.2 Fabric

Building fabric and construction details are key parts during the modelling process. By creating the 3-dimensional model, the next step was to assign the construction materials and data to the model. At this stage, the Apache tool within the IES-VE software was used. The building materials assigned to the model were obtained from three different sources: IES material library (IES, 2015a), ASHRAE Fundamental Handbook (ASHRAE, 2009), and Sami Al-Sanea (Al-Sanea *et al.*, 2016).

The modelled house is a reinforced concrete frame filled by hollow concrete block walls. The external walls are insulated with expanded polystyrene and covered by an external limestone layer. Both external and internal walls are covered by cement plaster layer. The roof and floors are constructed by reinforced concrete slabs. The roof concrete slab is covered by five layers including bitumen layer, cement plaster, gravel, another cement plaster, and tile. The roof was not covered by any thermal insulation layer. The windows are double glazed with a 6mm air cavity and constructed with an aluminium frame. A detailed description of the construction specifications and material properties can be seen in Table 6-5 to Table 6-10.

Table 6-5: External walls specifications

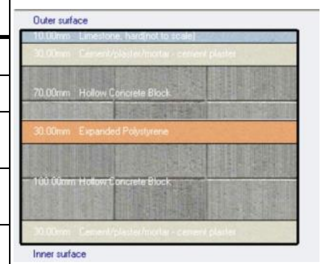
Materials (outside to inside)	Thickness (mm)	Conductivity (W/m.K)	Density (Kg/m^3)	Specific Heat Capacity (J/Kg.K)	
Limestone	10	1.5	2180	720	
Cement Plaster	30	0.72	1860	800	
Hollow Concrete Block	70	1.04	1105	840	
Expanded Polystyrene	30	0.035	25	1400	
Hollow Concrete Block	100	1.04	1105	840	
Cement Plaster	25	0.72	1860	800	
Total thickness: 265 mm		**Total U-value: 0.78 (W/m^2.k)**		**Total R-value: 1.09 (m^{2}k/W)**	

Table 6-6: Internal walls specifications

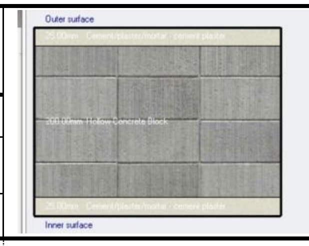
Materials (outside to inside)	Thickness (mm)	Conductivity (W/m.K)	Density (Kg/m3)	Specific Heat Capacity (J/Kg.K)	
Cement Plaster	25	0.72	1860	800	
Hollow Concrete Block	200	1.04	1105	840	
Cement Plaster	25	0.72	1860	800	
Total thickness (mm)	250	**Total U-value (W/m^2.k)**	1.9	**Total R-value (m^{2}k/W)**	0.26

Table 6-7: Roof specifications

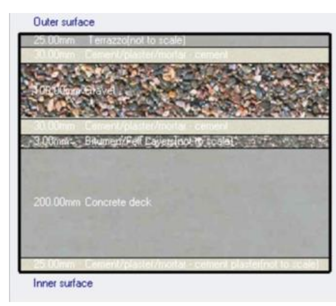
Materials (outside to inside)	Thickness (mm)	Conductivity (W/m.K)	Density (Kg/m3)	Specific Heat Capacity (J/Kg.K)	
Terrazzo Tile	25	1.8	2560	800	
Cement Plaster	30	0.72	1860	800	
Gravel	100	0.52	2050	184	
Cement Plaster	30	0.72	1860	800	
Bitumen layer	3	0.5	1700	1000	
Concrete deck	200	2	2400	1000	
Cement Plaster	25	0.72	1860	800	
Total thickness (mm)	413	**Total U-value (W/m2.k)**	1.75	**Total R-value (m2k/W)**	0.23

Table 6-8: Ground floor specifications

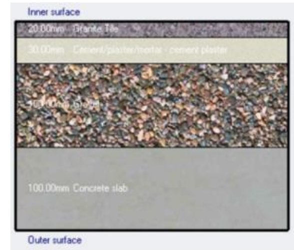
Materials (top to bottom)	Thickness (mm)	Conductivity (W/m.K)	Density (Kg/m3)	Specific Heat Capacity (J/Kg.K)	
Granite Tile	20	2.9	2650	900	
Cement Plaster	30	0.72	1860	800	
Gravel	100	0.52	2050	184	
Concrete slab	100	2	2400	1000	
Total thickness (mm)	250	**Total U-value ($W/m^2.k$)**	1.99	**Total R-value (m^2k/W)**	0.09

Table 6-9: Internal floors specifications

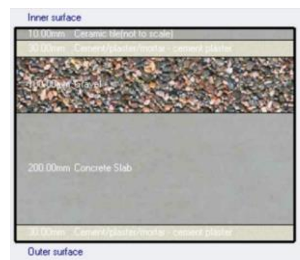
Materials (top to bottom)	Thickness (mm)	Conductivity (W/m.K)	Density (Kg/m3)	Specific Heat Capacity (J/Kg.K)	
Ceramic Tile	10	1.3	2300	840	
Cement Plaster	30	0.72	1860	800	
Gravel	100	0.52	2050	184	
Concrete slab	200	2	2400	1000	
Cement Plaster	30	0.72	1860	800	
Total thickness (mm)	390	**Total U-value ($W/m^2.k$)**	1.63	**Total R-value (m^2k/W)**	0.21

Table 6-10: Windows specifications

Materials (top to bottom)	Thickness (mm)	Total U-value ($W/m^2.k$)	Total R-value (m^2k/W)	
Glazing	6	2.6	0.40	
Cavity (air)	6			
Glazing	6			

6.5.2.1 Infiltration rate

Infiltration is the uncontrolled outdoor air that enters a building through windows, doors, or cracks in the building envelope due to pressure differences (Jain and Dewan, 1990).

Hence, the infiltration rate is highly dependent on the construction technique and age of a building. The infiltration rate could be significantly minimized by a sealed envelope and well-fitted doors and windows. The infiltration rate is expressed by the air changes per hour (ACH) and can accurately be measured by a blower door test.

Due to the limitation of measurement equipment's availability, the infiltration rate could not be measured for the case study villa. Norbert Lechner presented a set of common infiltration rates based on the building type or age and international standard requirements (Jain and Dewan, 1990). The infiltration rates were listed from higher than 8 ACH in an old leaky house to lower than 0.6 in an airtight Passivhaus building. In a standard modern house, which is similar to the case study discussed in this research, the infiltration rate was shown to be between 0.5 to 1 ACH. It migh be considered that around 0.5 ACH is a low value. However, by referening the constrction method followed in SA, this could be achieveble. The reinforced concrete structures with the continous concrete block walls that is covered with a continious cement plaster layer throughout the intire building envelope could provide lower ACH rates. To support this argument, different infiltration valuse were tested during the simulation process. The tested values ranged from 0.25 ACH to 2 ACH. It was found that a 0.7 ACH provided the best result when comparing the modeled results with the acutal measured data. Consequently, an infiltration rate of 0.7 ACH was assumed for the modelling of the case study villa.

6.5.3 HVAC

The details of the HVAC systems used in the villa were collected during the site visit. In brief, the main cooling system used in the house is a split wall-mounted system. Each functional space of the house, excluding toilets, corridors, and stair zone, contains one cooling unit. Auxiliary ventilation fans were installed in the kitchen and toilets. During the site visit, the set-point temperature for the HVAC units in the house was checked and found to be 25.5°C. This set-point was considered during the modelling of the villa in IES-VE. The specification of the HVAC system is summarized in Table 6-11 below.

Table 6-11: HVAC details

Type of HVAC system	split wall mounted
Energy-efficiency	Cooling Energy Efficiency Rating (EER): 3.25w/w (11.08 (Btu/h)/w). (Manufacturer)
Cooling set-point	Cooling : 25.5°C
Auxiliary ventilation	The auxiliary ventilation for kitchens is 50 1/s, and for toilets/bathrooms is 25 1/s (ASHRAE, 2009).
Energy of auxiliary ventilation	The energy for auxiliary ventilation is 1 W/(l/s) for kitchens, and 0.5 W/(l/s) for toilets/bathrooms. (Manufacturer)

6.5.4 People, Lighting and Equipment

IES-VE and its simulation engine Apache tool require the input for the internal gains and power density for people, lighting, and equipment. People gains are required by specifying both sensible gain and latent gain in watt per person as well as the number of occupants for each space. These values were considered according to ASHRAE and illustrated in Table 6-12. In terms of lighting power, IES-VE provides two options by either entering the total lighting power in wattage (W) or watt per meter squared (W/m^2) for each space in the model. The lighting fixtures details for each space were collected during the site visit and described in Table 6-13 below. The power density inputs in Table 6-14 were considered according to a survey study conducted by Abdulghani Monawar (Monawar, 2001a). These details were considered during the modelling of the villa.

Table 6-12: People heat gains (ASHRAE, 2009)

Zone	Sensible heat (W/person)	Latent Heat (W/person)
Living and guest zones	65	30
Sleeping zone	40	30
Kitchen zone	80	80

Table 6-13: Light fixtures of the case study villa

Zone	type	Number of fixtures and power consumption (W/fixture)	Total wattage
Guest zones	LED	4 (20W) + 12 (6W)	152
Living spaces	LED	4 (20W) + 20 (6W)	200
Master bedroom	LED	4 (20W) + 12 (6W)	152
Sleeping rooms	LED	4 (20W)	80
Kitchen	LED	6 (20W)	120
Toilets	LED	1 (20W)	20

Table 6-14: Power density of main zones

Zone	Power density (W/m^2)
Guest zones	5
Living	7
Sleeping zone	7
Kitchen zone	30

6.5.5 Occupancy Profiles

Occupants' behaviour has been considered as a sophisticated aspect when quantifying a built environment. A number of studies have investigated occupancy patterns and their influence on the built environment. It has been discovered that occupants play a critical role in building operation. However, it was also found that the prediction of occupants' behaviour is one of the most challenging aspects in the design process (Yan *et al.*, 2015; Hong *et al.*, 2016; Delzendeh *et al.*, 2017)

In the modelling process, occupants schedule and profiles are an integral part when conducting a computational analysis for the building performance. Occupants' behaviour and the way they use and control their building offers considerable uncertainty when modelling and predicting the energy performance of a building. However, one of the restrictions and limitations when collecting the data was direct communication with the occupants of the villa. It was not possible to communicate directly with the occupants to ask them about the way they use the spaces. Furthermore, communicating with female occupants by the author was not possible. As a result, attempts were made to determine occupants' behaviour and use of spaces by analysis and observation of the monitored indoor temperature during the three summer months.

It was observed that indoor temperatures were high during specific times of the day and low during other times. This sudden fluctuation in indoor temperatures indicates the time when air-conditioning was running or not. By conducting this analysis, it was possible to identify the times when the air-conditioning was running, indicating the use of occupants for that space. Consequently, the cooling schedules for each measured room were determined based on monitored indoor temperatures. Then, the same schedules were used for the inputs of occupants' profiles, lightings profiles and equipment profiles. This assumption was made as the occupants' existence in a space would lead to the use of space cooling and equipment. Nevertheless, lighting in sleeping zone was not linked to these profiles as they cannot be linked to occupants' existence. For instance, lighting in the sleeping rooms were assumed to be on one hour before and after the occupants use as the occupants in this zone would be sleeping. Since the kitchen space was not monitored, It should also be mentioned that the kitchen occupancy profiles were considered based on a survey study conducted by Abdulghani Monawar (Monawar, 2001a). The daily profiles for the monitored spaces are summarized in Table 6-15 to Table 6-18 below.

Table 6-15: Daily profiles for Kitchen

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Weekday							50%	50%				100%	100%	100%					100%					
Weekend									50%	50%	100%	100%	50%	50%	50%	50%	100%	100%	100%	100%	100%	100%	100%	
Equipment	10%	10%	10%	10%	10%	10%	100%	50%	50%	50%	100%	100%	100%	50%	50%	50%	50%	50%	100	100	50%	10%	10%	10%

Table 6-16: Daily profiles for living zones

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Weekday									50%	50%	100%	100%	100%	100%	100%	100%	100%	100%						
Weekend										50%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	

Table 6-17: Daily profiles for sleeping zones

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Weekday	100%	100%	100%	100%	100%	100%	100%	100%	50%	50%													100%	100%
Weekend	100%	100%	100%	100%	100%	100%	100%	100%	50%	50%													100%	100%

Table 6-18: Daily profiles for guest spaces

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Weekday																								
Weekend															50%	50%	50%	100%	100%	100%	100%	100%	100%	

6.6 MODEL VALIDATION

The validation of the model is a fundamental step before any further development. As described previously in this chapter, there could be considerable differences between predicted data and actual performance and energy consumption measurements, known as the performance gap. Although IES-VE has been fully validated by ASHRAE Standard 140 (IES Validation results, 2019), the IES-VE model of the villa was additionally validated against the actual measured data to assure confidence and bridge the performance gap of the IES model. The validation process was conducted in two stages: (1) envelope validation, (2) energy consumption validation. The envelope validation aimed to ensure the validity of the thermal envelope performance of the villa model by performing a free-running simulation for a specific period when the house was unoccupied. On the other hand, the energy consumption validation represents the validity of the systems used in the virtual model by comparing the predicted total energy consumption in IES-VE against the actual total consumption acquired from the electricity bills.

6.6.1 Modelled Envelope Validation

To ensure the validity of the thermal envelope performance of the IES model, a simulation was conducted from 15th June to 20th of June when the house was free-running. For that period, all the systems of the house, including HVAC, lighting, and equipment, where set to be off as the house was unoccupied during this period. As a result, the free-running simulation will mainly assess the thermal envelope performance and materials used in the IES-VE model against the actual building construction by comparing the indoor temperatures of the virtual model with the monitored temperatures. In other words, the modelled envelope performance will be tested as it is the only parameter affecting the indoor temperature when all the systems were off.

6.6.1.1 Employing real weather data

A current hourly EPW weather file generated from Meteonorm was used for the validation and simulation process. However, in order to confirm the integrity of the data and maximum consistency between indoor measured and simulated data, the weather file was modified during the period of the monitoring to correspond with the measured site-specific weather data. Although the measured data were set at a 10 minutes reporting interval, the recorded data for each hour were averaged prior to using them in the EPW file. The software Element 1.0.6 was used to modify the weather file. Element is a free cross-platform software tool developed by Big Ladder Software. The software can browse and edit weather data files, including EPW format, for building energy modelling with automatic preservation of psychrometric and solar relationships (Elements, 2019). The monitored outdoor weather parameters, including DBT and RH, were employed in the EPW weather file before the simulation. The modified weather file was then used in IES-VE to perform the simulation for the virtual model.

In the beginning, several simulations were conducted. However, a significant daily temperature fluctuation was observed, which was divergent from the measured data. Even on the ground floor living area, which was central in the house and not connected directly to any external surface, the simulation results have shown significantly higher temperatures than the monitored data. Having assessed the simulation data throughout an extensive simulation process, it was revealed that the assumed ground temperatures in IES-VE were causing this difference. Further detailed analysis of the effect of the ground temperature will be discussed in the following subsection.

6.6.1.2 Ground temperature

In IES-VE, the default adjacent condition of the ground floor (ground temperature) is assumed to be outside air temperature, making this surface exposed to external conditions. However, the ground temperature depends significantly on the thermal properties of the soil and depth of the ground (Kavanaugh and Rafferty, 1997; Florides and Kalogirou, 2005b; Cui *et al.*, 2011). Furthermore, both a building and the ground temperature beneath it will affect each other (Hassan and Sumiyoshi, 2017). By referring to the IES-VE manual, the software provided three different options when setting adjacent surface conditions. Among these options is the *Temperature from Profile*, which was recommended to be the option for the ground floor (IES, 2015b). In this option, a monthly profile is created in APpro tool within the software package to specify a ground temperature for each month.

Nevertheless, the default temperatures assigned in IES-VE are based on the United Kingdom's monthly average ground temperatures. Hence, the ground temperature profile was modified by using the average monthly ground temperature from the EPW weather file of Hail. However, it was noticed that the simulated indoor temperatures significantly dropped below the measured temperatures, which is opposite to the previous setting. As a consequence, a significant effort was devoted in order to find out a suitable method to estimate the ground temperature settings.

In the beginning, it was noticed that the given average ground temperature is considered at a depth of 1 metre. According to experimental studies conducted in this matter (Florides and Kalogirou, 2005a; Cui *et al.*, 2011), ground temperature variation, both daily and annually, depends significantly on the depth of the ground. A ground temperature of 1-metre depth and below has shown less sensitivity to the daily ambient temperature. At two to three metres, the highest ground temperature recorded was about five to six months later than the highest ground surface temperature (Florides and Kalogirou, 2005a). Hence, the highest average ground temperature in the weather file was set to be for September, which is about two months temperature lag because of the 1-metre depth considered in the weather file (Climate Consultant, 2019b). On the other hand, the daily ambient temperature fluctuation was apparent at a depth of 0.5 metre and above, which is the layer adjacent to the building floor (Florides and Kalogirou, 2005a).

Due to the lack of studies and measurements of ground temperatures in the region, an estimation of the monthly average ground temperature was considered based on the literature analysis. Hence, an appropriate ground temperature estimation was found to be by shifting the EPW weather file ground temperature two months back.

6.6.1.3 The envelope validation results

Having applied the modifications in the weather file and the ground temperature, Figure 6-18 to Figure 6-21 below show the comparison between the predicted IES-VE indoor temperatures and the monitored indoor temperature for different spaces in the house. The visual representation of the comparison indicated a good agreement between measured and simulated data. In the GF and FF living rooms, it should be mentioned that there was a diurnal swing in the measured data while this wing was less in the actual data. This could be attributed to the location of the spaces and data loggers installed in these two spaces. These two spaces where the spaces least affected by outdoor conditions due to their central location within the house. In addition, the data loggers were installed in the rear internal walls of the spaces, where they have been less influenced by the outdoor conditions, which was not the case in the other two spaces. Furthermore, the simulated results account for the average temperature of the entire space, which was affected by adjacent spaces. Hence, the fluctuation in the indoor temperature was apparent in the simulated result while it was less in the measured temperature.

To further verify the validity of the villa model, a statistical analysis was conducted to quantify the discrepancy between the measured and modelled data. One recognised approach is by calculating the Coefficient of Variation of the Root Mean Square Error (CVRMSE) in accordance with ASHRAE standard (ASHRAE, 2009). The results show that the CVRMSE for the GF living room, FF living room, male guest room, and stair zone was 1.7%, 3.3%, 2.6%, and 1.1%, respectively. The ASHRAE guideline points out that when the CVRMSE is less than 15% for monthly data and less than 30% for hourly data, the model is considered calibrated. By taken the acceptability limit of the hourly data into consideration, the statistical analysis revealed a very good validity level for the computational model.

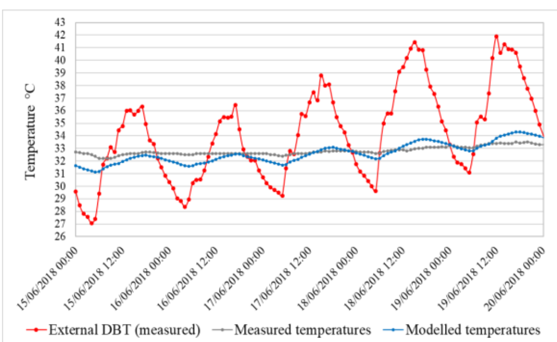


Figure 6-18: Ground floor living room

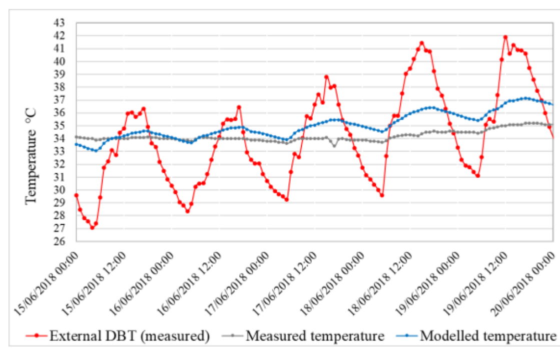


Figure 6-19: First floor living room

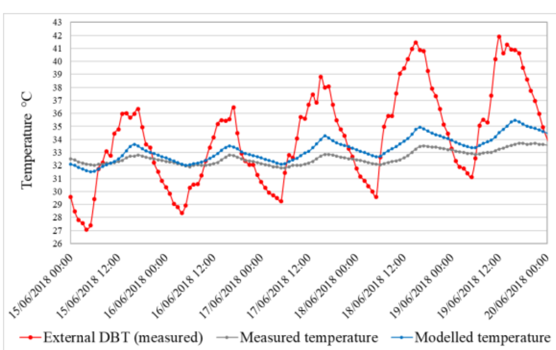


Figure 6-20: Guest room

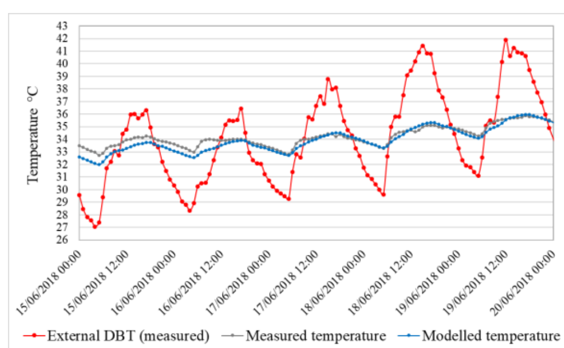


Figure 6-21: Stair zone

6.6.2 Energy Consumption Validation

This section aims to investigate and assure the validity of the systems used in the model, including HVAC, lighting, and equipment, by comparing the predicted total energy consumption against the electricity bills. The actual energy consumption of the villa was acquired during the data collection period from the electricity supply company (SEC, 2019). The obtained electricity bills covered the five summer months from May to September. This period represents the peak energy consumption in the year due to air conditioning.

Prior to conducting the energy comparison, it should be noted that the collected electricity bills were based on the Islamic Hijri Calendar. Hence, the monthly bills were converted to the Gregorian English Calendar to coincide with the actual data with the simulated energy consumption.

At this step, the assigned building systems and profiles mentioned previously were taken into account. The energy consumption of the case study villa can now be predicted based on the systems inputs. Then, the simulated energy consumption was compared with the actual energy consumption for each month. The results of the comparison are shown in Figure 6-22, which demonstrate a very good agreement between the predicted and actual total energy consumption. Based on the results, the expected energy consumption for the five months was approximately 15391 kWh, compared with the actual consumption of 15411 kWh. Although the results should very close numbers in terms of the total energy consumption during the entire summer season, this was not the case in the monthly baces. For instance, the actual consumption was less in June when compared to the predicted consumption. This could be attributed to the occupants behaviour and appliances use, which is always difficult to model.

By validating the IES-VE model, the next step was to identify a base case of energy consumption of the typical Saudi residential villa. This step will be explained in the following section.

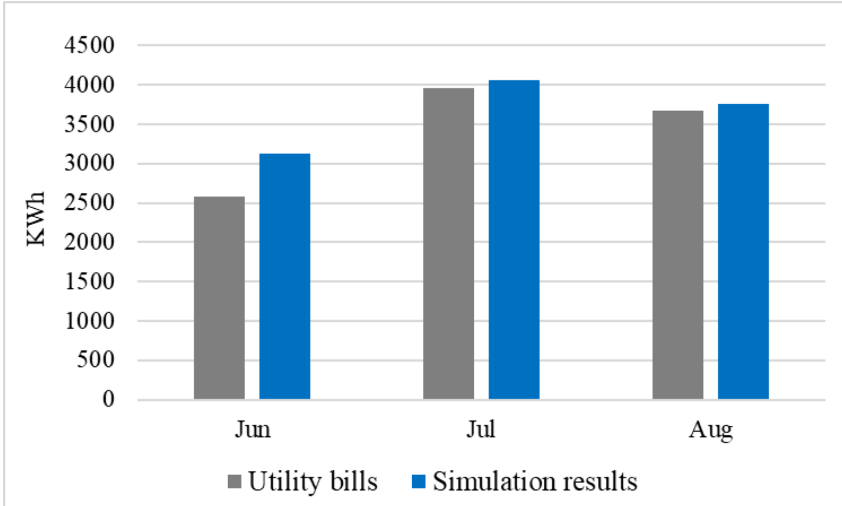


Figure 6-22: Total energy consumption comparison

6.7 IDENTIFYING THE BASE CASE ENERGY CONSUMPTION

Having validated the computational model, the next step was to create a baseline rate of energy consumption for this typical Saudi house. The existing profiles and energy consumption were considered and calculated when some parts of the villa were not used. Consequently, typical residential daily profiles, based on a survey study conducted in Saudi Arabia, were used (Monawar, 2001b). The objective behind that was to develop a fully operating baseline case based on typical Saudi occupancy profiles. The profiles were classified to three main categories, including occupancy, equipment, and lighting. Each category was sub-divided to four different profiles based on the building zones: guest zone, living zone, kitchen zone, and sleeping zone (see Figure 6-23). The energy consumption analysis of the base case will be discussed in the following section.

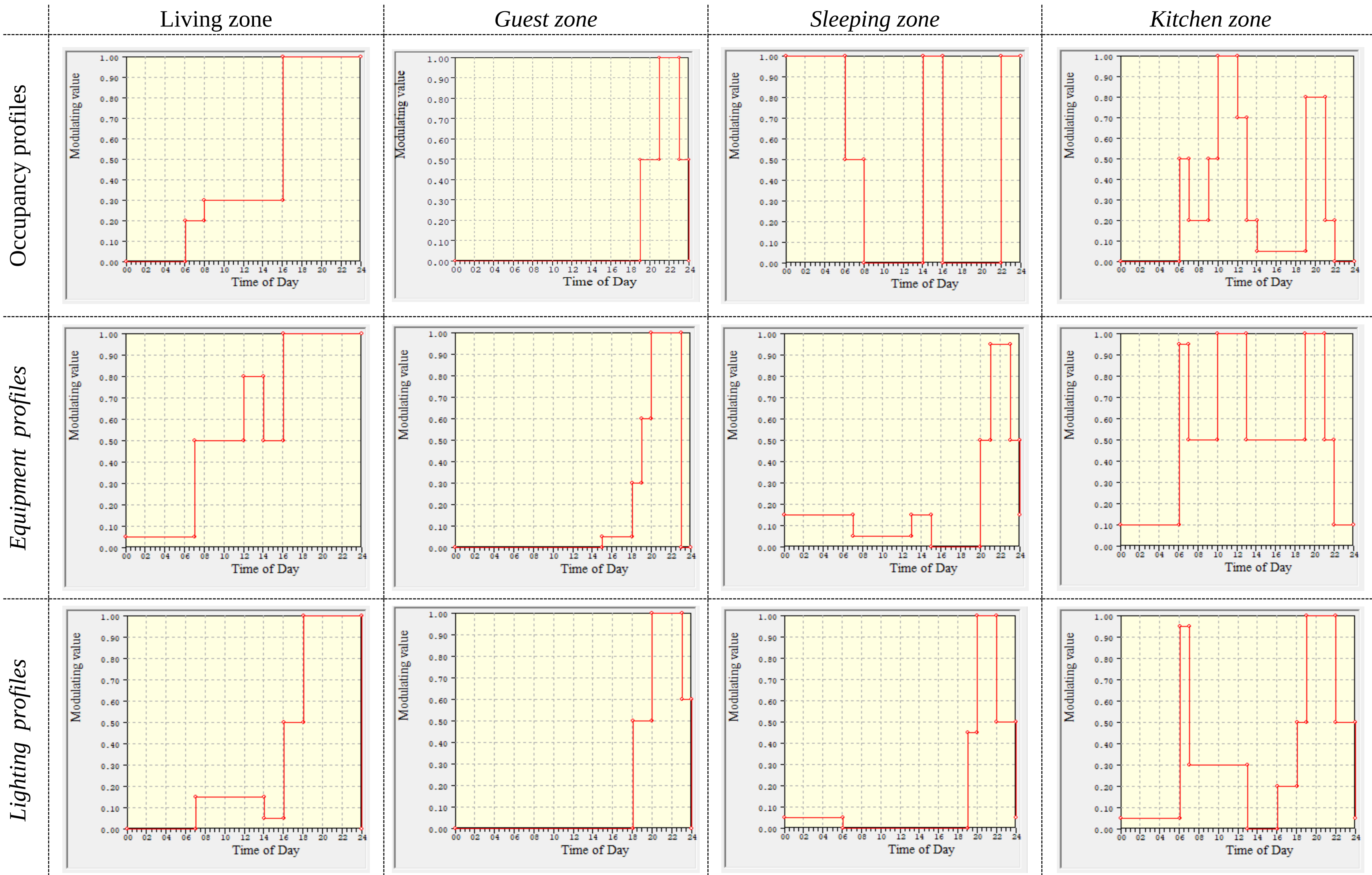


Figure 6-23: Daily occupancy, equipment, and lighting profiles for each zone (Monawar, 2001b)

6.7.1 *The Base Case Energy Consumption*

Considering the modification on the profiles to reflect the typical Saudi occupants' pattern, the model was simulated in IES-VE in order to determine the baseline case energy consumption. Figure 6-24 summarises the obtained results of the monthly electricity consumption for the summer period. The total energy consumption for the base case model is estimated to be approximately 32415 kWh during the summer season. Of the total energy consumption, space cooling energy consumes nearly 28337 kWh, which accounts for 88% of the total electricity use (Figure 6-25). Lighting electricity has shown the lowest consumption rate, only 3%, when compared to cooling and equipment consumption. Indeed, this is attributed to the high-efficiency lighting fixtures (LED) used in the house.

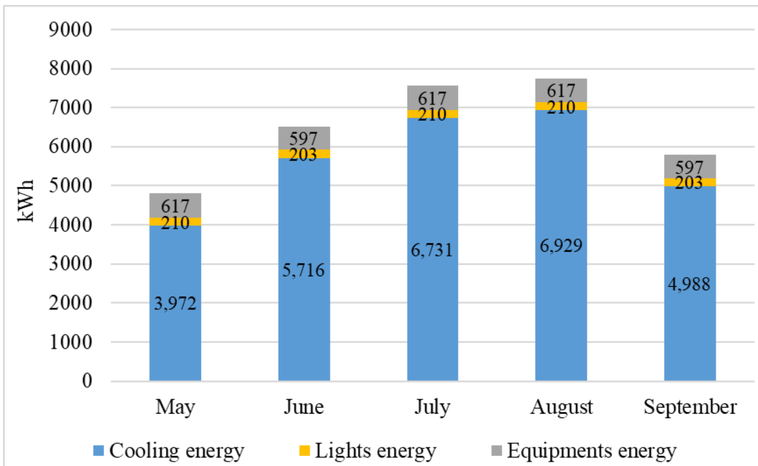


Figure 6-24: Monthly energy consumption rate for the base case model during the summer

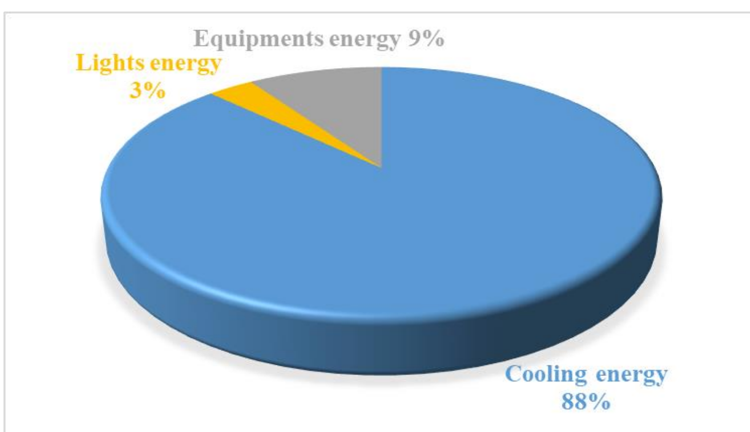


Figure 6-25: Distribution of energy use for the base case model

Having identified the base case energy consumption of a typical Saudi house, the next step was considering the integration and analysis of a PDEC tower in the house in order to investigate its performance. The analysis of this step is discussed in the following chapter.

CHAPTER 7. THE INTEGRATION AND PERFROMANCE ASSESSMENT OF THE PDEC TOWER IN A TYPICAL SAUDI HOUSE

7.1 CHAPTER OVERVIEW

As mentioned previously, this chapter comprises the second part, stage three, of this research. In this chapter, the main research aspects will be discussed. The previous findings in stage one and two are brought together to study the virtual integration of a PDEC tower in the model of an existing typical Saudi villa that was described in the previously. As described in the previous chapter, the model of the present case of the house was utilised as a base case model for further investigations and analysis, using typical Saudi occupancy profiles. Then, a PDEC tower was virtually integrated into the base case model. Comparison and analysis between the base case and the PDEC case is discussed. The analysis then revealed the opportunity for further enhancement of the PDEC performance through the alteration and modification of the buildings' openings. Hence, further parametric analysis was conducted, resulting in additional developed cases to maximise the PDEC tower. Moreover, energy consumption and thermal comfort level assessment of the developed cases are among the topics that will be discussed in this chapter.

7.2 THE INTEGRATION OF THE PDEC TOWER: *THE PDEC CASE*

The PDEC tower was virtually integrated into the villa model in IES-VE and was based on the modelling and validation process discussed in section 5.2 and 5.3 previously. The PDEC tower was located centrally and internally within the house and surrounded by the main spaces of the house including the GF living room, FF living room, guest room, and master bedroom (Figure 7-1). The open stair zone was also connected to the tower through the open living spaces in the ground and first floors. The structure of the PDEC tower was almost similar to the rest of the building. As shown in Figure 7-2, the tower model is subdivided vertically into three main sections encompassing windcatcher, spray zone, and cooling tower (supply section) zone. The PDEC tower is modelled to supply the evaporated cooled air to the surrounding spaces on both ground and first floors. The tower specifications are summarized in Table 7-1. The tower cross-section dimensions are 1.5m x 2.4m (3.7m^2) following an aspect ratio of 3:2, which is recommended in the literature for rectangular shaped PDEC towers (Kang and Strand, 2016). The width of the tower is parallel to the prevailing wind direction to make the wider side of the tower facing the prevailing wind direction, North-West, during the summer (Figure 7-3).

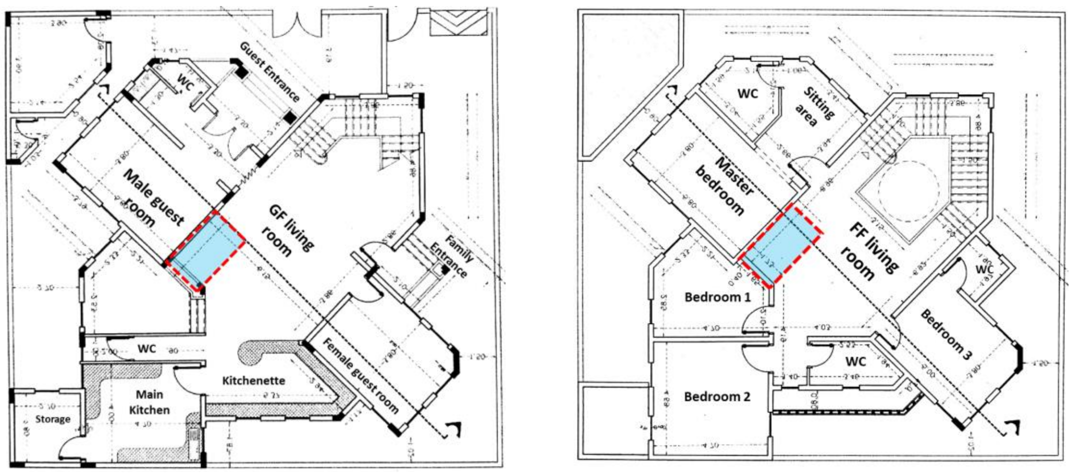


Figure 7-1: The location of the PDEC tower within the villa

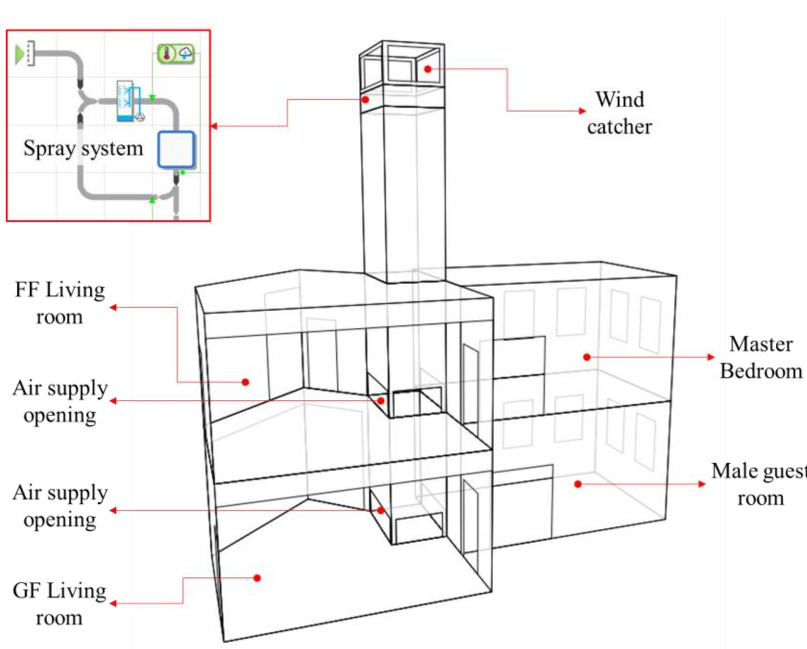


Figure 7-2: Details of the PDEC tower

Table 7-1: PDEC tower specifications

	PDEC tower specifications
Tower Height	12.8 m
Tower cross-section	1.5m x 2.4m (3.7m^2)
Wind Catcher	Four sides louvre openings with 80% openable area
Wind catcher openings	(2) 0.8m high x 2.2m width + (2) 0.8m x 1.3m (total area: 5.76 m^2)
GF supply openings	(2) 0.7m high x 2.2m width for the GF living room and guest room + (1) 0.7m high x 1.3 width for the GF living room (total area: 4 m^2)
FF supply openings	(2) 0.7m high x 2.2m width for the FF living room and master bedroom + (1) 0.7m high x 1.3 width for the FF living room (total area: 4 m^2)

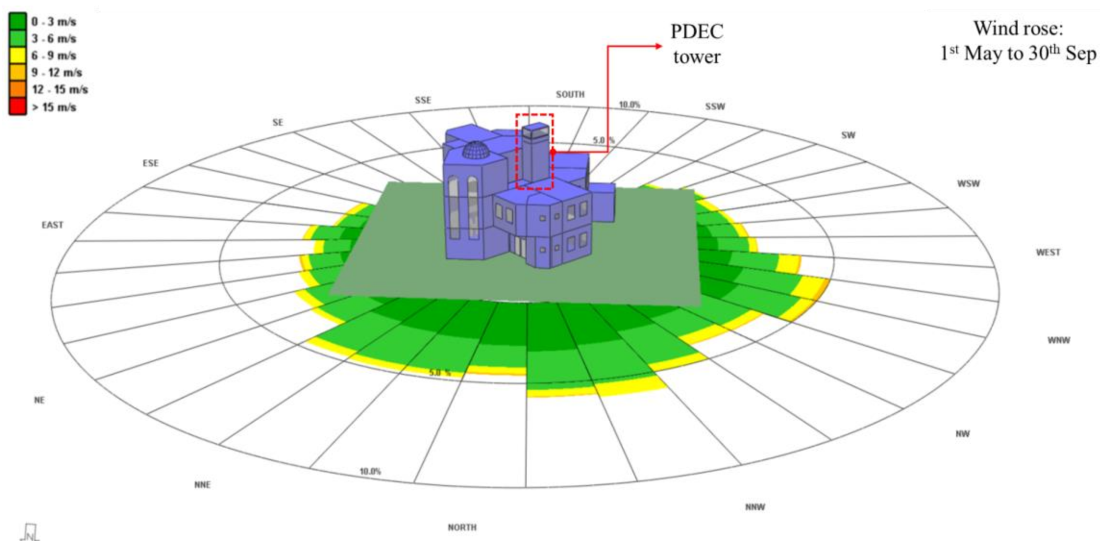


Figure 7-3: The integration of the PDEC tower and wind rose from May to September

The windcatcher was a four-sided air inlet openings located at the top of the PDEC tower. The openings were controlled with movable louvres with 80% openable area. The opening sizes of the windcatcher were 0.8m x 2.2m and 0.8m x 1.3m, on the length and width sides of the rectangular tower, respectively.

Essentially, the system relies on the water spray as a heat sink to absorb the heat from the captured air. The spray zone was modelled just below the windcatcher to cool the incoming air before it enters the targeted spaces. The spray system was modelled using ApacheHVAC software within the IES-VE package. The spray tool within the software was set and assigned to the spray zone. Generally speaking, a temperature reduction of 80% of DBT-WBT depression is achievable (Ford, Schiano-Phan and Francis, 2010). Hence, the efficiency of the spray system was assumed to be 80%, although the assessment of the PDEC towers in Dar Al-Rahmaniah Library (CHAPTER 4) showed better efficiencies in the hot, dry Saudi climate. Even though the system is considered passive cooling and air is buoyancy-driven, the system consumes electrical energy due to the pump needed to pump the water to the top of the tower. However, the energy required to run the passive system is significantly lower when compared to a conventional cooling system. The water pump power of the PDEC model was set to be 0.37kW.

The cooling tower is the third and lower section of the PDEC tower. This section is the internal part of the tower that is surrounded by the interior cooled spaces on the ground and first floor. The tower contains six internal air supply openings placed to allow the air to flow between the tower and attached rooms. On the ground level of the tower, three supply openings were placed at the bottom of the tower, where two of them supply the cooled air to the GF living room while the third one serves the men guest room. Similarly, the other three openings are located on the first-floor level supplying air to the FF living room and Master Bedroom. The two wider sides of the tower have larger openings (0.7m high x 2.2m width) while the narrower North East side has a smaller opening (0.7m high x 1.3 width). In order to enhance the supply airflow, the supply openings were designed to have a total area larger than the tower cross-sectional area.

Initially, the PDEC system was set to be working continuously (24/7) in order to find out the cooling capacity and performance of the PDEC tower for the targeted spaces. At this step, the base case with the integrated PDEC tower was named the PDEC Case. The mechanical cooling operation set-up was kept similar to the base case without any further changes. Given these inputs, the cooling system will become a mixed-mode cooling for the targeted spaces around the PDEC tower were both active (mechanical) and passive (PDEC) cooling work in conjunction, at some points, during the cooling process. In other words, the mechanical cooling system will be working with the PDEC system once the cooling performance of the PDEC system is not enough to meet the cooling set-point requirement during the occupied hours.

During the mixed-mode cooling (see Table 7-2), the existing windows located on the north-western wall of the male guest room, and master bedroom were opened at the maximum openable area of 50% to allow the PDEC air to circulate within these spaces. Additionally, the top part of the large stair zone windows (at second-floor level) were also modelled to be open at 50%. The total openable area of the external windows was 6.3 m^2, which is larger than the tower cross-sectional area to enhance the air circulation within these space.

Table 7-2: Mixed-mode cooling and ventilation inputs for the PDEC case

	Type	cooling set-point	operation	spaces
Mechanical cooling system	Split wall-mounted	25.5°C	Occupants' profiles	all functional spaces
PDEC system	Spray (80% efficiency) + 0.37kw water pump	no set-point	continuously (24/7)	GF living room + FF living room + guest room + master bedroom + stair zone
Window operation	Top floor stair zone openings and NW openings of the MGR and MB are open 24/7 at 50%			
Openable area	Stair windows: 3.3 m^2 / male guest room: 1.5 m^2 / master bedroom: 1.5 m^2			

7.3 RESULTS AND ANALYSIS OF THE PDEC CASE

As anticipated, the simulated results demonstrated the ability of the PDEC tower to cool natural air in the hot, dry Saudi climate. The PDEC tower provided a considerable amount of cooling to the four passively cooled spaces. Due to the large difference between the outdoor DBT and WBT, and low RH levels, the PDEC only was able to drop the external DBT by more than 15°C in the occupied spaces and more than 17°C within the PDEC tower during the hottest period of the summer season. The difference between the outdoor

RH and indoor RH ranged between 20 to 30% and 30 to 45% in the occupied spaces and the tower, respectively. The increase in the indoor RH is attributed to the added moisture in the air stream of the PDEC tower. Despite the overall optimistic performance of the PDEC tower, the mechanical cooling was still working during parts of the occupied hours to cover the need for extra cooling. As expected, based on the previous analysis in CHAPTER 4, the need for the mechanical cooling was attributed to two main reasons: (1) high DBT during peak summer times, (2) specific wind conditions. To better understand the impact of different weather conditions on the building, further investigation, encompassing energy consumption and thermal performance analysis, of the PDEC case compared with the base case is discussed in the following section.

7.3.1 The Performance of the Base Case and the PDEC Case

Initially, only the GF living room and master bedroom (MB) were selected for further analysis. The selection of these two spaces was for three reasons. First, the GF living room and MB have almost similar characteristics (size, location within the house) to the FF living room and male guest room (MGR), respectively. Hence, the selection of the two spaces would minimise repetitive results as the other spaces would encounter similar conditions. Second, the selected spaces were chosen to account for all the different scenarios. For instance, the GF living room is located in the centre of the house with a large open space connected to all the different spaces around it. On the other hand, the MB is a smaller space located on the first floor towards the prevailing wind direction side of the villa. Third, the GF living room is occupied during most of the day hours while the MB is generally used during the night hours. The different characteristics of the two spaces will account for different scenarios that might affect the PDEC performance.

For the BC and PDEC case, the DBT, WBT, and indoor temperatures of the two selected spaces were initially plotted in graphs for every summer month and are shown in Figure 7-4 to Figure 7-13. Based on the results, it is clear that the PDEC tower supplied a significant amount of cooling during the five summer months for both spaces. It was apparent that the indoor temperatures were cooler during May and September due to the relatively cooler external DBT. The indoor temperature dropped even below the set point temperature (25.5^{o}C), reaching below 18^{o}C during the night hours. In June, July, and

August, the lowest indoor temperatures were found to be 20.0°C, 21.2°C, and 20.5°C, respectively, in the GF living room. In the MB, the lowest temperatures were slightly higher, reaching 22.0°C in June, 22.6°C in July, and 22.7°C in August. Generally, the GF living room showed better performance when compared to the MB. The location of the space, at the bottom level, which is protected from most of the different weather conditions by the surrounding spaces, has helped to improve the cooling performance of the PDEC. Additionally, the high openings at the top of the stair zone provided stack ventilation that developed the air movement due to the temperature differences between the levels for most of the summer period. On the contrary, the PDEC tower provided a lower cooling performance for the MB despite the overall acceptable performance. Under specific conditions, the PDEC case has even demonstrated worse performance than the BC with indoor temperatures exceeding 38°C. To further investigate the wind effect, the analysis continued including all the four spaces for the hottest period.

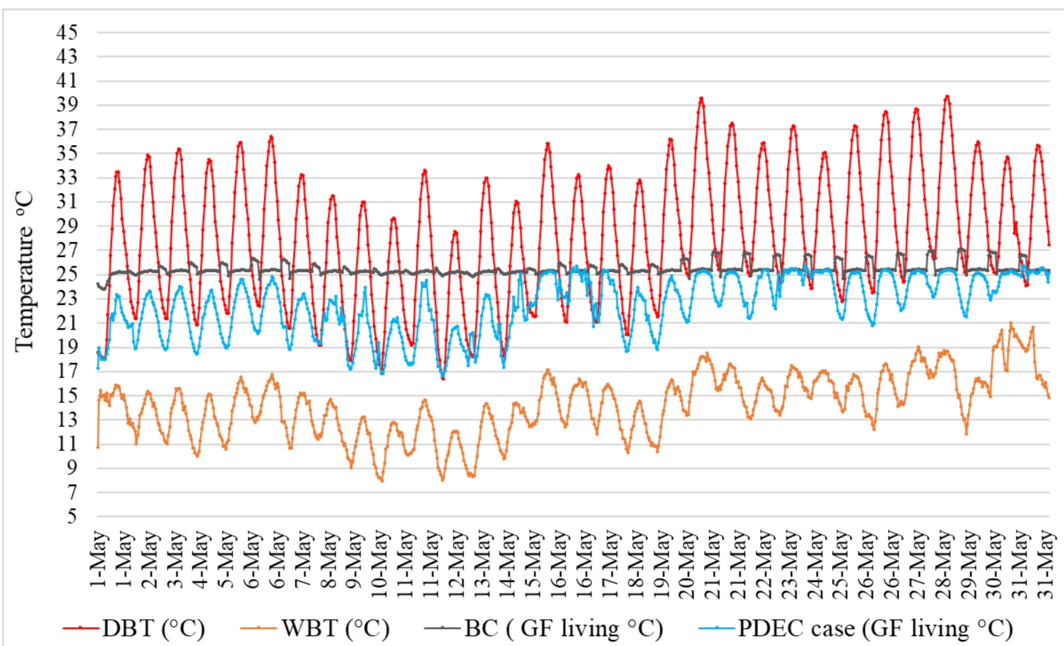


Figure 7-4: External DBT, WBT, and GF living room temperature for the BC and PDEC case during May

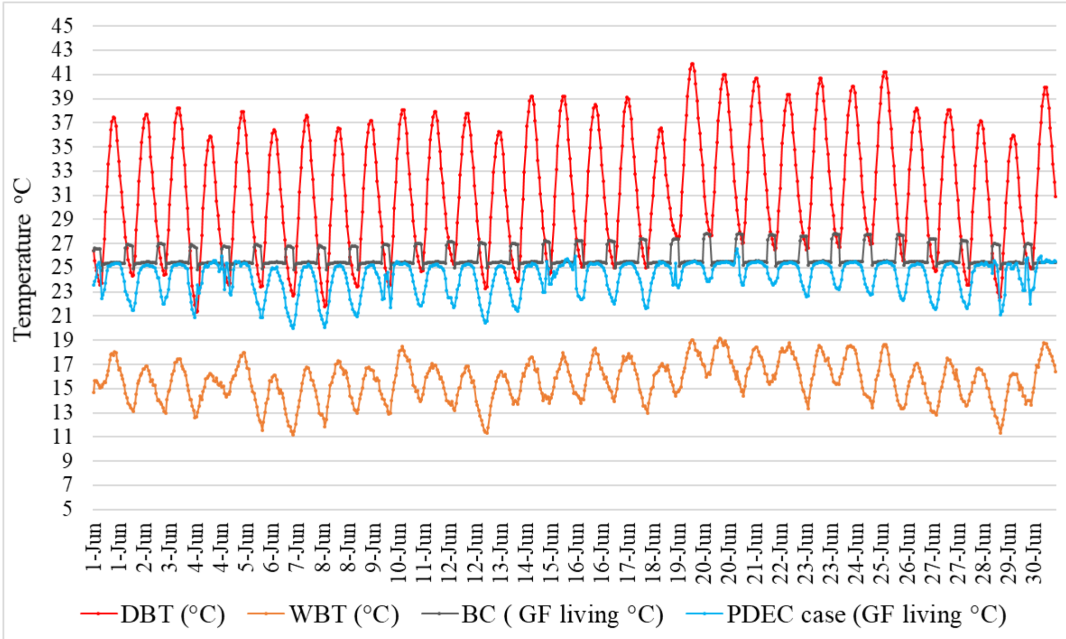


Figure 7-5: External DBT, WBT, and GF living room temperature for the BC and PDEC case during June

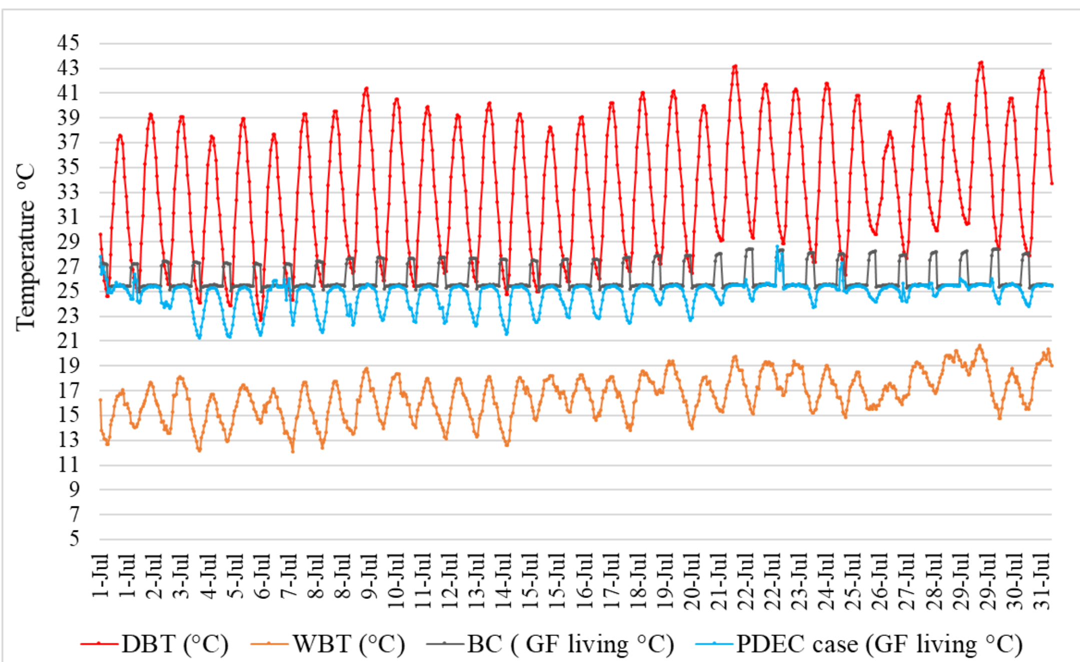


Figure 7-6: External DBT, WBT, and GF living room temperature for the BC and PDEC case during July

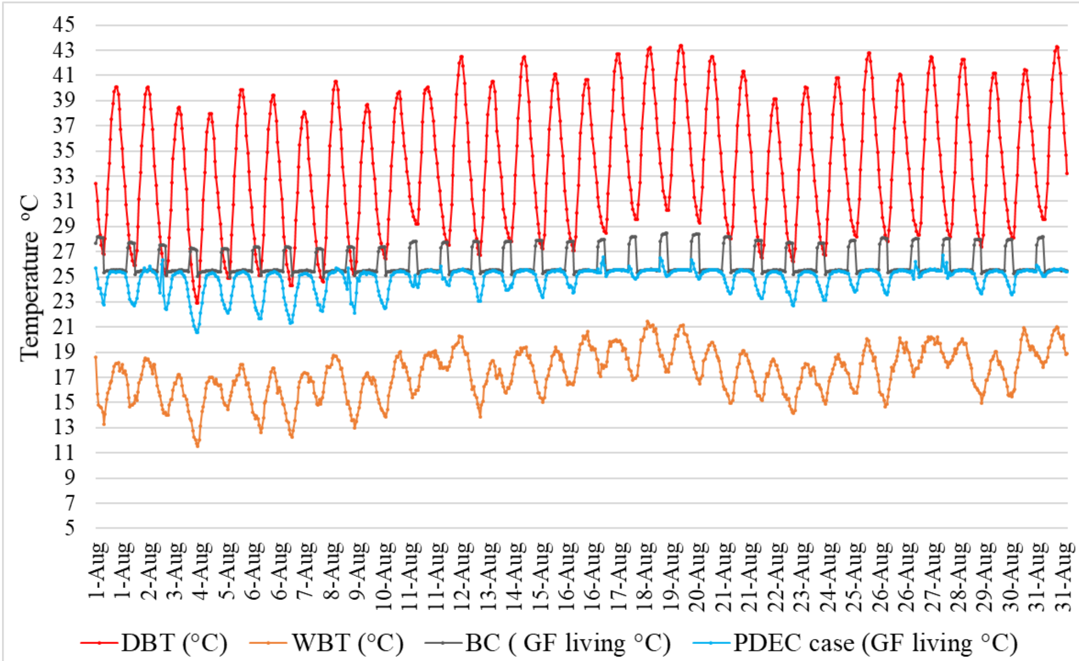


Figure 7-7: External DBT, WBT, and GF living room temperature for the BC and PDEC case during Aug

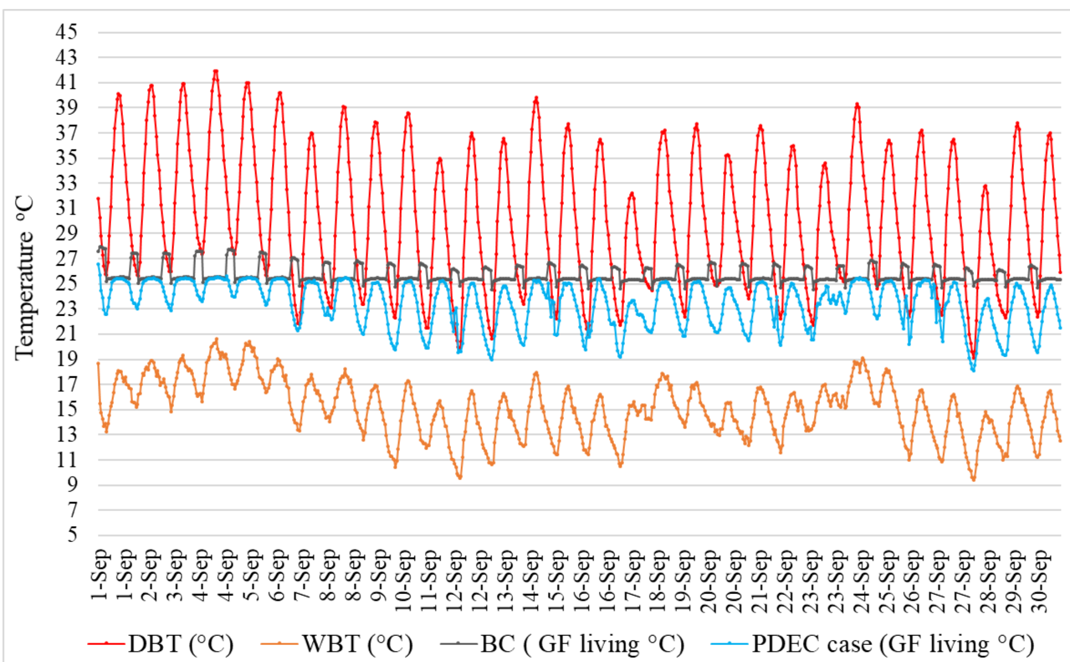


Figure 7-8: External DBT, WBT, and GF living room temperature for the BC and PDEC case during September

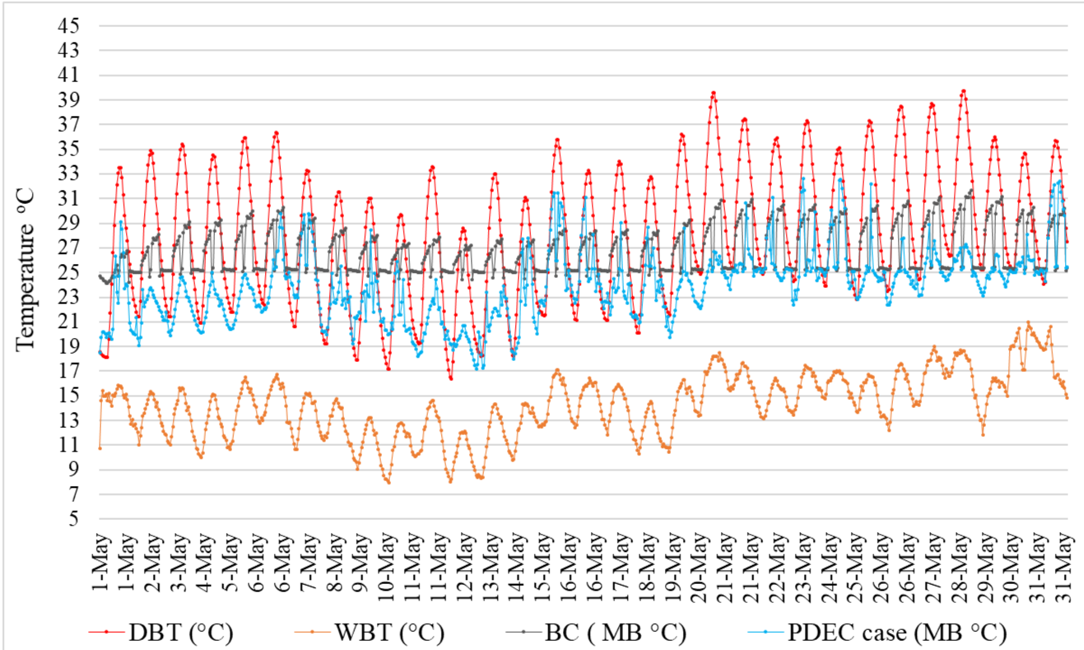


Figure 7-9: External DBT, WBT, and master bedroom temperature for the BC and PDEC case during May

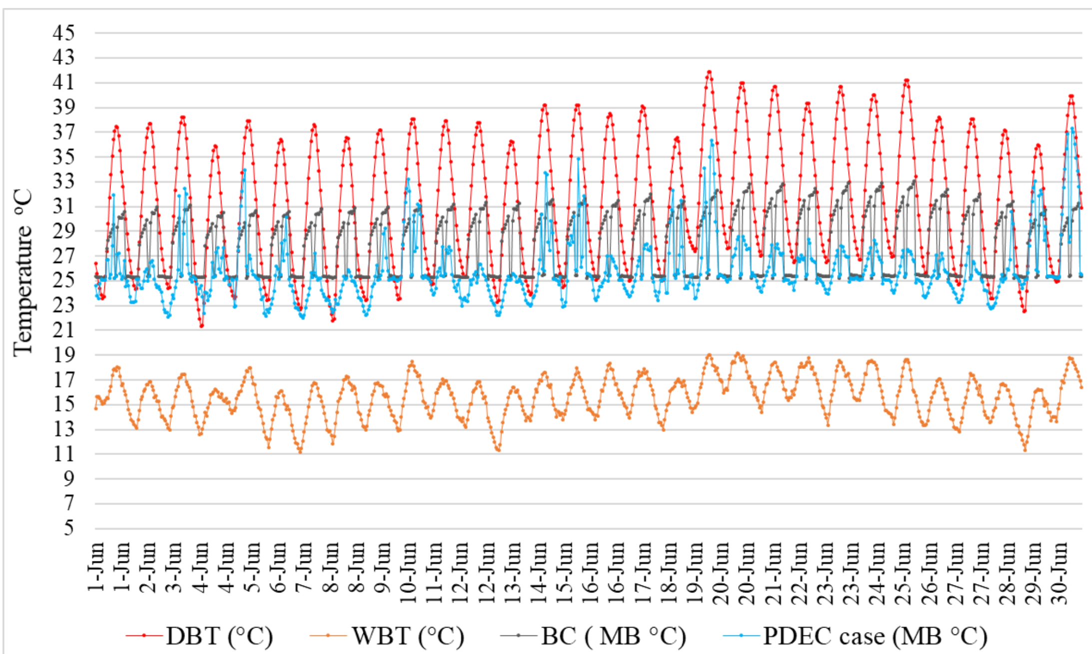


Figure 7-10: External DBT, WBT, and master bedroom temperature for the BC and PDEC case during June

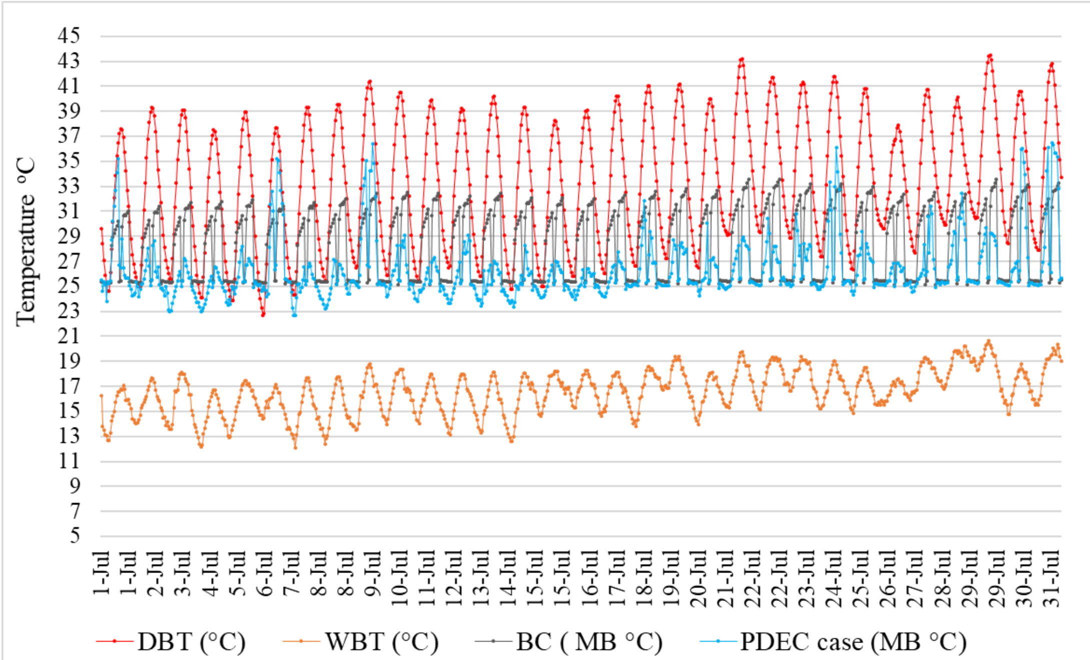


Figure 7-11: External DBT, WBT, and master bedroom temperature for the BC and PDEC case during July

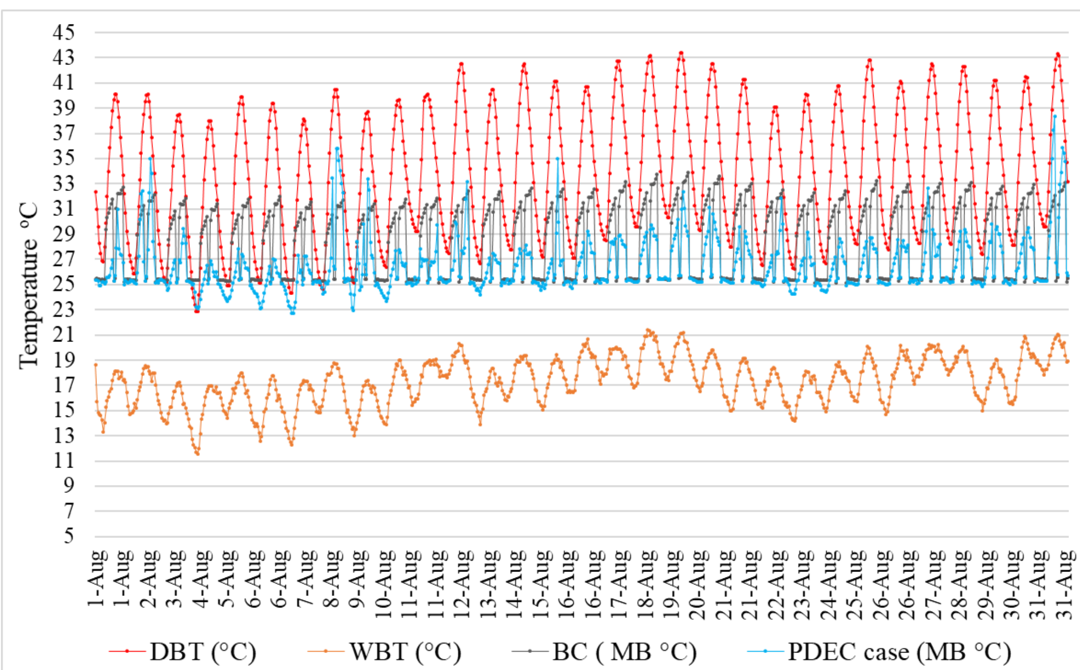


Figure 7-12: External DBT, WBT, and master bedroom temperature for the BC and PDEC case during August

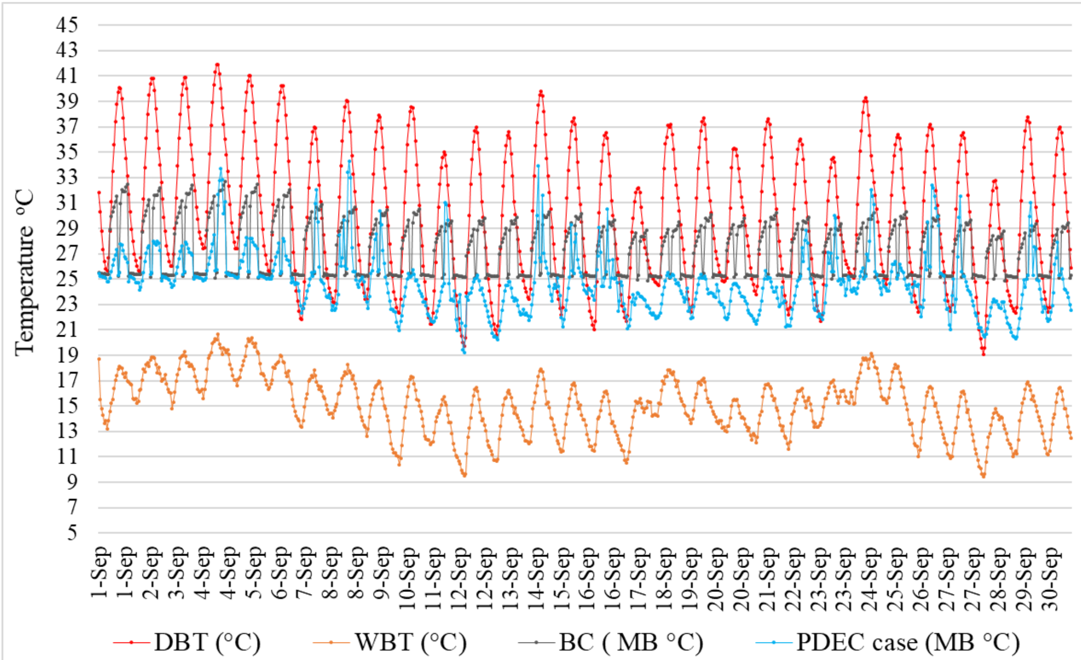


Figure 7-13: External DBT, WBT, and master bedroom temperature for the BC and PDEC case during September

7.3.2 Hottest Period

The end of July, from 21st to 31st, represented the hottest DBT of the summer. As shown in Figure 7-14 to Figure 7-17, the PDEC provided significant amounts of cooling for all the different spaces, even during unoccupied hours when the mechanical cooling was not working. Although all spaces were negatively affected by different weather conditions as shown in the graphs below, the MGR and MB, which are located in the North West side of the house, have shown the lowest level of cooling performance of the cooling tower. As expected, the high indoor temperatures occurred during higher wind speeds from the north and north-west directions, allowing external hot air to enter the spaces. This finding agrees with the results in the previous two chapters. Due to the location of the MGR and MB with openings facing the prevailing wind direction, the PDEC case demonstrated less cooling performance than the BC for several days, with indoor temperatures exceeding 36°C during the same period. During the times of high internal temperatures, the RH decreased rapidly because of the external hot, dry air directly entering through the external openings of the MGR and MB. Further analysis was undertaken by investigating two hot days with different conditions in the following section.

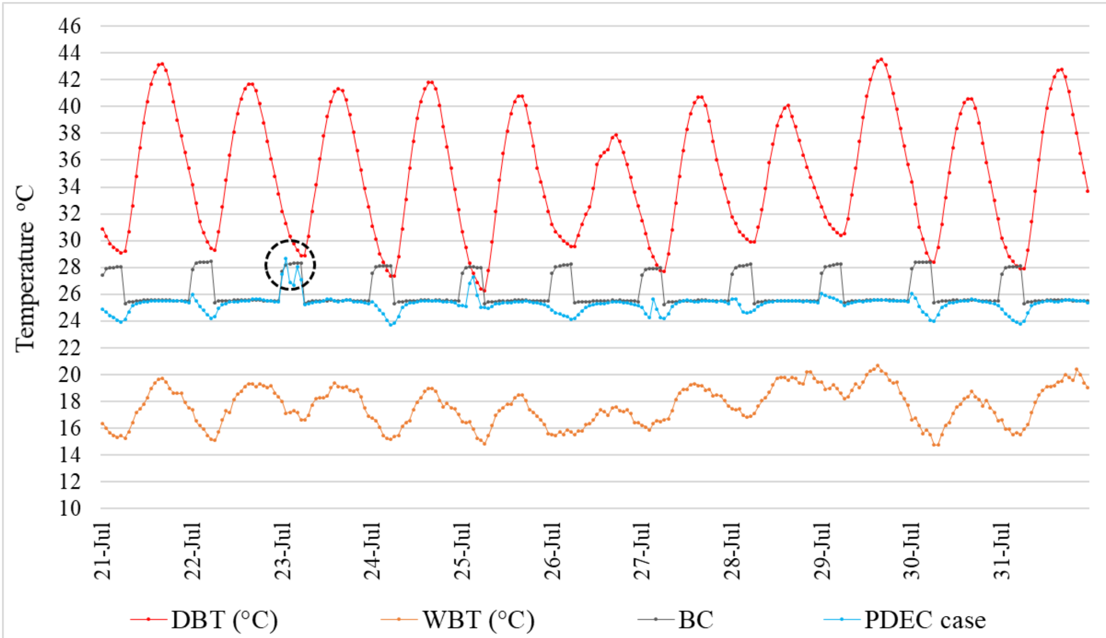


Figure 7-14: External DBT, WBT, and GF living room temperature for the BC and PDEC case during the hottest period (21st – 31st July)

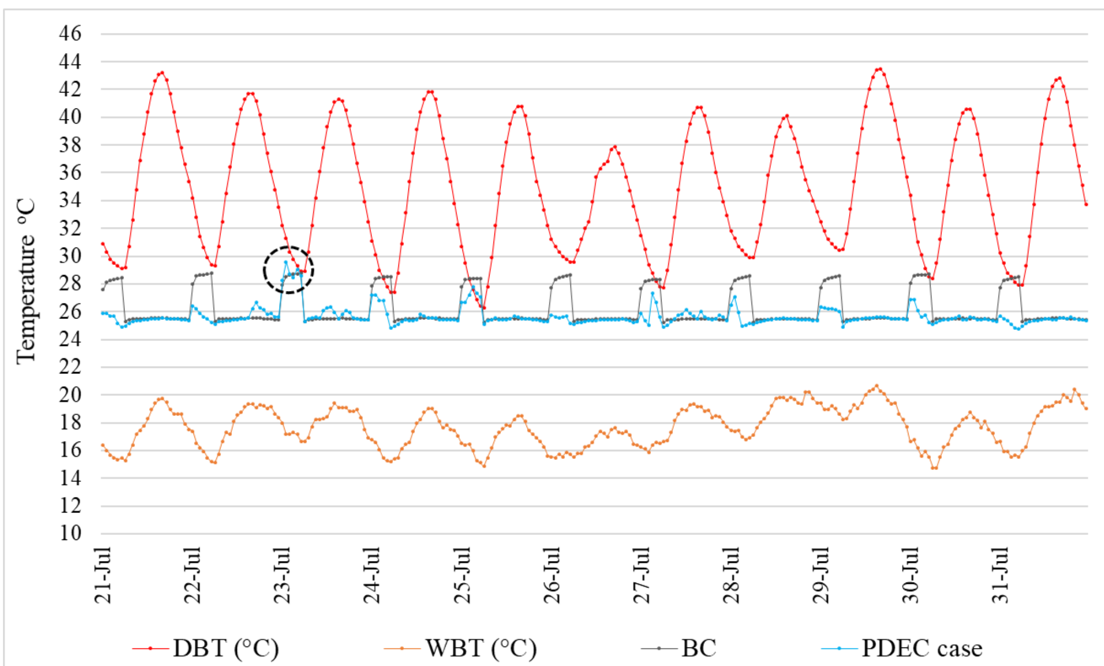


Figure 7-15: External DBT, WBT, and FF living room temperature for the BC and PDEC case during the hottest period (21st – 31st July)

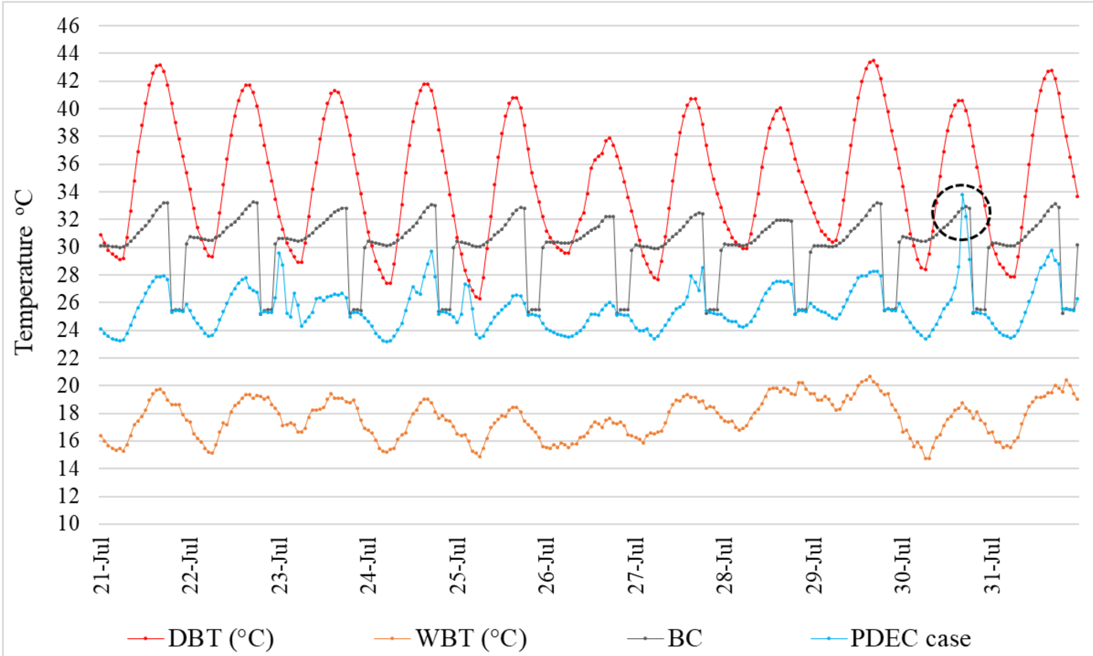


Figure 7-16: External DBT, WBT, and MGR temperatures for the BC and PDEC case during the hottest period (21st – 31st July)

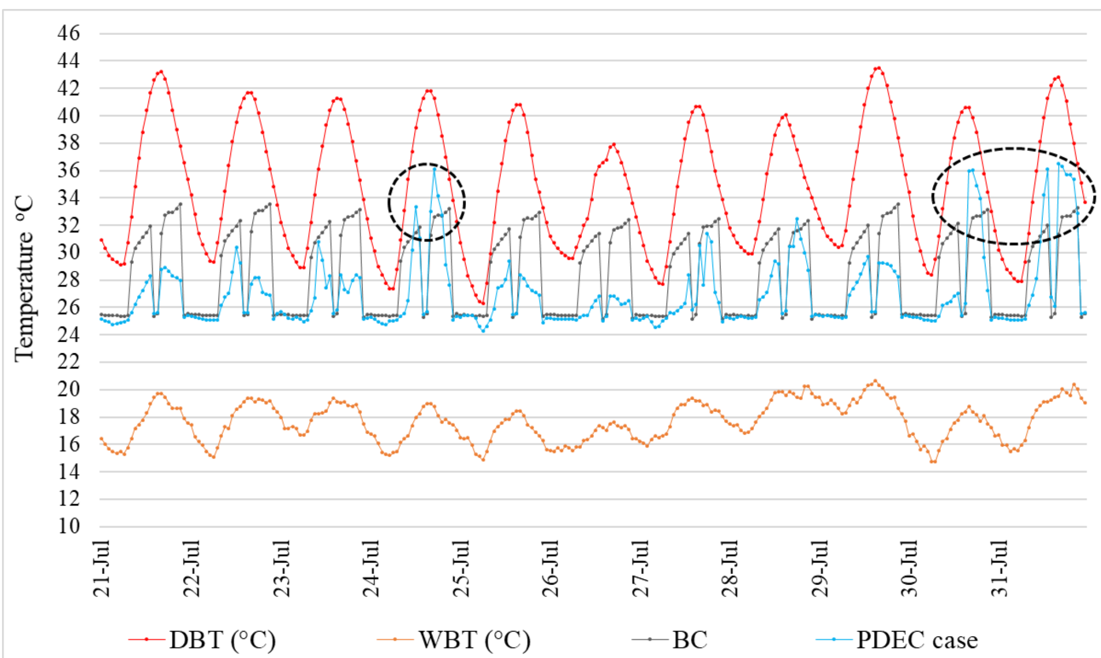


Figure 7-17: External DBT, WBT, and master bedroom temperature for the BC and PDEC case during the hottest period (21st – 31st July)

7.3.3 Calm vs Windy Day

Two hot days with different scenarios were considered. For scenario (i) the hottest day (29th July) in the summer was considered. The external DBT peaked around 43.5°C while the minimum temperature was about 30.5°C, with an average daily temperature of approximately 37°C. The maximum external WBT was roughly 20.5°C, with an average external RH of around 19.5%. The weather was generally calm during this day, with an average wind speed of 2m/s. The wind direction was fluctuating from NW to E throughout the day.

The second scenario (ii) represents another hot summer day as well (31st August). However, the wind conditions were opposite to those of scenario (i). The maximum external DBT and WBT were approximately 43°C and 21°C, respectively. The average daily temperature was around 36°C while the mean daily RH was about 22.5%. The wind speed exceeded 5m/s during most of the day, with a maximum wind speed of 8.5m/s. The wind direction was mostly coming from the NW (towards the MGR and MB) but changed to the east for two hours from 14:00 to 16:00 (towards the Stair zone). Figure 7-18 shows the IES-VE 3D model of the PDEC case with wind roses for the two scenarios.

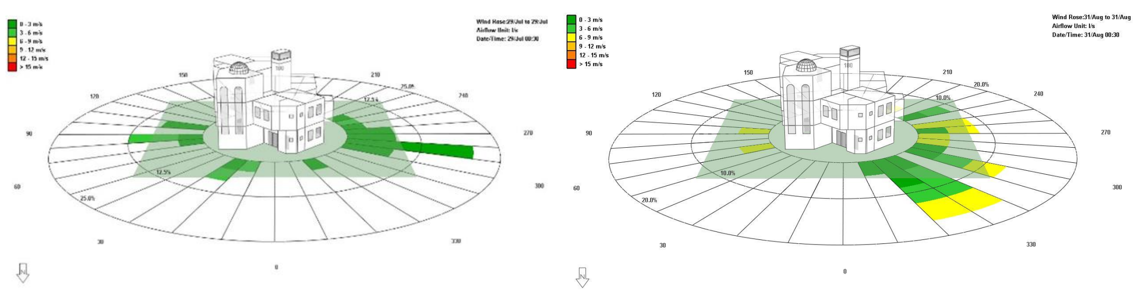


Figure 7-18: 3D model of the PDEC case for the two scenarios: (i) left - (ii) right

Since the MB was the most affected space, it was considered for the analysis in this section. During the 29th of July, the PDEC provided a great amount of cooling with maximum internal temperatures around 29.5°C compared to the BC indoor peak, which was above 33.5°C. Figure 7-19 below shows the external DBT and WBT, and indoor temperature of the MB for the BC and PDEC case during the 29th July. As shown in the graph, the indoor temperatures of the PDEC case were almost 2 to 5°C below the BC indoor temperatures during the unoccupied hours (mechanical cooling not running). The indoor RH increased from nearly 10% to above 50% during peak hours due to the added moisture from the PDEC tower (Figure 7-20).

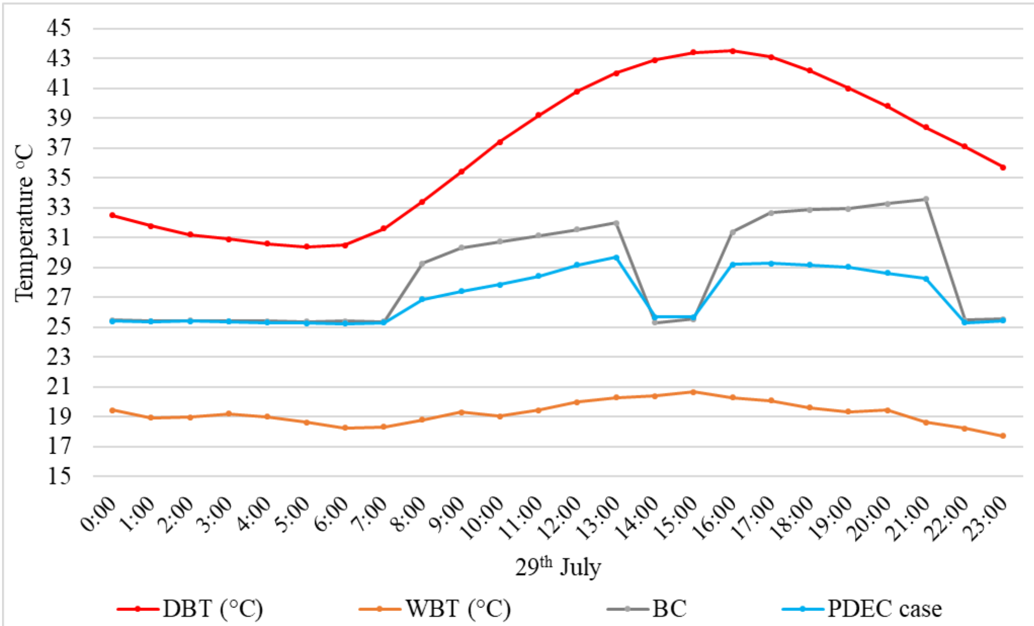


Figure 7-19: External DBT, WBT, and indoor temperatures for the BC and PDEC case during the hottest day (MB)

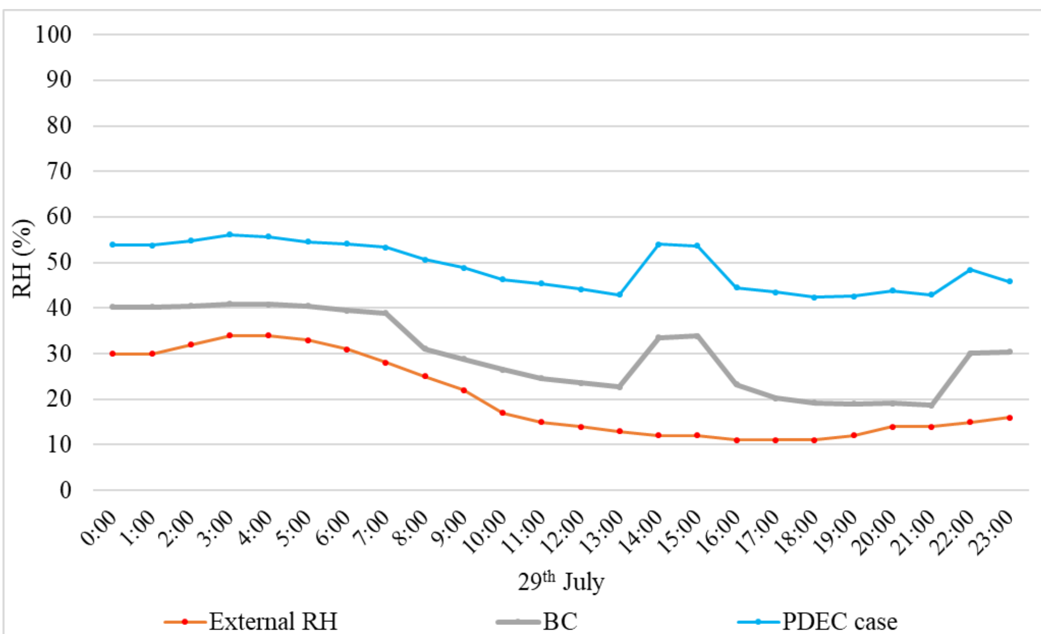


Figure 7-20: External and internal RH for the BC and PDEC case during the hottest day (MB)

Conversely, the PDEC performance was less effective in the second scenario, as shown in Figure 7-21 and Figure 7-22. The results revealed that the PDEC case demonstrated even worse performance than the BC despite running the PDEC tower. Surprisingly, the indoor temperatures of the PDEC case exceeded 38°C while the indoor peak of the BC was approximately 33°C. During the times of the high internal temperatures, the RH plunged to nearly 15% (close to outdoor RH). Between 14:00 and 16:00, the temperatures in both cases dropped down due to the mechanical cooling running in the room during these hours.

Nevertheless, the temperatures of the PDEC case were slightly higher than the set-point temperature (25.5°C) of the mechanical cooling. The poor efficiency of the tower is explicitly linked to the wind effect. The influence of wind was apparent leading to the hot dry air entering the space through the North West openings of the MB during high-speed prevailing winds. The influence of wind speed and direction was also reflected in the energy consumption due to the added hot air to the space. To clarify that, energy consumption analysis was conducted for both cases in the following section.

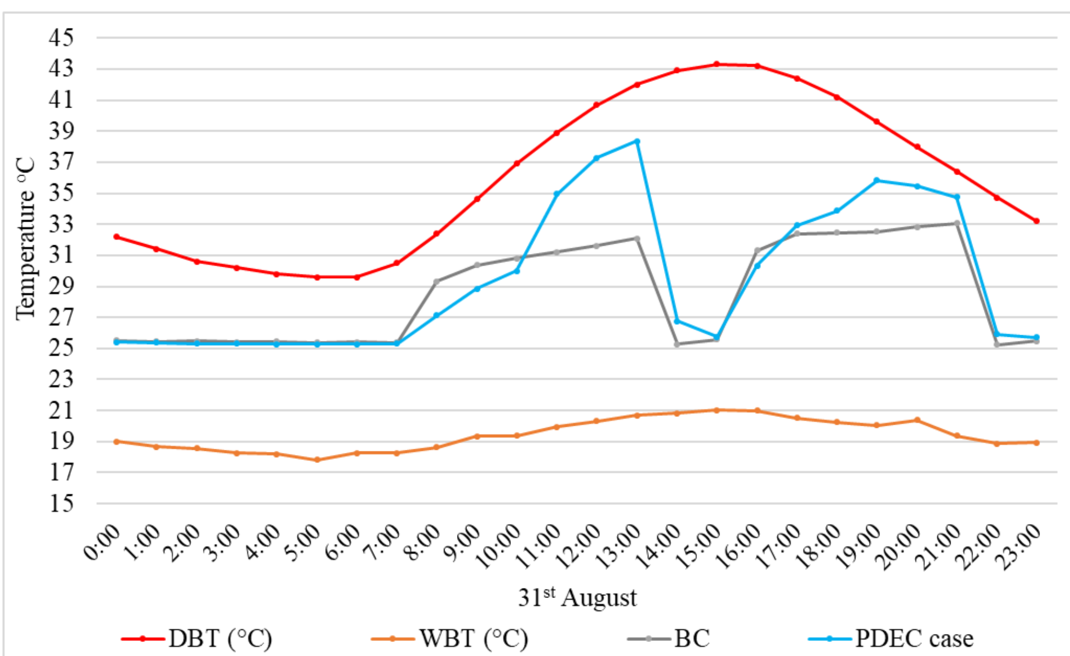


Figure 7-21: External DBT, WBT, and indoor temperatures for the BC and PDEC case during a hot windy day (MB)

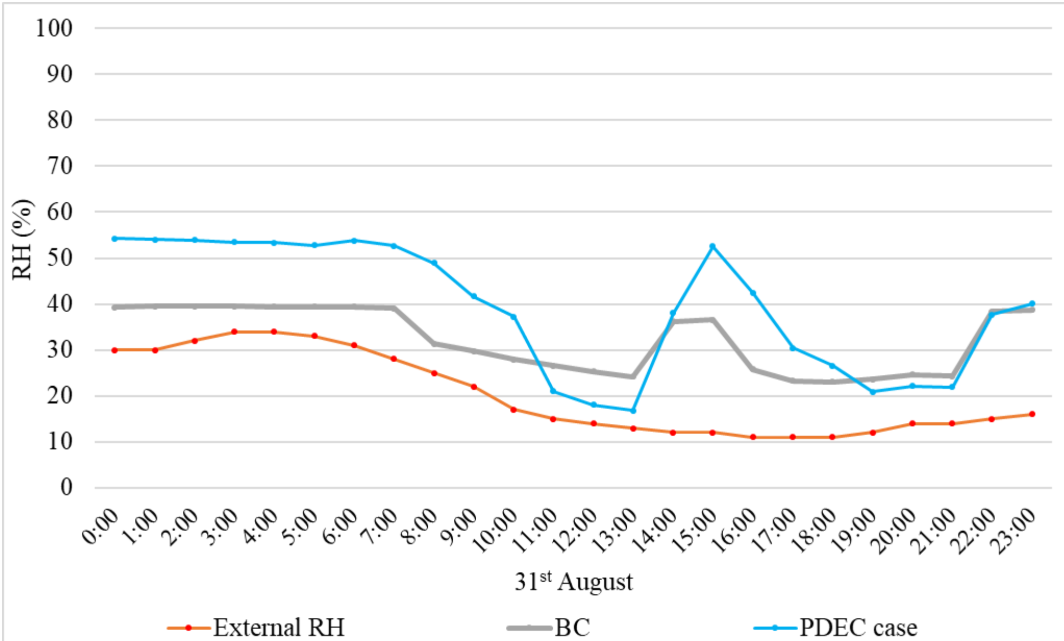


Figure 7-22: External and internal RH for the BC and PDEC case during a hot windy day (MB)

7.3.4 Cooling Energy Consumption

Firstly, daily cooling energy consumption was examined for the two scenarios discussed above. Figure 7-23 and Figure 7-24 show the cooling consumption rate for the 29th July and 31st August for both cases. It should be noted that the cooling energy for the PDEC case encompasses the water pump energy used for the PDEC tower. Although the PDEC had shown a convincing performance on the scenario (i), the total energy used for cooling was not reduced when compared to the BC cooling consumption. The mechanical cooling consumption, only, in the PDEC case, was reduced by around 3.4% on that day. However, the total cooling energy consumption was approximately similar (253kWh) for both cases when adding the water pump energy, which consumed around 8.9kWh, to the mechanical cooling of the PDEC case. The higher energy consumption in the PDEC case occurs during hours when additional mechanical cooling is used in the house. For instance, the air conditioning in the sleeping rooms works between 14:00 and 16:00 in addition to the two open living rooms in the house. As a result, the cooling energy increased due to the higher air change rate in the passively cooled spaces while they are mechanically conditioned during these hours. The circulation of evaporated air within the space increased the mechanical cooling use to reach the required set-point, which could not be reached solely by the PDEC tower during such extreme conditions.

Given the PDEC performance in the second scenario above, the case was even worse. The cooling energy consumption for the PDEC case was more than the BC for most of the day. The mechanical cooling use increased by roughly 3.4% in the PDEC case when compared to the BC. The total cooling energy of the PDEC case (including water pump energy) went up by approximately 7% during the 31st August, leading to a total consumption of around 264kWh compared to 245kWh for the BC. As shown in Figure 7-24, the increased consumption for the PDEC case started after 10:00 when the wind speed exceeded 4.5m/s and reached above 6.5m/s for the rest of the day. The maximum difference between the two cases occurred between 14:00 and 16:00 because of additional mechanical cooling running for the MB, which was required to decrease the space temperature from around 38°C in the PDEC case compared to 32°C in the BC. Besides, the shift of wind direction to the east during these hours increased the FF living room temperature due to the stair zone eastern openings, which increased the load on mechanical cooling to reach the set-point.

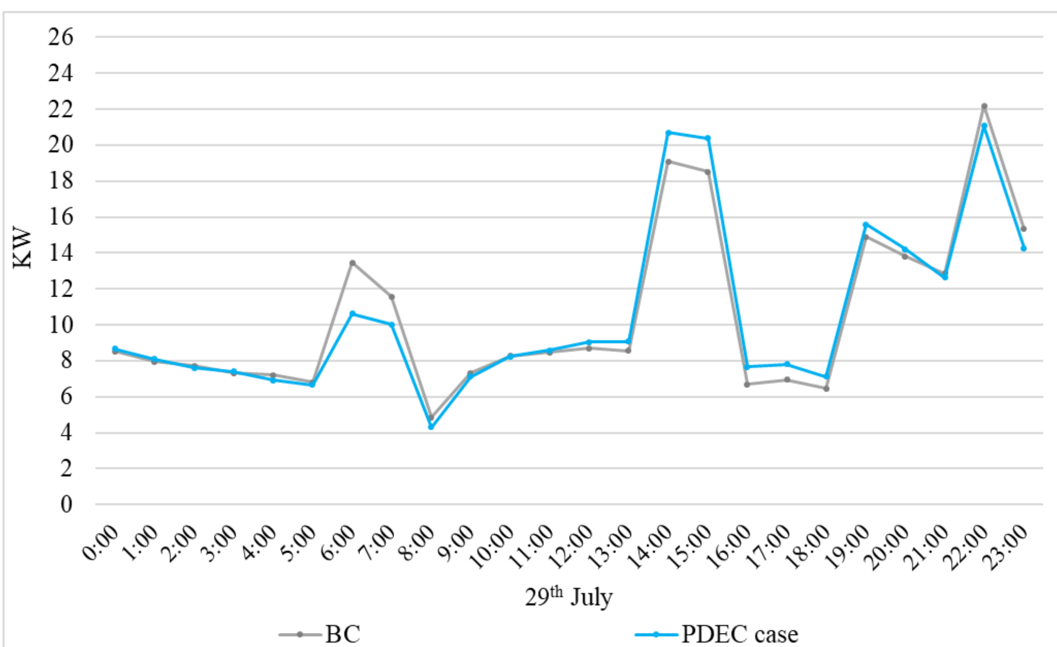


Figure 7-23: Cooling energy consumption rate for the BC and PDEC case during the hottest day

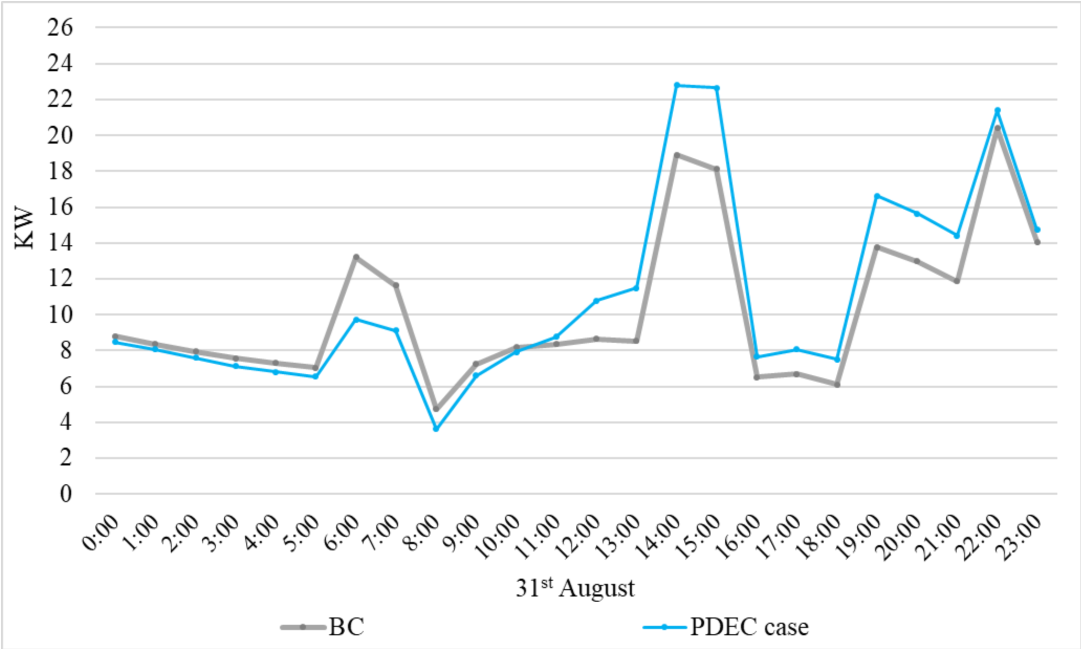


Figure 7-24: Cooling energy consumption rate for the BC and PDEC case during the windy day

Apart from the extreme conditions in the previously discussed scenarios, the PDEC introduced an overall excellent cooling performance, with lower energy consumptions. For the whole summer season, the PDEC case performed better in terms of total energy consumption. The cooling energy consumption during the summer declined by approximately 22.2%, from 28337kWh in the BC to 22032kWh in the PDEC case (Figure 7-25).

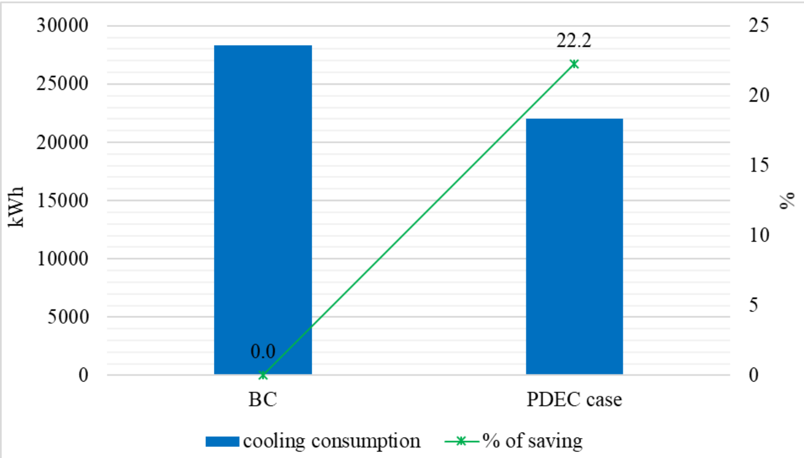


Figure 7-25: Cooling energy consumption for the BC and PDEC case during the summer

7.3.5 Wind Direction Effect and Wind Speed Effect

It was apparent from the initial analysis that certain wind conditions negatively influenced every space cooled by the PDEC tower. To clarify the effect of wind speed and wind direction on all the different rooms, a parametric analysis was undertaken of the relationship between the wind speed/direction on one side and the indoor temperatures of the four spaces on the other side. For the wind speed analysis, the analysis was performed by sorting the wind speeds from low to high and correlating them against the room/space condition. Similarly, the process was repeated for the wind direction effect, but by sorting the wind direction based on degree angle from 0^{o} to 360^{o}, were north is (0^{o}), East (90^{o}), south (180^{o}), West (270^{o}), and 360^{o} return to north (see Figure 7-26 below).

As expected, it was evident that the wind direction and speed had a direct influence on the performance of the PDEC tower for every single space. This finding corresponds with the results discussed in the case study of Dar Al-Rahmaniah Library (see CHAPTER 4). On the right side of Figure 7-26, each graph demonstrates the relationship between wind speed and indoor temperature for every space. Likewise, the wind direction effect on each space is presented on the left side of the figure. The results proved that the wind speed greatly affected the PDEC effectiveness, but in an inverse correlation. As the wind speed increases, the cooling performance of the tower becomes less effective. The indoor temperature ranged from approximately 17°C during near calm conditions to above 37°C, at higher wind speeds.

It should be noted that the MGR and MB were the most affected spaces due to their location towards the prevailing wind direction. This was also further illustrated in the wind direction graphs, where all the spaces were influenced by wind direction. It can be seen that the MGR and MB were negatively impacted by the north-west wind, which is the side of exhaust windows of these two spaces. On the other side of the building, GF and FF living rooms were experiencing relatively higher indoor temperature during North and East wind directions as the wind directly struck the stair zone openings that were opened to exhaust the hot air during the passive cooling process.

Having analysed the wind effect as well as the energy performance under different weather conditions, it could be said that proper design and operation of both the PDEC tower and the integrated building could advance the performance of the PDEC tower. Special consideration for every passively cooled space based on the weather and space conditions could improve the distribution of the PDEC cooled air, stabilise the room/space condition, and ultimately decrease the energy consumption under most weather conditions. Therefore, a parametric analysis involving modification to the opening design and operation of both the building and the PDEC tower was conducted and is discussed in the following section to maximise the cooling capability of the PDEC tower.

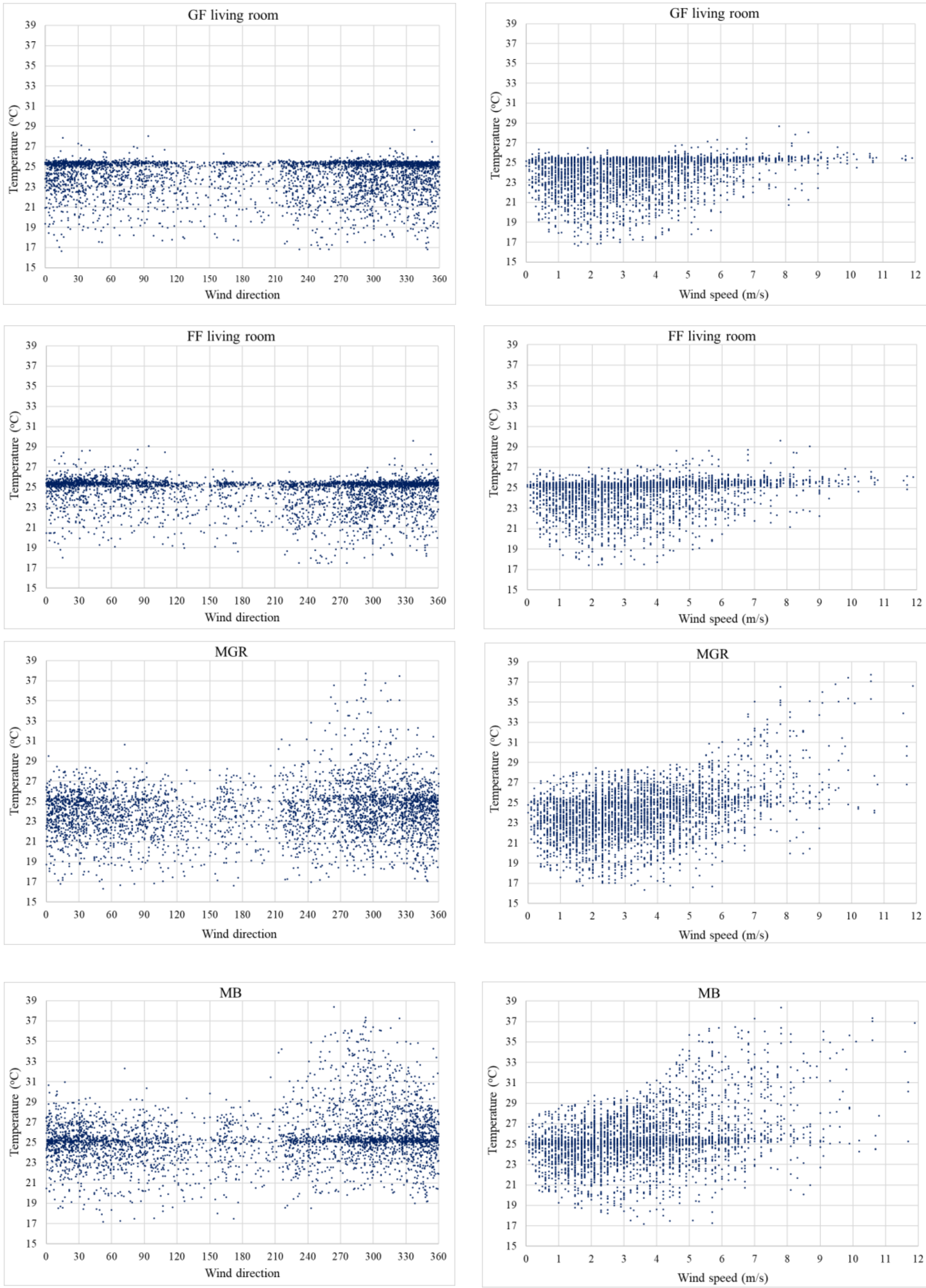


Figure 7-26: Wind direction effect (left) and wind speed effect (Right) on the four spaces during mixed-mode cooling

7.4 PARAMETRIC ANALYSIS

By running the simulation for the PDEC case, it was found that the PDEC tower could provide a significant amount of cooling and reduce the use of the existing conventional cooling system. The overall results were expected, and reflected the previous case study and computational analysis in CHAPTER 4 and CHAPTER 5. However, the building assessed in this chapter, with different characteristics of the passively cooled spaces (size, layout, and locations), makes the cooling performance of the PDEC tower for specific or all spaces less efficient in some cases. The research then continued to attempt to improve the PDEC tower efficiency to minimise the cooling energy consumption and to maintain thermal comfort for the passively cooled spaces. Therefore, a parametric analysis approach was conducted to enhance the cooling performance of the PDEC tower for each coupled space through the architectural elements of the house. The parametric analysis was fulfilled in two stages: (1) the PDEC case parametric analysis, and (2) the developed case parametric analysis. The investigation during each stage is summarized in Figure 7-27 below and explained in the following two subsections.

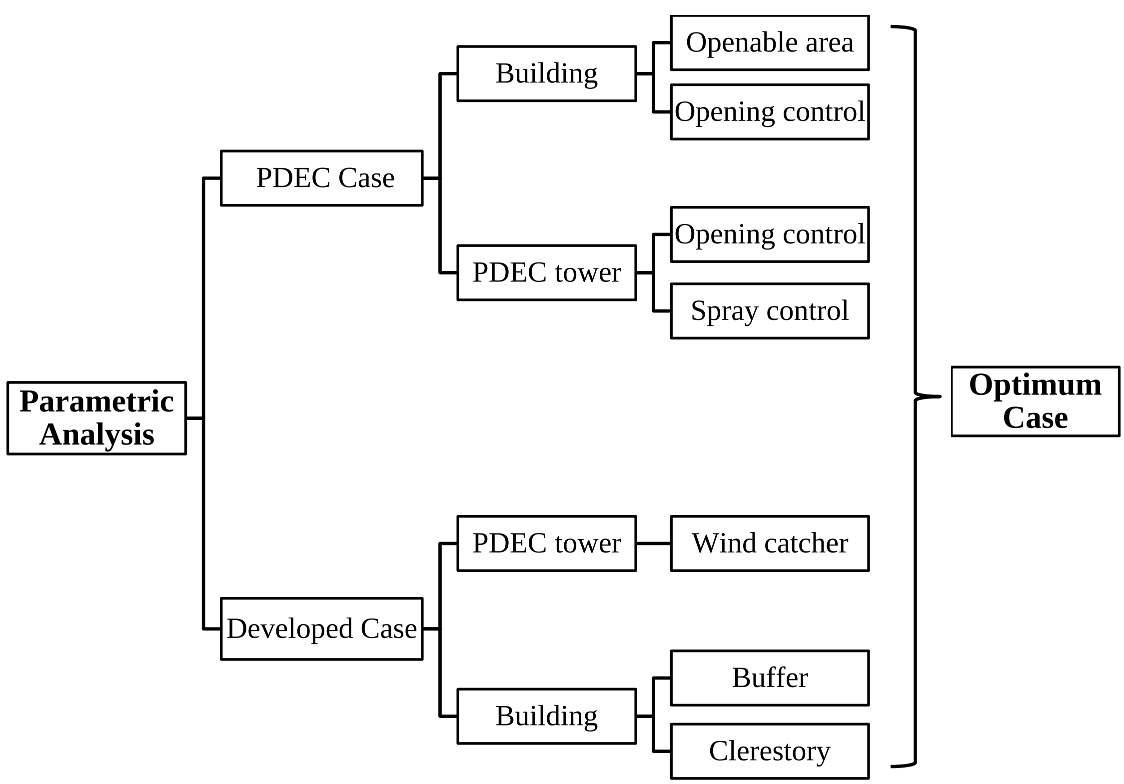


Figure 7-27: Parametric analysis structure and stages

7.4.1 *Stage 1: The PDEC Case Parametric Analysis.*

The PDEC case analysis was performed based on the existing architectural design of the case study villa, and the virtually integrated PDEC tower. The studied parameters during this stage were limited to the current architectural design elements and the PDEC tower, including openable window area, opening operation control, and spray control (on/off). These parameters were assessed based on the occupancy of the room, the effect of the wind (direction and speed) on the passively cooled spaces, and indoor temperature. The simulation process at this stage is summarized in Figure 7-28 below.

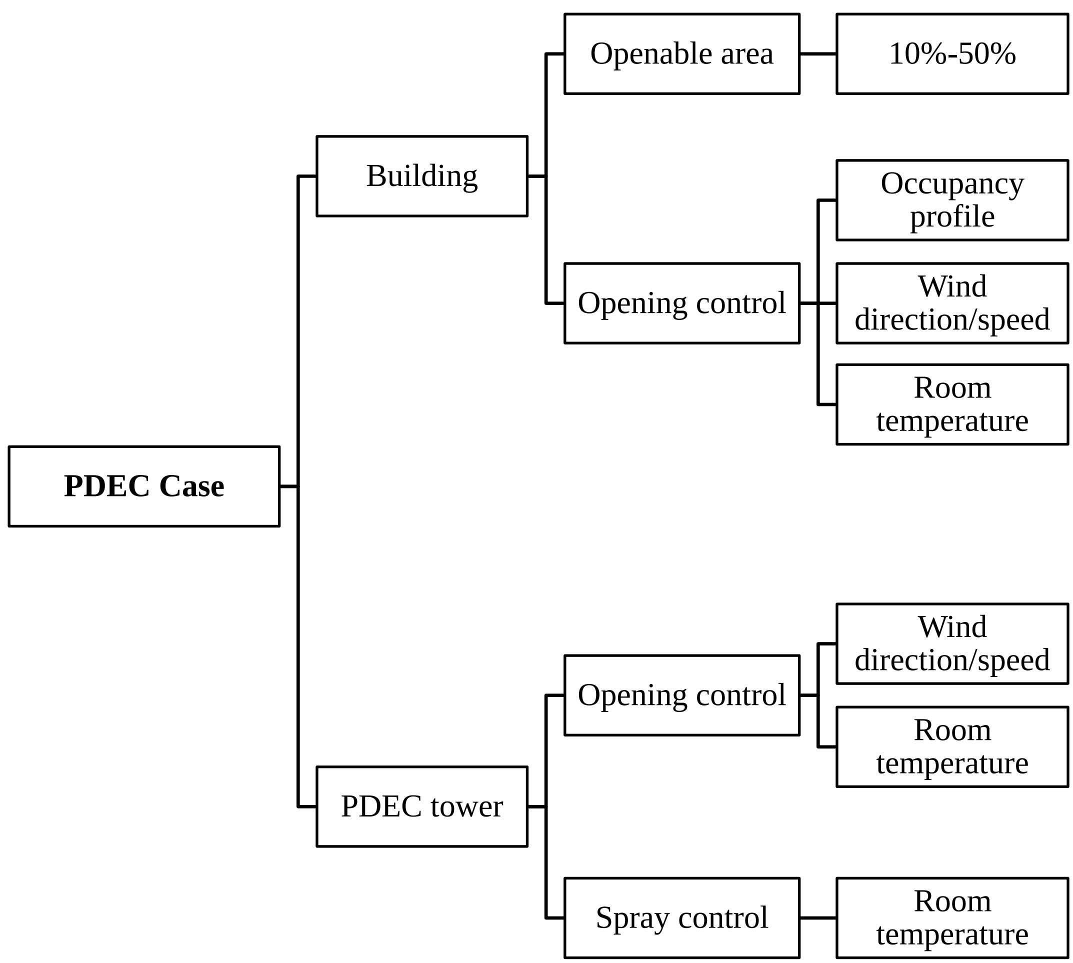


Figure 7-28: Parametric analysis outline of the first stage

At this stage, the influence of window openable area for the passively cooled spaces was assessed. Since the first PDEC case was simulated with 50% openable area for the external windows, four additional simulations were performed by reducing the external windows openable area by 10% for each simulation step and down to 10% openable area. The size of the external openable area was additionally tested for every single cooled space while keeping the other spaces with specific external opening size. The purpose was to find out whether the openable area could improve the air movement and provide a balanced and adequate cooling amount based on the size of each space.

Furthermore, the opening operation control (opened/closed) was assessed for the rooms' windows, tower supply openings, and wind catcher opening. The operation control was examined based on different variables that could affect to cooling performance including occupants' use of the different spaces, wind direction, wind speed, and indoor room temperature. Many simulations were conducted to determine the optimum opening schedule for every room and tower opening in terms of minimising energy consumption and improving thermal comfort.

The window operation control was initially assessed by linking the opening schedule to the occupants' use for every space. Further analysis focused on the effect of wind speed and direction in order to minimise the influence of unwanted wind pressure. At this step, the opening operation schedule reacts based on the wind conditions, to control opening time in accordance with the needed positive or negative wind pressure. For instance, during the north-western wind direction, the windward wind catcher openings open while the leeward (sheltered) wind catcher openings become closed to catch and direct the air through the tower. Furthermore, the external north-western windows in the MGR and MB are set to be closed to stop the positive wind pressure on these opening and prevent the unwanted hot air from entering these spaces. In this scenario, the living rooms and stair zone will be negatively pressurised while the windows in the positively pressurised spaces are closed to enhance the PDEC air movement dependent upon the wind condition. In addition, the wind speed effect was investigated by controlling the opening schedule based on specific wind speed.

Another variable that was taken into account when performing the parametric analysis was the room temperature in order to enhance and maintain thermal comfort. Under specific circumstances, the PDEC tower provided more cooling than what was needed to cool the spaces due to the climatic dependencey of the system. As a result, all the tower openings and space openable windows as well as the PDEC spray system were also controlled based on the indoor room temperature to maintain the required comfort level. Bearing in mind the set-point temperature set for the mechanical cooling system, the PDEC system and all the openable windows were set to be off when the space temperature reached 24.5°C. The PDEC operating set-point was set 1°C below the mechanical cooling set-point (25.5°C) in order to ensure that the mechanical cooling system worked only when the PDEC tower did not meet the required cooling amount during the occupied hours. Besides, the set-point for the tower was considered for thermal comfort reasons, which will be discussed later in section 7.6. At the end of this stage, the intensive analysis provided the optimum PDEC case scenario by balancing the lowest possible energy consumption with the maximum possible thermal comfort level without any modification to the building.

7.4.2 Stage 2: The Developed Case Analysis

In this stage, the optimum PDEC case scenario in stage 1 was considered as the start point for further development. Since the first stage parametric analysis was limited to the current design elements of the case study villa, additional revisions were implemented to the villa model or the PDEC tower to enhance the PDEC tower performance and maintain the thermal comfort level. The studied parameters were investigated based on the findings and recommendations in CHAPTER 4 and 5 in order to neutralise the negative effect of the wind, which is found to be the main contributor to the performance fluctuations of the PDEC tower. The further developments and modifications to the house model involved the addition of a X-shaped wind catcher layout, a buffer zone to the external windows, and roof clerestory openings (Figure 7-29).

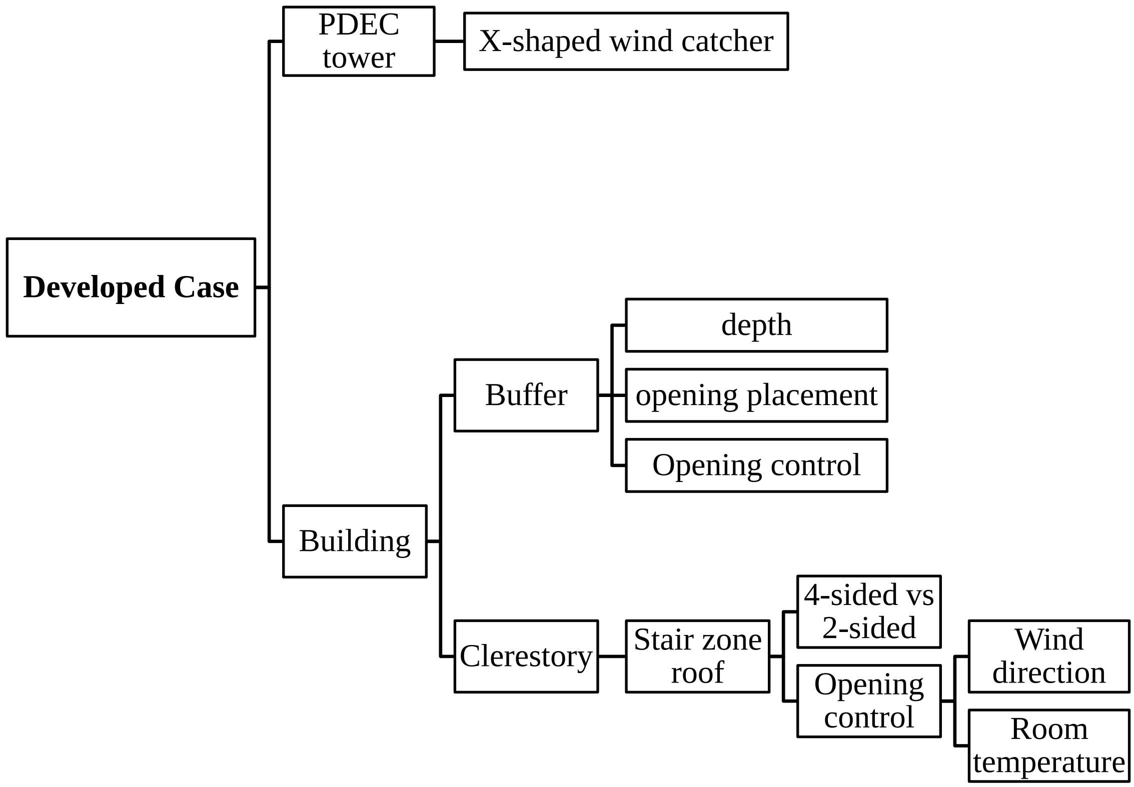


Figure 7-29: Parametric analysis outline of the second stage

The X-shaped layout of the windcatcher was the only modification considered in the PDEC tower. It was taken into account based on the analysis in stage 1 and the windcatcher design of the Dar Al-Rahmaniah library. The purpose was to improve the airflow within the tower by conveying the incoming air from each direction directly to the spray zone. The suggested wind catcher configuration was investigated as an alternative to controlling the windcatcher openings.

The second parameter investigated in this stage was the buffer zone. In each exhaust window in the passively cooled spaces, a buffer shape design was implemented to minimise the undesirable positive wind pressure effect. The addition of the buffer configuration aimed to negatively pressurise the windows to improve the airflow patterns coming through the PDEC tower towards the passively cooled spaces and ultimately leaving through the windows. The buffer zone was designed bearing in mind three different aspects including the depth, opening placement, and opening control.

The last parameter assessed in this stage was the integration of roof openings for the stair zone, and a high buffer zone with top leeward openings for the MGR and MB. The roof openings were designed to act as a solar chimney, taking advantage of the height of the three levels stair zone underneath it. The incorporated roof openings would exhaust the hot air in the GF and FF living room through the stair zone, which would then be replaced by the cool evaporated air from the PDEC tower. The roof openings were designed by raising part of the stair zone roof by 1m above the top roof level (instead of the existing dome). The sides (walls) of the raised part were then used to place louver openings. The effect of the openings was investigated in terms of the number and location of openings, and the opening control. In the beginning, it was essential to find out the appropriate design, size and placement of the openings. Hence, the analysis included two different configurations: 4-sided and 2-sided clerestory openings. Then, the best configuration was considered to assess the opening control. The wind effect and indoor temperature were the two parameters taken into account when operating the roof openings. For the MGR and MB, the buffer zone was raised to a certain level above the roof. Then, leeward louver openings were placed at the top of the buffer zone to exhaust the air. During the development process, the existing north western windows of the MGR and MB were replaced with one high horizontal opening for each room to enhance air circulation within the space. The horizontal openings operation were tested based on the occupancy use of each room and/or the room temperature to find out the best operating schedule. The top leeward openings were operated and tested dependant on the wind condition.

Ultimately, five scenarios (cases) were selected for the analysis and discussion of the development process based on the improvement achieved for each case as some of the tested variables did not provide further improvement. Additional explanation of the selected cases is discussed in the following section.

7.4.3 Simulation Scenarios

During the parametric analysis, the best-case scenario for each studied parameter was considered for further investigation for each space. The continuous development and assessment, and the consideration and integration of different settings led to an optimum case where the highest PDEC performance, minimum energy consumption, and acceptable comfort levels were achieved (Figure 7-30). As shown in the figure below, each passively conditioned space within the house was finally developed with specific opening configurations and operation schedules based on different factors affecting each spaces. As mentioned previously, the factors onsidered in the design and operation of each passively cooled space involved weather parameters, occupancy use, and thermal comfort.

Due to the high number of simulations and amount of data analysed, it was not possible to discuss all the findings, especially for the analyses where no noticeable improvements were observed. As a result, the best-case scenario for each studied parameter, where noticeable improvement was observed, will be discussed. The description and details of each discussed case are explained in Table 7-3, Table 7-4, and Table 7-5 below. The PDEC case, PDECctl, and PDECctl2 represent the analysis and development cases during stage 1. This means that the improvement achieved in these cases was based on the existing window design of the villa with no further additions or modifications. PDECctl2 case was the best case discovered during this stage where maximum comfort was achieved with lower energy consumption. Then, the PDECctl2 case was used as a start point for the further enhancement performed in stage 2, which is represented by cases PDECbuf, and ultimately PDECopt. In the PDECbuf case, the existing external windows of each passively cooled space were protected by a buffer zone with an opening in the top. In the PDECopt, 4-sided roof openings were considered instead of the stair zone windows to exhaust the air in the living rooms. In the MGR and MB, the design of a double-skin type buffer zone with top leeward openings was considered in addition to the replacement of the existing north western windows with a high horizontal opening for each space. The results and analysis of these simulations will be discussed in detail in the results section.

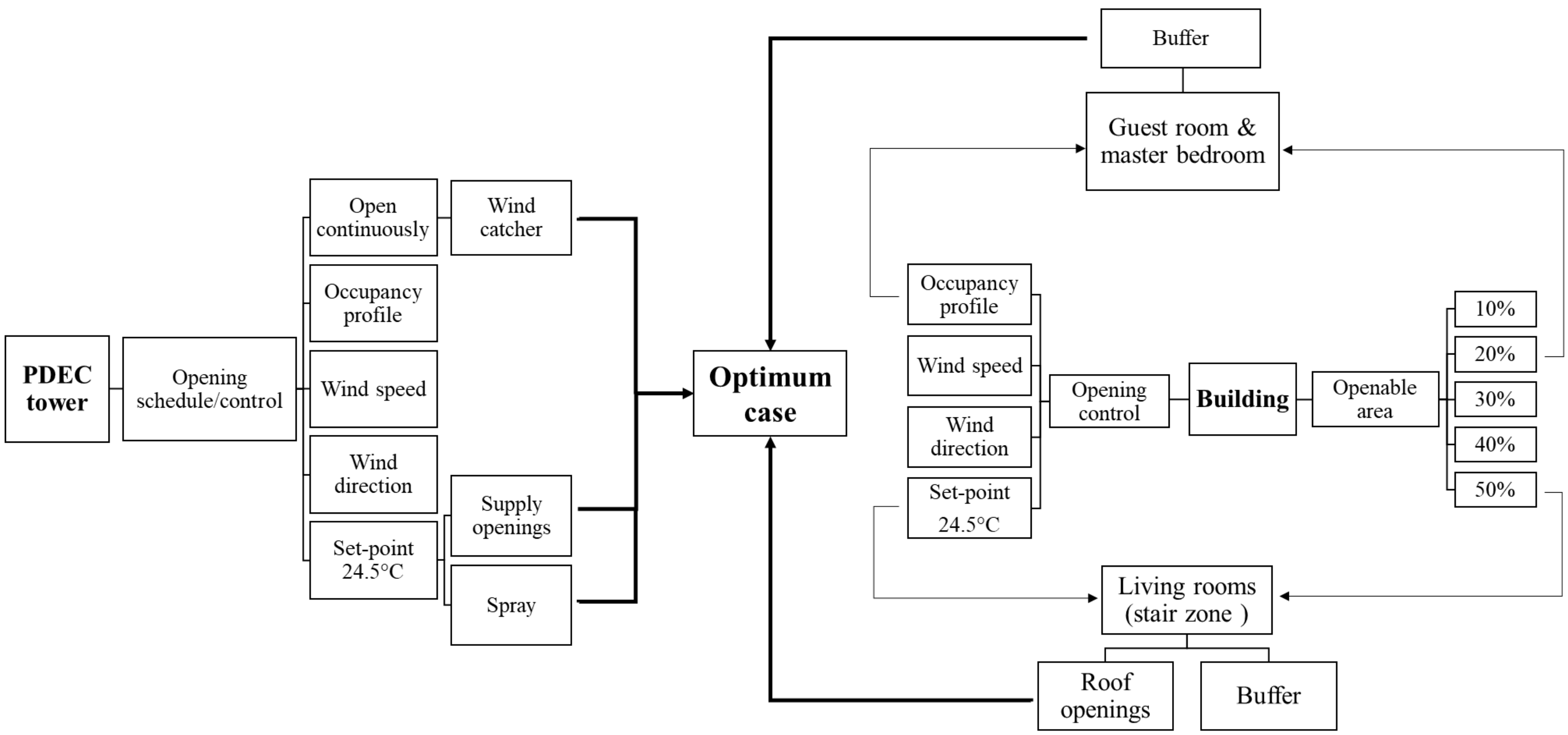


Figure 7-30: Simulation process to achieve the optimum case

Table 7-3: Description and details of the simulation scenarios (Stage: 1)

Simulation name	Abbreviation	Spray	Wind-catcher openings	PDEC supply openings			External windows		
				Living	MGR	MB	Stair zone	MGR	MB
Base case	**BC**	-	-	-	-	-	0%	0%	0%
Base case + Integrated PDEC tower	**PDEC case**	ON (24/7)	Open (24/7)	Open (24/7)	Open (24/7)	Open (24/7)	50% of window open continuously	50% of window open continuously	50% of window open continuously
PDEC case + Window opening control	**PDECctl**	ON (24/7)	Open (24/7)	Open (24/7)	Open (24/7)	Open (24/7)	50% of window open continuously	20% of window open & linked to occupancy profile	20% of window open & linked to occupancy profile
PDECctl + Wind catcher control	**PDECctl2**	ON when rooms temp. exceeds 24.5	Linked to wind direction	Open when room temp. exceeds 24.5	Open when room temp. exceeds 24.5	Open when room temp. exceeds 24.5	50% of window open when indoor temp. exceeds 24.5	20% of window open & linked to occupancy profile	20% of window open & linked to occupancy profile

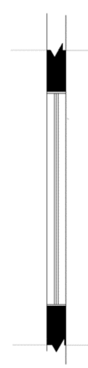
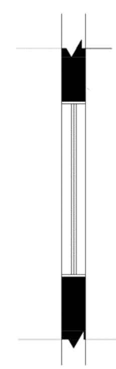
	Stair zone opening	MGR/MB opening
Configuration		

Table 7-4: Description and details of the simulation scenario of the buffer parameter (Stage: 2)

Simulation name	**Abbreviation**	**Spray**	**Windcatcher openings**	**PDEC supply openings**			**External windows**		
				Living	**MGR**	**MB**	**Stair zone**	**MGR**	**MB**
PDECctl2 + buffer zone added to ext. windows	**PDEC$_{BUF}$**	ON when rooms temp. exceeds 24.5	Linked to wind direction	Open when room temp. exceeds 24.5	Open when room temp. exceeds 24.5	Open when room temp. exceeds 24.5	Buffer zone added (50% of Window open when indoor temp. exceeds 24.5)	Buffer zone (20% of window open & linked to occupancy profile)	Buffer zone (20% of window open & linked to occupancy profile)

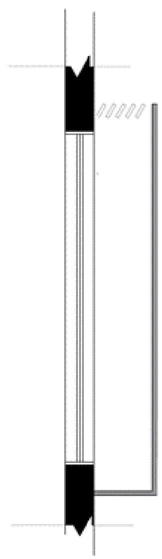
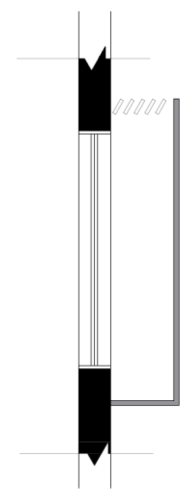
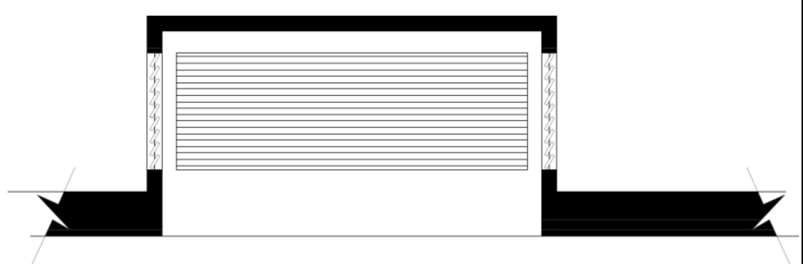
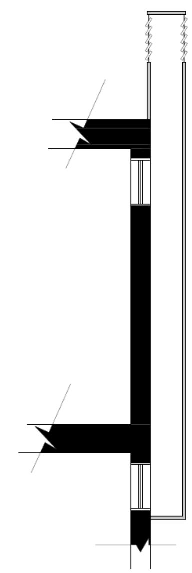
	Stair zone opening	**MGR/MB opening**
Configuration		

Table 7-5: Description and details of the simulation scenario of the optimum case (Stage:2)

Simulation name	Abbreviation	Spray	Windcatcher openings	PDEC supply openings			External windows		
				Living	MGR	MB	Stair zone	MGR	MB
PDEC Optimum case	**$PDEC_{OPT}$**	ON when indoor temperature exceeds 24.5	Open continuously	Open when room temp. exceeds 24.5	Open when room temp. exceeds 24.5	Open when room temp. exceeds 24.5	4-sided roof openings open when indoor temp. exceeds 24.5	high horizontal opening + Buffer zone with top leeward openings	high horizontal opening + Buffer zone with top leeward openings

	Stair zone opening	MGR/MB opening
Configuration		

7.5 RESULTS AND DISCUSSION OF THE PARAMETRIC STUDY

The outcomes of the development of the PDEC case throughout the parametric analysis process showed a continuous improvement of the PDEC tower performance until finally reaching an optimum case. In the five cases described above, there was a noticeable enhancement in either energy consumption or thermal comfort. The process of achieving an optimum integrated design involved the consideration of two key factors: (1) the effect of different weather conditions on every single space, and (2) the impact of each space on the others as they were being cooled by one passive system. It was evident from the previous analysis that spaces in the same location within the house were negatively influenced by specific wind direction during high wind speed, such as the MGR and MB during prevailing NW winds. Moreover, the small spaces, such as the MB, were negatively affecting the cooling performance needed in the larger living spaces during the day hours and undesired weather conditions. As a result, the development process involved the consideration of the two factors mentioned above in order to supply PDEC air adequately.

Generally, it can be said that the openable area and the control based on wind direction were the most two effective parameters in terms of the PDEC performance. Because of that, the spray and opening control based on occupancy use or room set point was initially neglected to assure the inclusion of all different weather conditions. So, the variables considered at first for the analysis and discussion of each case are as follows:

- PDECctl: openable area only.
- PDECctl2: openable area + windcatcher opening control (wind direction).
- PDECbuf: openable area + windcatcher opening control (wind direction) + buffer shape design.
- PDECopt: roof opening (open continuously) + horizontal opening (open continuously + high buffer zone with top leeward openings (wind control).

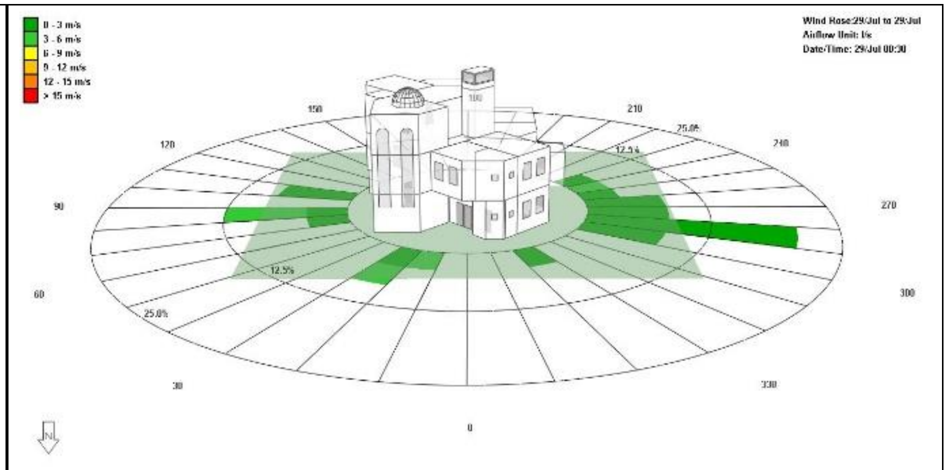
In this case, the PDEC tower will run continuously in all the cases to identify the level of improvement under extreme and different weather conditions. To start with, the results and analysis of the two extreme days (scenarios) discussed previously was repeated for the developed cases and compared with the initial PDEC case as well as the BC. Previously, only the MB was discussed as it was the most affected space among the four spaces. Currently, all the four spaces were considered in the discussion as the parameters and variable considered were different from space to another.

7.5.1 Hottest Day (Scenario (i))

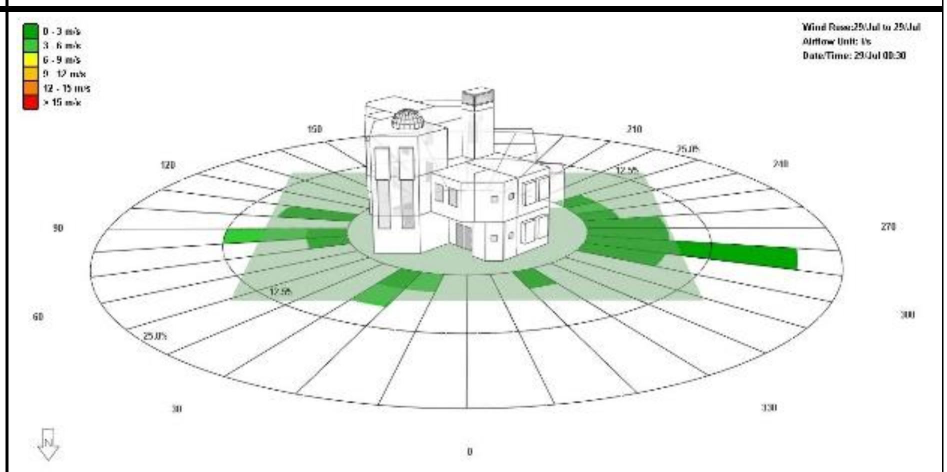
Although the wind conditions in this scenario (29th July) were near calm (Figure 7-31), the extremely hot DBT limited the ability of the PDEC tower to provide adequate cooling for the four spaces. This was reflected in the overall energy performance during that day, where the energy saved in the mechanical cooling was substituted by the energy needed for the water pump energy. However, the continuous development of the PDEC tower and the coupled house as one integrated design has shown considerable improvement. The development process, beginning from finding the suitable openable area for each space to the addition of wind barriers, has shown slight improvements in the affected spaces without affecting the others (see Figure 7-32, Figure 7-33, Figure 7-34, and Figure 7-35). In the living spaces, the indoor temperature did not present a noticeable improvement due to the central location of these spaces in addition to the high stair zone openings that were enhancing the air circulation in these two large spaces. However, there was a gradual improvement from the PDEC case to the PDECopt in the MB, which was most affected space. The window opening area in the MGR and MB were smaller than the opening area in the stair zone, which led to more cooling being supplied to the larger spaces.

Additionally, decreasing the external windows openable area in the MB had improved the air circulation in this smaller space by minimising excessive air movement, which increased the use of the mechanical cooling to reach the set point. The control of the windcatcher in PDECctl2 provided a further improvement to the PDEC performance by opening the windward openings, which enhanced the air circulation within the building. In stage 2 of the parametric analysis, the PDEC efficiency has further advanced due to the modification and improvement in the opening design. The addition of the buffer shaped design in PDECbuf, and then the development of 4-sided roof openings and a double-skin type buffer zone with top leeward openings in PDECopt, improved the cooling performance of the PDEC tower under such conditions. In the PDECopt case, the maximum internal temperature among all the different spaces was around 28°C compared to PDEC case indoor peak above 29.5°C, and 33.5 in BC.

PDEC case – PDECctl – PDECctl2



PDECbuf



PDECopt

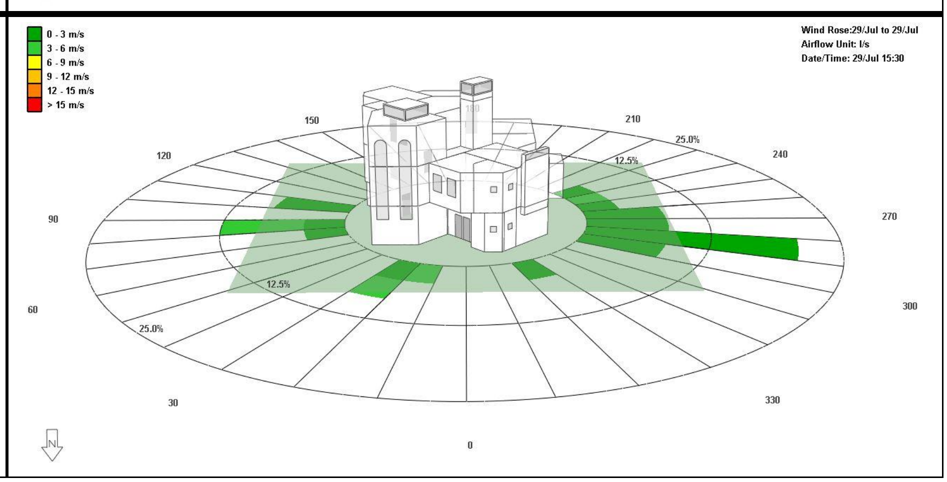


Figure 7-31: Wind speed and Wind direction rose on the 29th July

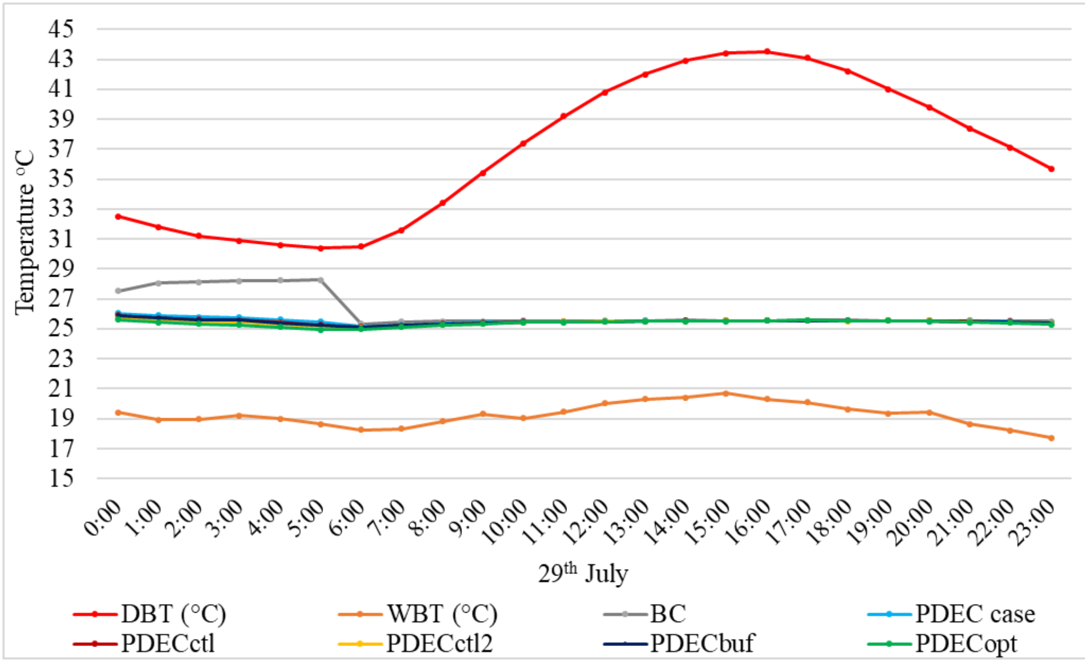


Figure 7-32: External DBT, WBT, and indoor temperatures for different case during the hottest day (GF living room)

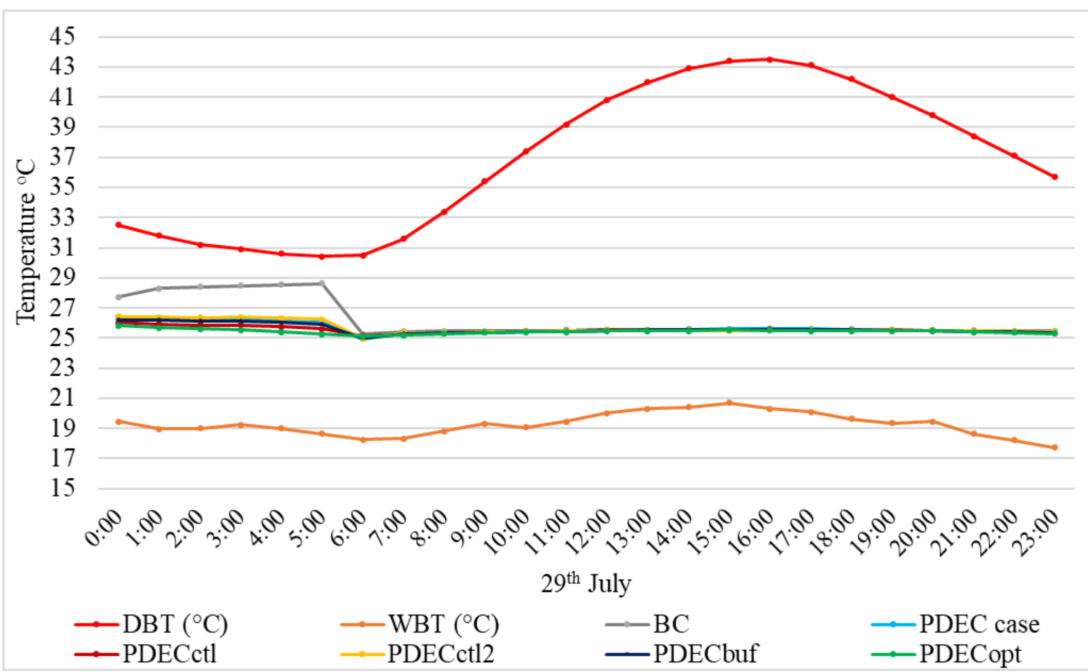


Figure 7-33: External DBT, WBT, and indoor temperatures for different case during the hottest day (FF living room)

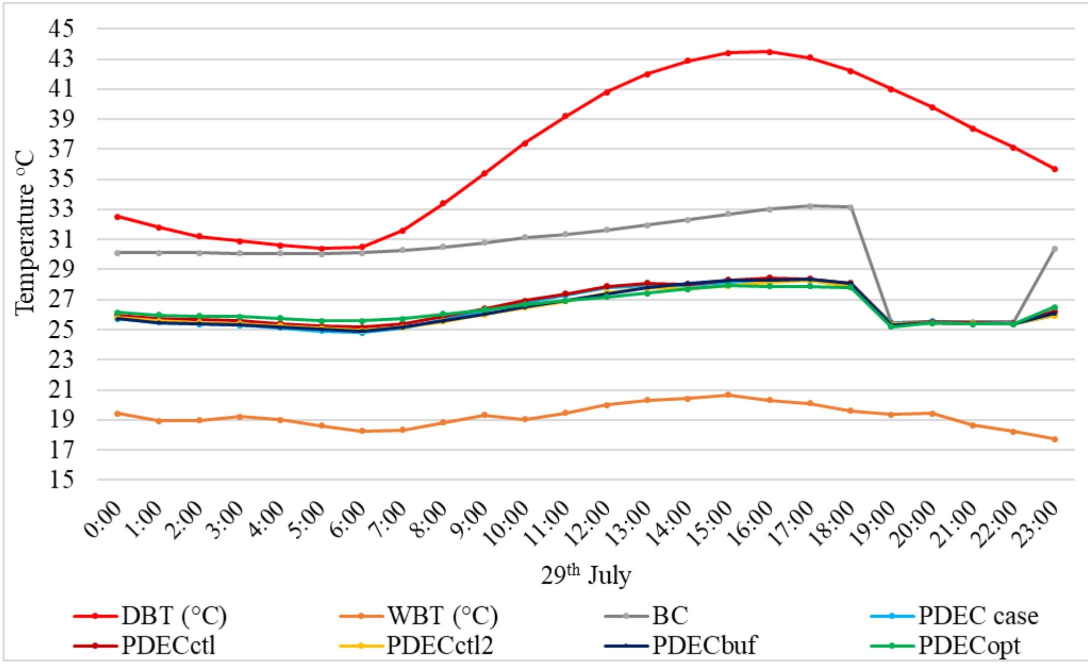


Figure 7-34: External DBT, WBT, and indoor temperatures for different case during the hottest day (guest room)

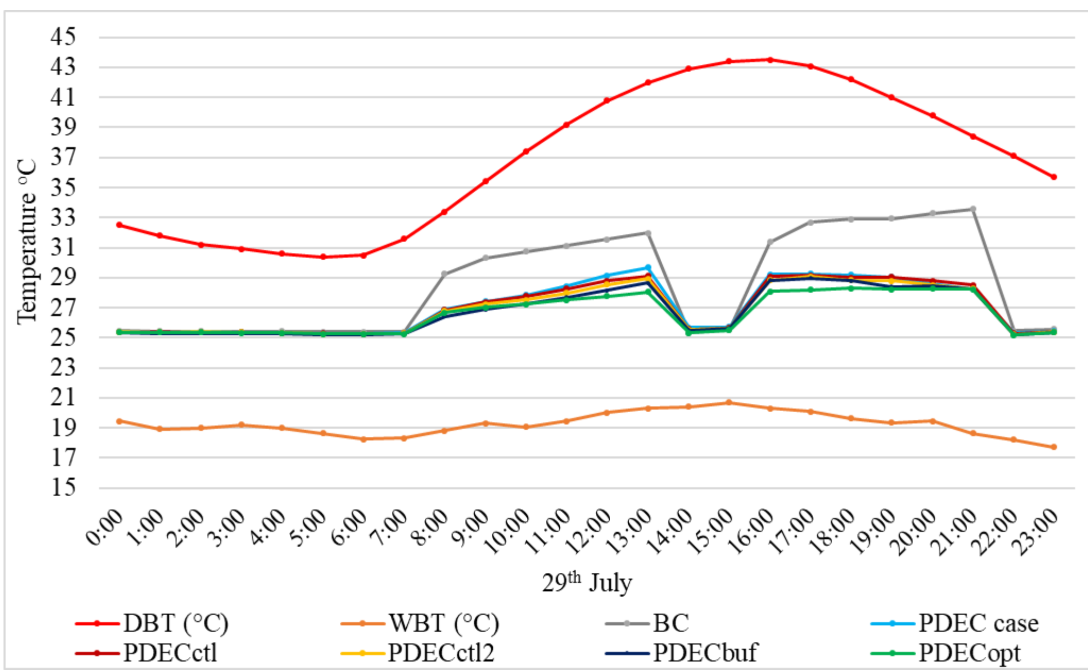


Figure 7-35: External DBT, WBT, and indoor temperatures for different case during the hottest day (MB)

The improvement carried out throughout the parametric analysis has also reflected on the energy consumption during this extremely hot day, as seen in Figure 7-36. The total cooling energy was approximately reduced by 3% in PDECctl, 4% in PDECctl2, 5.2% in PDECbuf, and 9% in the PDECopt case. This saving included the energy use of the water pump while the mechanical cooling energy reduction, only, ranged between 6.5% in the PDECctl to 12.3% in the PDECopt. The total cooling energy consumption of the PDECctl, PDECctl2, PDECbuf, and PDECopt were around 246kWh, 243kWh, 240kWh, and 231kWh respectively, compared to nearly 253kWh for the BC and PDEC case.

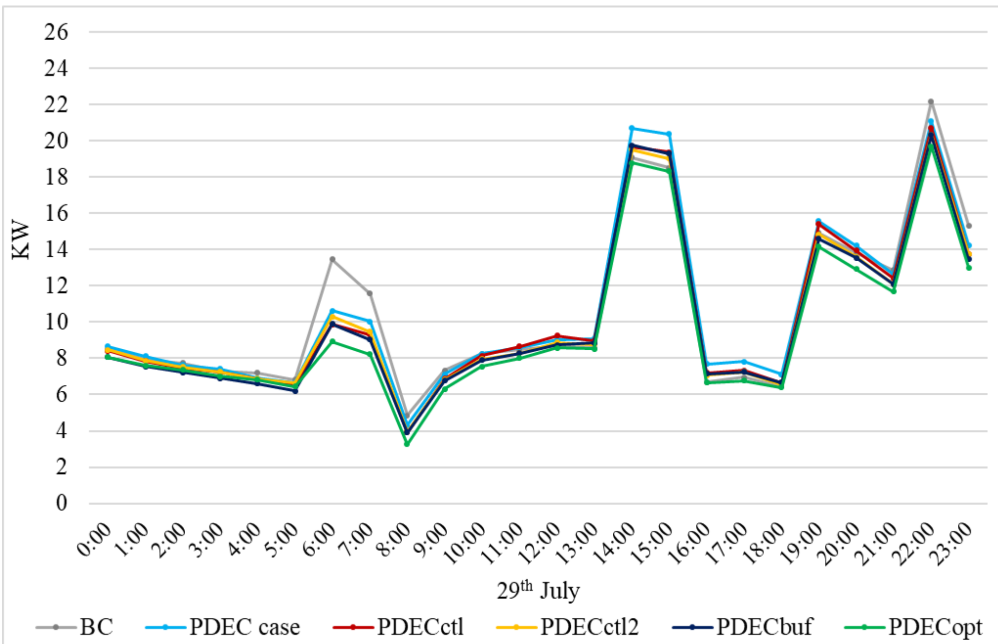


Figure 7-36: Cooling energy consumption rate for the different cases during the hottest day

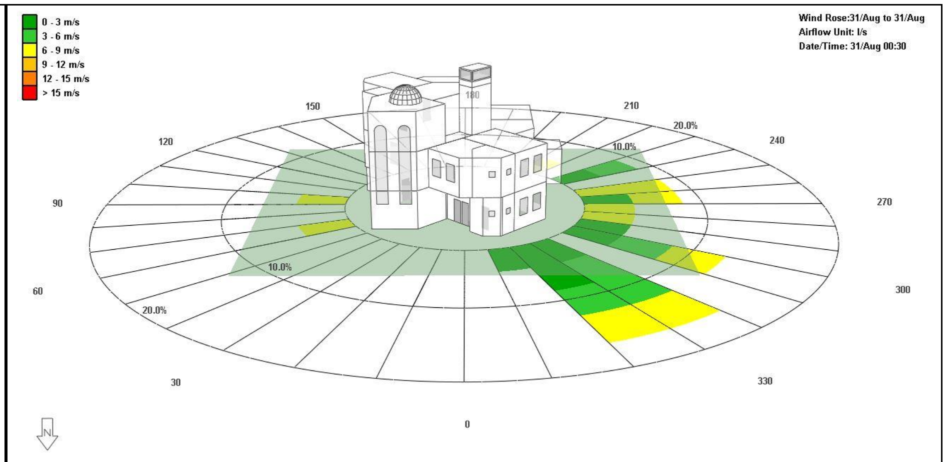
7.5.2 Hot, Windy Day (Scenario (ii))

The unstable weather condition with changing wind direction at higher wind speeds had made the case of this scenario more complicated (Figure 7-37). Similar to the first scenario, the development conducted during the parametric analysis provided gradual improvement in the PDEC performance. However, the development approach in stage 1 did not provide enough improvement to exceed the poor performance in the PDEC case. As shown in Figure 7-38 to Figure 7-41, the wind effect was significantly apparent in most of the first stage cases while considerable improvement was achieved during the second stage. Apart from the GF living room, all the other spaces were negatively influenced by specific wind directions. The fact that the GF living room was slightly (or not) affected is attributed to its low and central location within the house. In the FF living room, the indoor temperatures went up between 14:00 and 16:00 in the cases of Stage 1, although the PDECctl and PDECctl2 presented better performances. This increase was due to the change in wind direction to East, which created positive pressure on the Eastern two stair zone openings. In MGR and MB, less improvement was achieved in the PDECctl and PDECctl2 with internal temperatures peaked around 37^{o}C and 36.5^{o}C, respectively, compared to 38^{o}C in the PDEC case. The location of the windward windows of these two spaces did not improve the case significantly. The lower temperatures of these two spaces were achieved by the smaller window openable area and the control of the windcatcher openings. However, this strong impact of the wind leaded to the further improvement conducted in stage 2 of the parametric analysis.

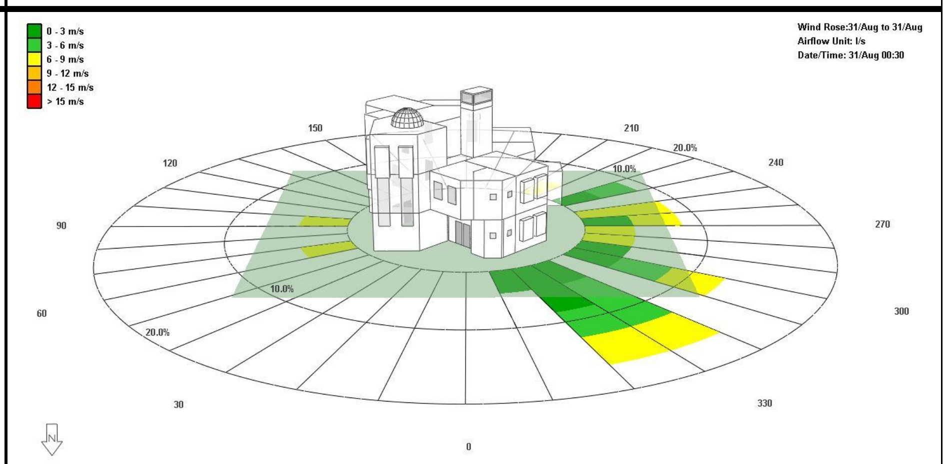
In stage 2, the key point was to negatively pressurize the external windows under such conditions in order to improve the airflow patterns. As a result, each existing window used during the passive cooling mode was initially protected by a simple barrier (PDECbuf). The outcomes have dramatically improved as shown in the figures below. When compared to the PDEC case, the maximum internal temperature in the PDECbuf case dropped by 9^{o}C to around 29^{o}C during peak time. However, the continuous development based on the analysis conducted in CHAPTER 4 and CHAPTER 5 provided a high chance for further enhancement.

Consequently, replacing the existing openings in the stair zone with 4-sided roof openings, as well as developing a double-skin type buffer zone with top two opposite openings in the MGR and MB, had shown the best performance in all the four spaces. In this case, the 4-sided roof openings were opening together while the top openings in the buffer zone of the MGR and MB operated in conjunction, such that the windward opening closed while the leeward opening opened to exhaust the air. The windcatcher openings were opening continuously in PDECopt case as the integrated design of the exhaust openings has already minimised the wind effect in each space. The results demonstrated additional reductions in indoor temperatures as maximum simulated temperature among all the four spaces reached approximately 27.5°C in the MB.

PDEC case – PDECctl – PDECctl2



PDECbuf



PDECopt

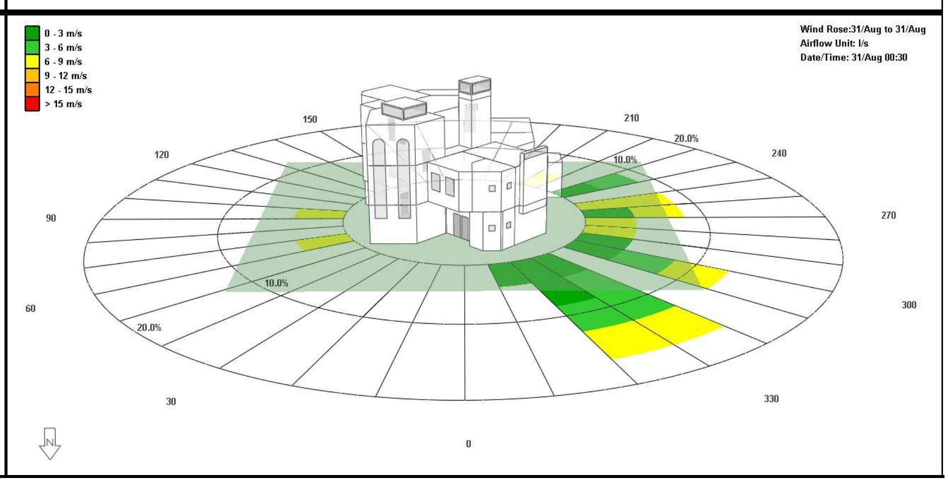


Figure 7-37: Wind speed and wind direction rose on the 31st August

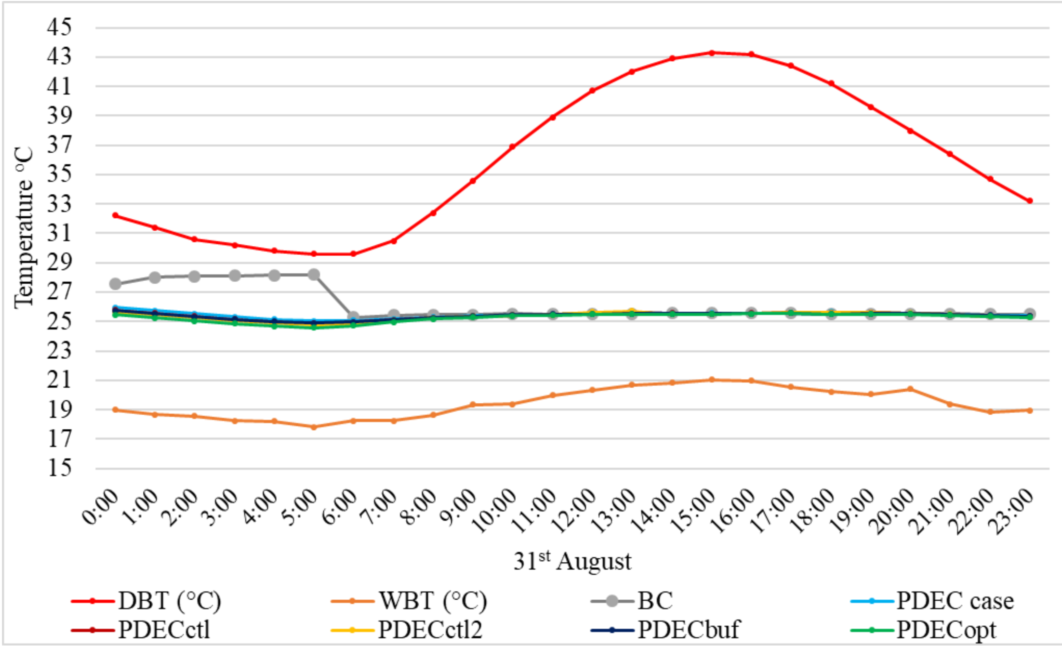


Figure 7-38: External DBT, WBT, and indoor temperatures for different case during a hot windy day (GF living room)

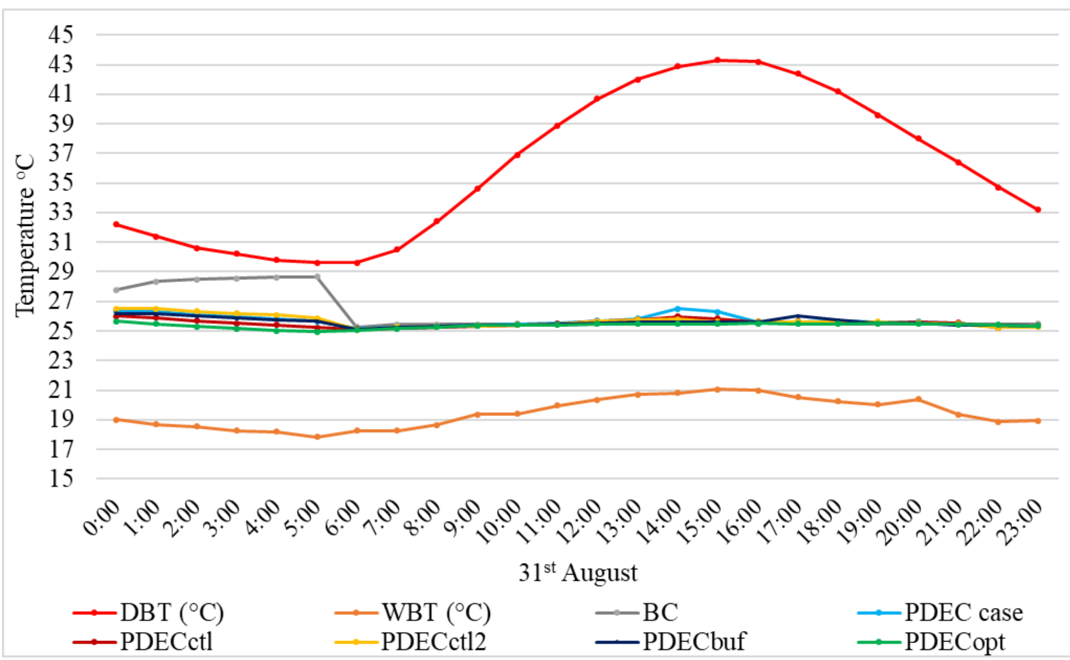


Figure 7-39: External DBT, WBT, and indoor temperatures for different case during a hot windy day (FF living room)

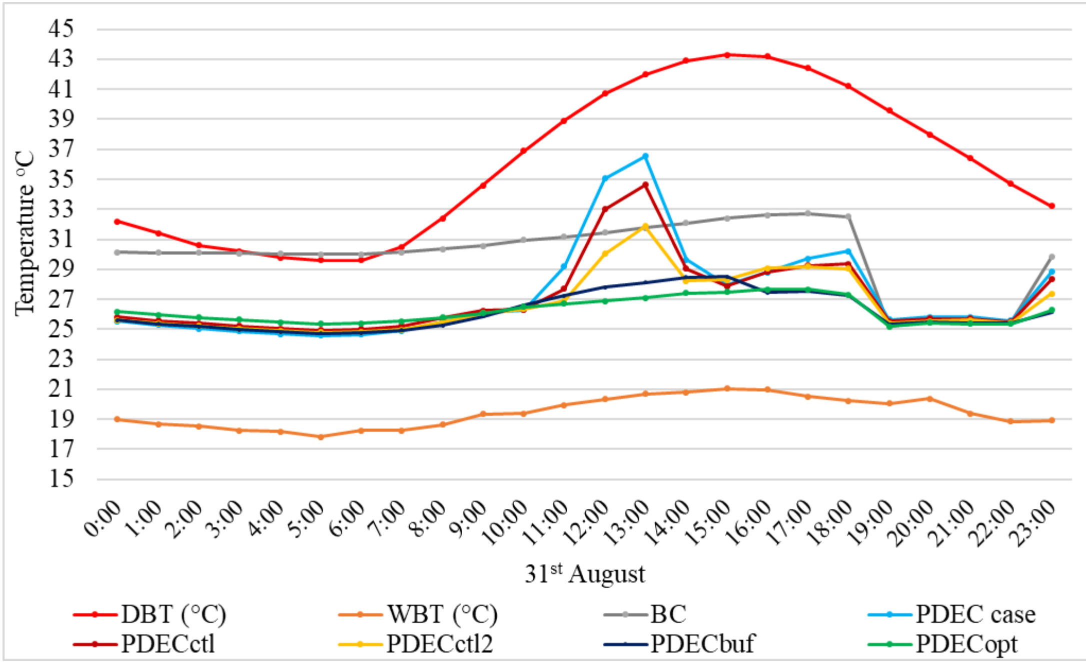


Figure 7-40: External DBT, WBT, and indoor temperatures for different case during a hot windy day (guest room)

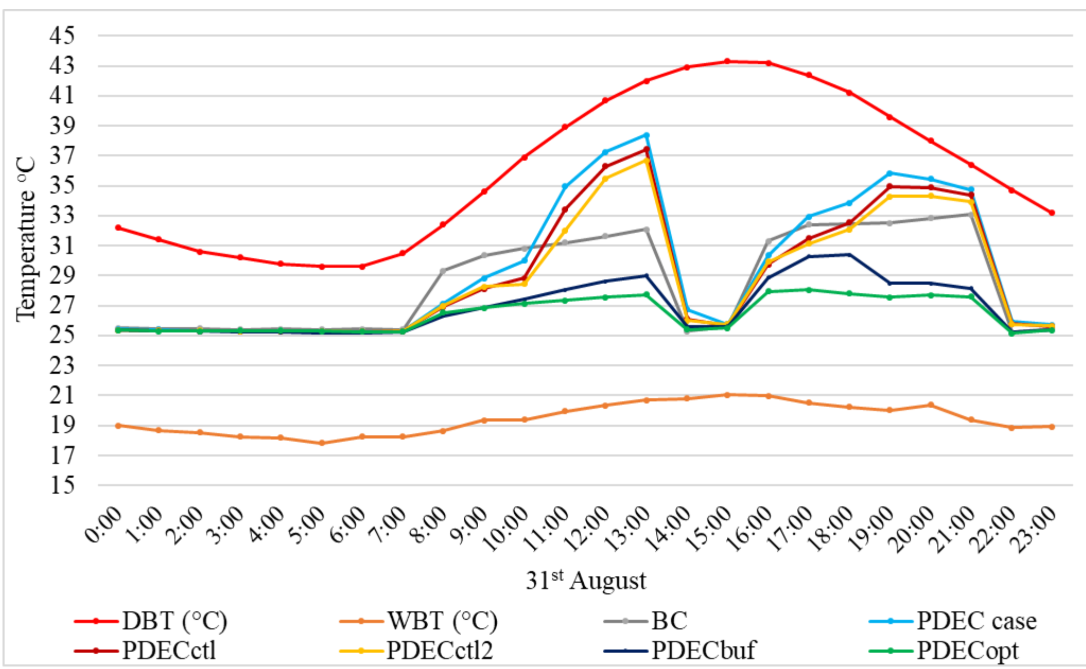


Figure 7-41: External DBT, WBT, and indoor temperatures for different case during a hot windy day (MB)

Based on the analysis discussed above, it was apparent that the cooling energy consumption would not improve in the cases of the first stage analysis (see Figure 7-42). Despite the relatively better performance of the PDECctl and PDECctl2 cases compared to the PDEC case, the total cooling energy consumption was still more than the BC. The total cooling energy consumption of the PDEC case, PDECctl and PDECctl2 were more than the BC (247kWh) by roughly 7% (264kWh), 2.4% (253kWh) and 2.2% (252kWh), relatively. The reduction in the PDECctl and PDECctl2 was achieved in the mechanical cooling while the water pump energy was the same as the PDEC system was running continuously.

The energy consumption started to improve in the second stage. Minimising the wind effect has improved the overall cooling energy use on this day. The total cooling energy consumption in the PDECbuf was decreased by approximately 3% (239kWh) when compared to the BC. Ultimately, the entire cooling energy consumption of the PDECopt was around 225kWh with a percentage reduction of around 8.7%.

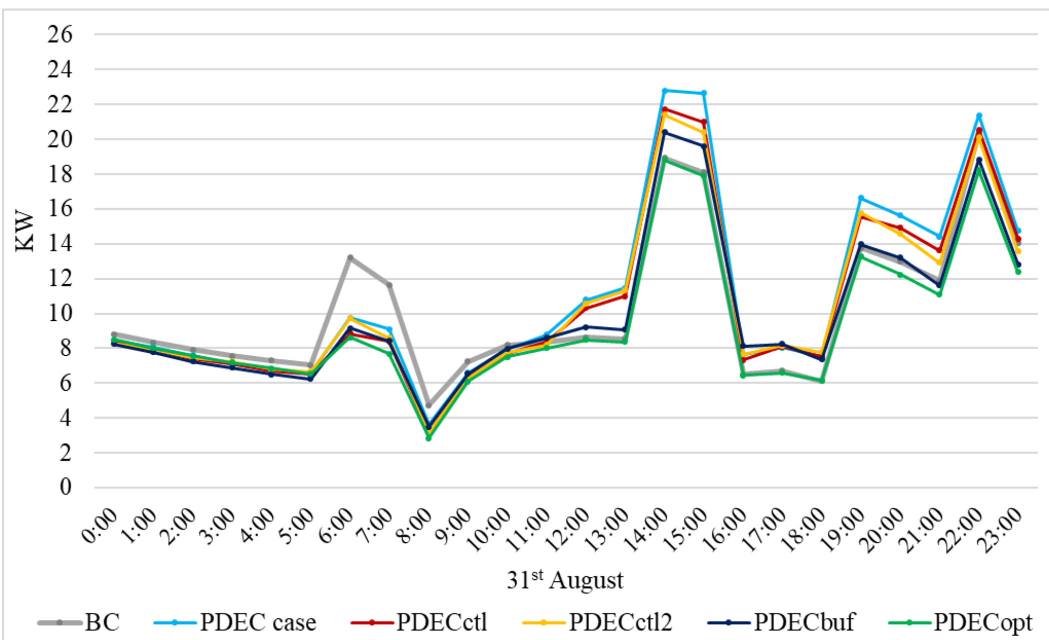


Figure 7-42: Cooling energy consumption rate for the different cases during hot windy day

7.5.3 Performance of the PDEC Only

Having analysed the PDEC efficiency in two extreme conditions above, the next step was to measure the overall PDEC performance in all the different cases throughout the summer season. Before analyzing mixed-mode space conditioning, the mechanical cooling was turned off while the initial setup of the PDEC tower was kept similar to those of section 7.5.1 and 7.5.2 above. The key reason for that was to identify the maximum cooling capacity of the PDEC tower without the use of mechanical cooling. The results were interpreted by ranging the indoor temperatures of each passively cooled space from less than or equal 18.5°C to above 33.5°C in steps of 1°C, and then correlating them against the percentage of hours falling in each degree Celsius (see Figure 7-43 to Figure 7-46).

The results illustrate how the PDEC efficiency evolved during the parametric analysis. It can be seen in the graphs below that the PDEC case presented the worst cooling performance among the other cases in all the four spaces. The two cases of stage 1 showed poor performance where temperatures went above 33.5°C even though the results have developed during this stage. As anticipated, the MB showed the worst results among the other spaces where indoor temperatures exceeded 30.5°C for around 10% of the hours in the PDEC case while this percentage decreased to 7% in the PDECctl and 5.7% in the PDECctl2 cases. In the PDECbuf case, the percentage of MB indoor temperatures exceeding 30.5°C significantly declined to less than 1% while it was zero in the PDECopt. In the optimum case, only 1% of the hours exceeded 29.5°C (below 30.5°C) in the FF living room and MB while the other two spaces represented even better cooling performance with maximum temperatures between 28.5°C and 29.5°C for less than 1% of the summertime. The percentage of hours at lower indoor temperatures had increased during the development process. Apparently, the PDECopt case presented the best cooling capacity of the PDEC tower where cooling was distributed efficiently and adequately in all the four spaces leading to lower indoor temperatures during the whole summer. By comparing the five PDEC cases without the use of mechanical cooling, the next step aimed to find out the effect of the improvement on the operation and energy consumption of the mechanical cooling.

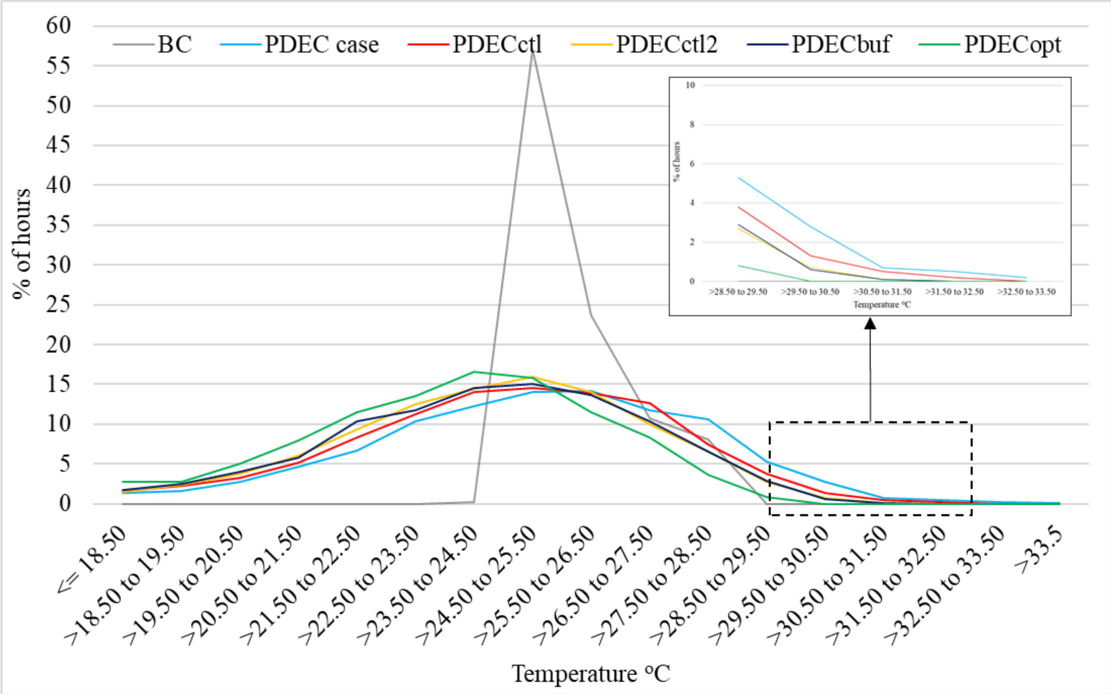


Figure 7-43: Persentage of hours in a temperature range for different cases in the GF living room (PDEC only)

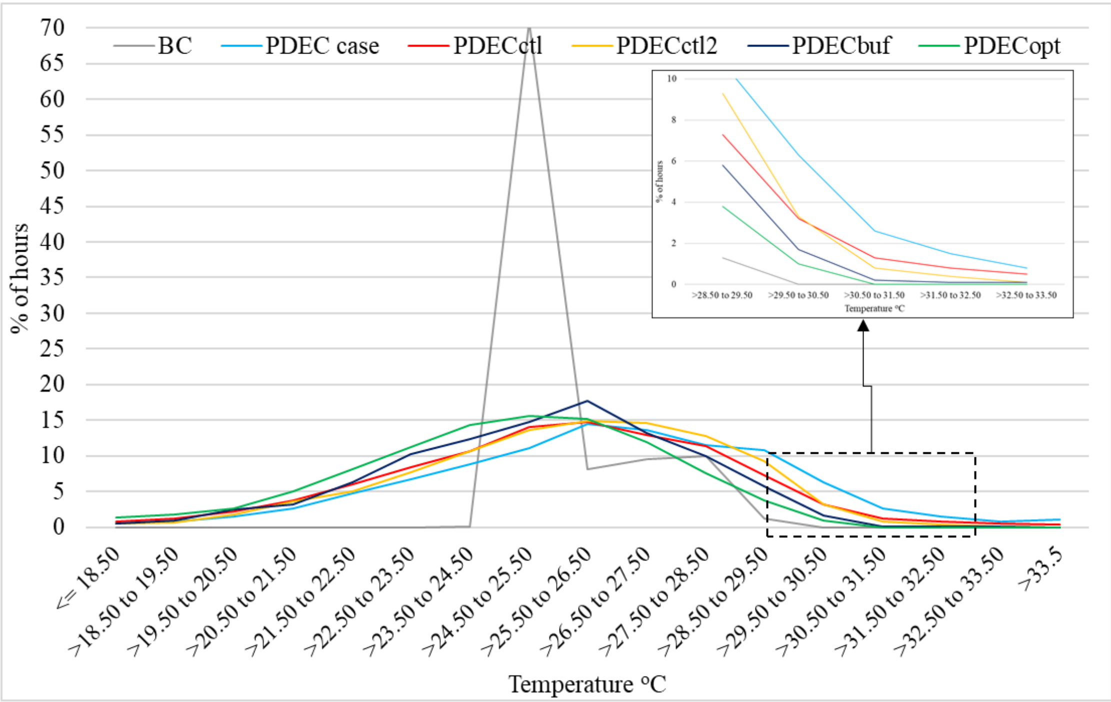


Figure 7-44: Persentage of hours in a temperature range for different cases in the FF living room (PDEC only)

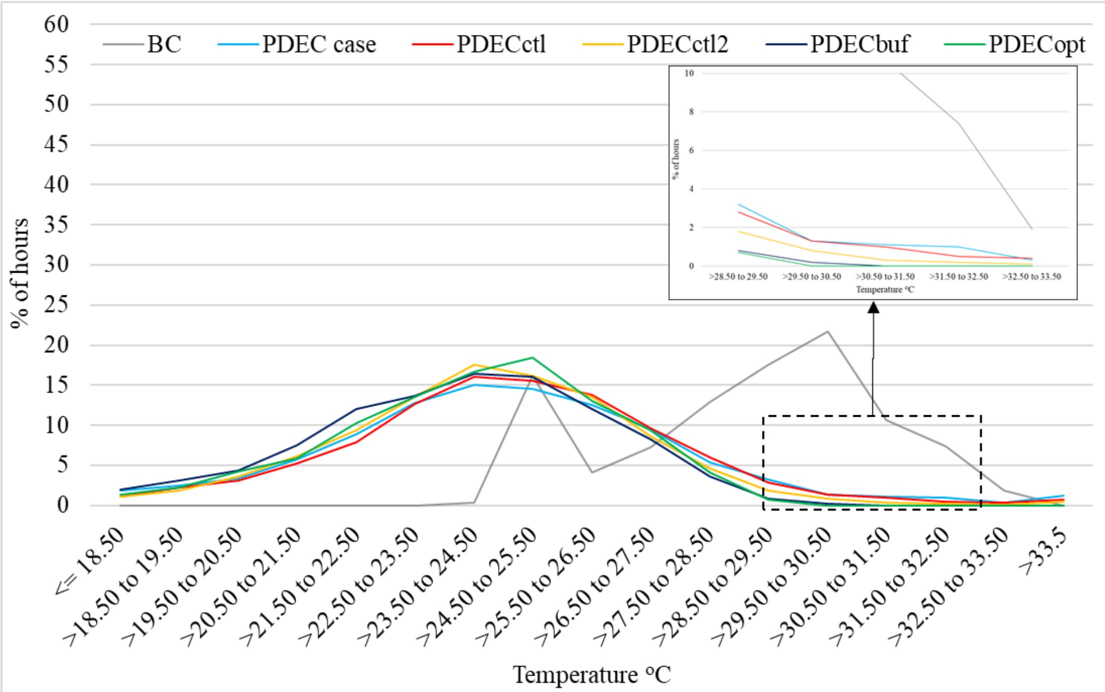


Figure 7-45: Persentage of hours in a temperature range for different cases in the guest room (PDEC only)

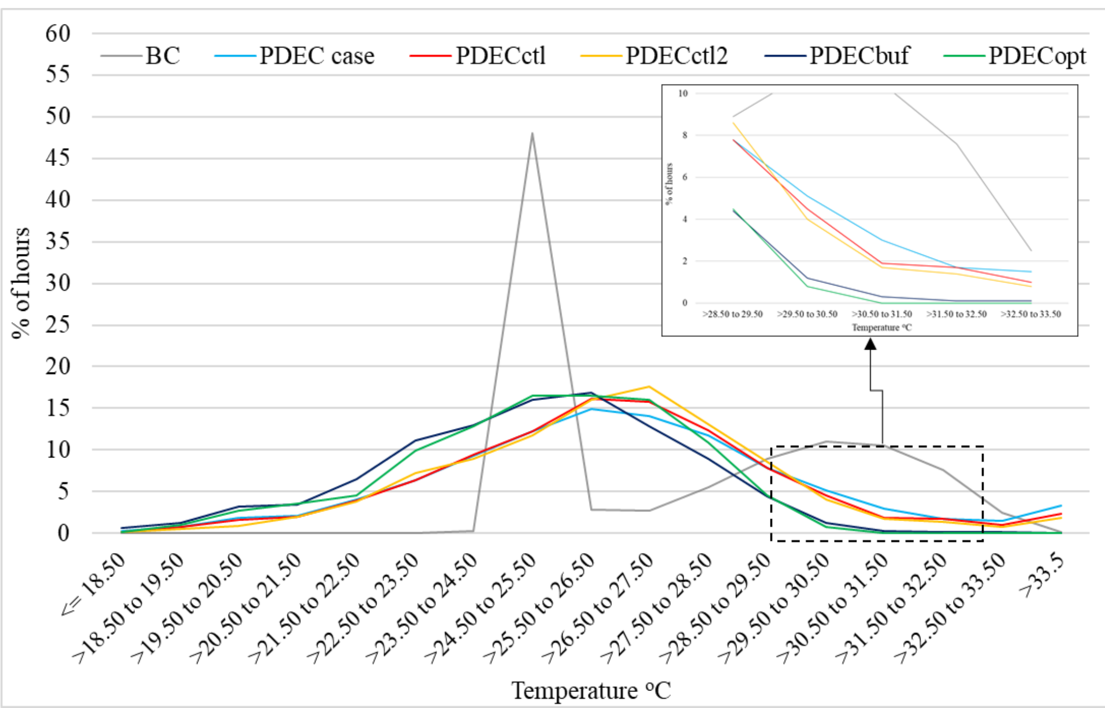


Figure 7-46: Persentage of hours in a temperature range for different cases in the MB (PDEC only)

7.5.4 Performance and Energy Consumption During Mixed-mode Cooling (24/7 PDEC)

By investigating the cooling efficiency of the PDEC tower in the different cases, it was apparent that the mechanical cooling was needed during some times to cover the extra required cooling. As a result, the same analysis process was repeated, but with the mechanical cooling running during the occupied hours if PDEC cooling was not enough to reach the required set-point. At this stage, the PDEC tower was set to run continuously, similar to the cooling operation set used in scenarios 1 and 2 previously. The aim was to find out the maximum cooling performance of the PDEC tower with the mechanical cooling in terms of cooling capacity achieved and energy consumption.

The results for the four spaces are represented in Figure 7-47 to Figure 7-50 below. Clearly, the developed integration between the PDEC tower and the villa was reflected in the use of mechanical cooling. In all the cases, most of the hours were falling between 24.5 to 25.5^{o}C due to the mechanical cooling running to provide cooling at this set-point. However, most of the percentage of hours were below 24.5^{o}C in PDECopt, leading to less need to run the mechanical cooling. In the PDECopt, the percentage of hours equalled or were below 24.5^{o}C in four spaces was approximately: 63% in the GF living room, 48% in the FF living room, 58% in the MGR, and 37% in the MB. In the MGR and MB, this percenatge was more in the PDECbuf case but decreased in the other two larger spaces. It was more important to provide more cooling in the living spaces as they were occupied during the day time (peak DBT) while the MGR and MB are used at night when temperatures are cooler. This balanced distribution between spaces appeared positively in the overall cooling energy needed, which is further discussed below.

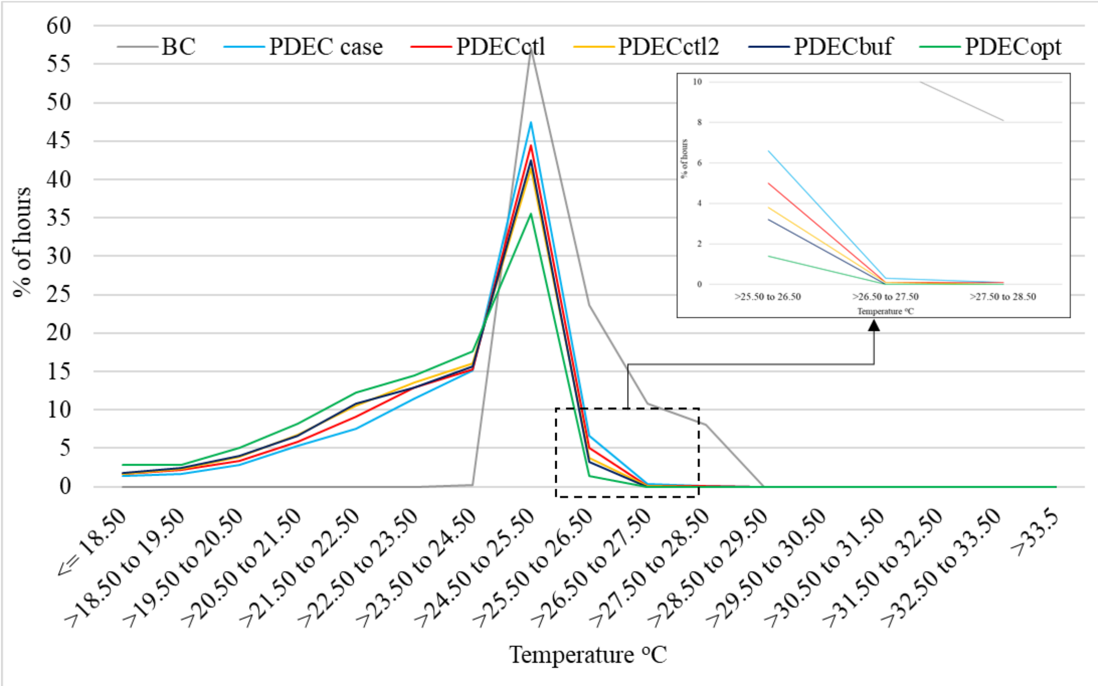


Figure 7-47: Persentage of hours in a temperature range for different cases in the GF living room (mixed-mode 24/7)

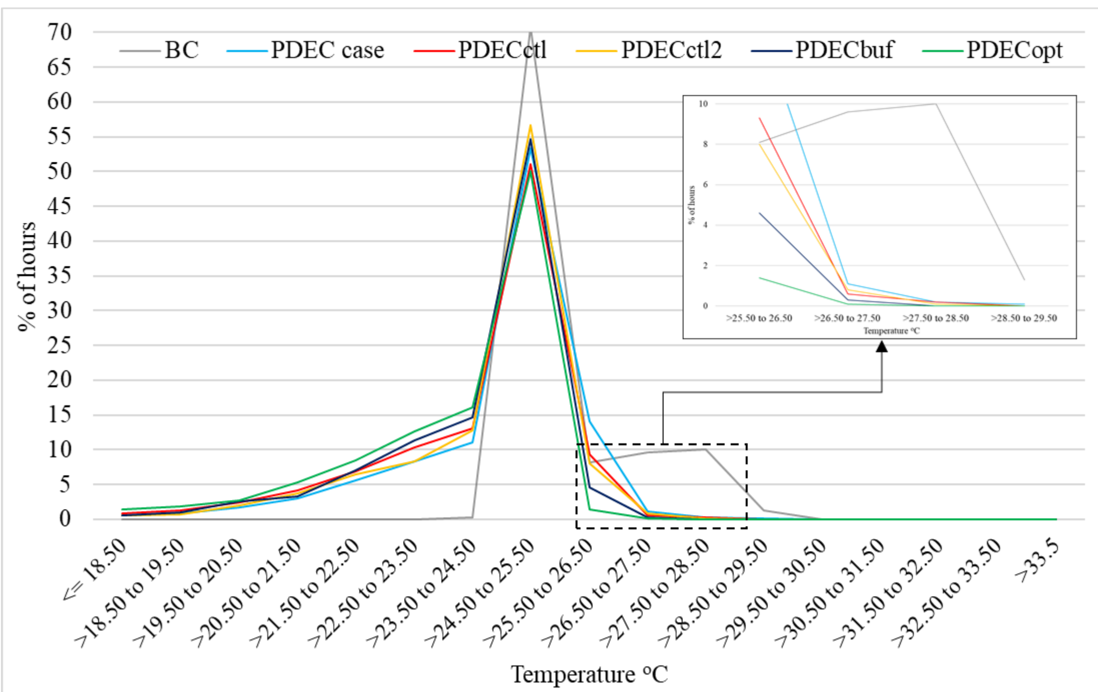


Figure 7-48: Persentage of hours in a temperature range for different cases in the FF living room (mixed-mode 24/7)

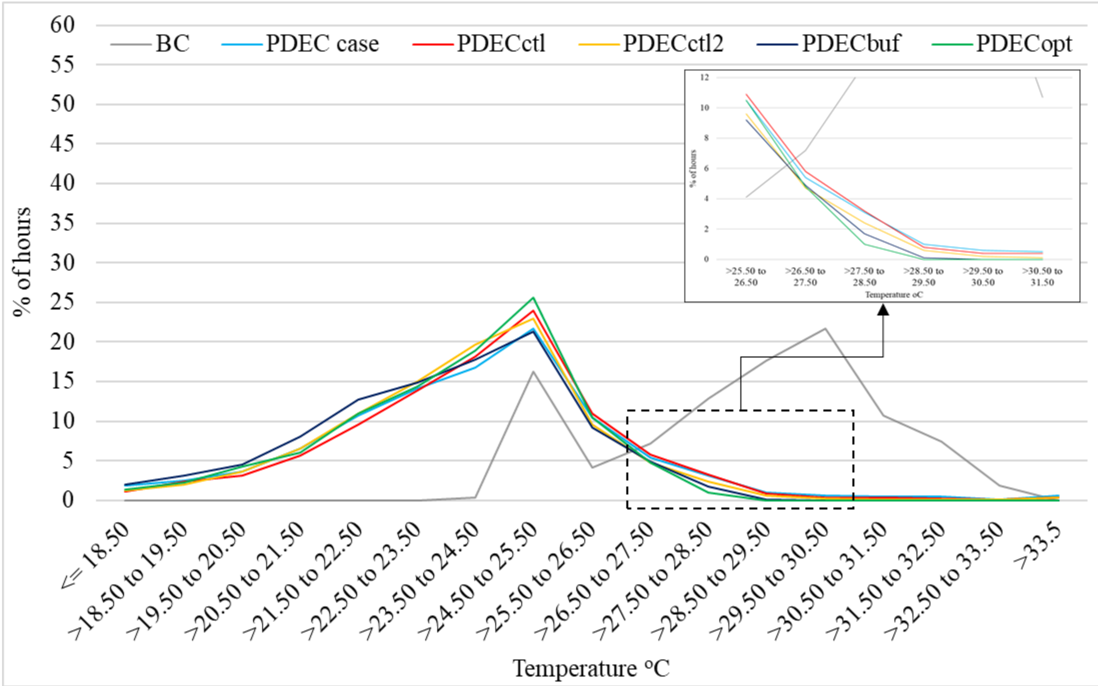


Figure 7-49: Persentage of hours in a temperature range for different cases in the MGR (mixed-mode 24/7)

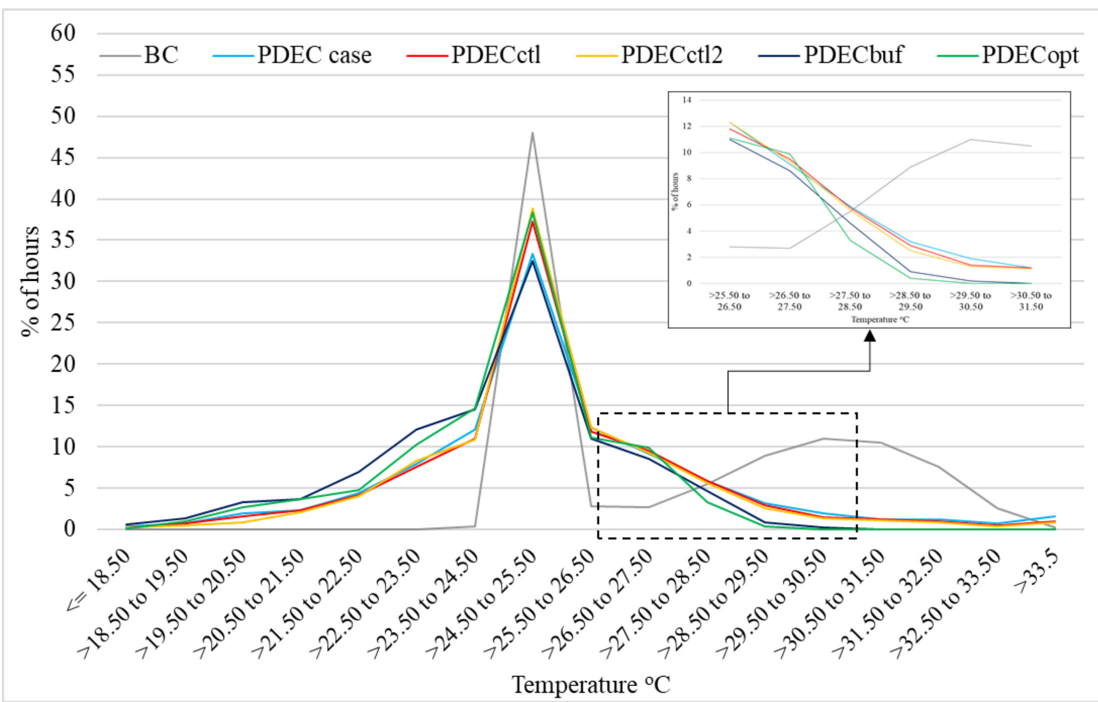


Figure 7-50: Persentage of hours in a temperature range for different cases in the MB (mixed-mode 24/7)

As shown in Figure 7-51, the enhancement achieved during the parametric analysis was apparent in the energy consumption. Figure 7-51 shows the total cooling energy consumption and percentage of reduction during the entire summer season for all the cases discussed above. The amount of energy needed to cool the building was additionally reduced from 22.2% in the initial PDEC case to 36.2% in the optimum case. Bearing in mind that the PDEC tower was linked to only four spaces in the house (almost 50% of the functional space's area), the total energy consumed for cooling was decreased from 28337kWh in the BC to 18091kWh in the PDECopt case. However, this reduction was achieved regardless of the required temperature set-point, leading to low (below comfort) temperatures at sometimes. As a result, control of the PDEC tower was needed to maintain required temperatures.

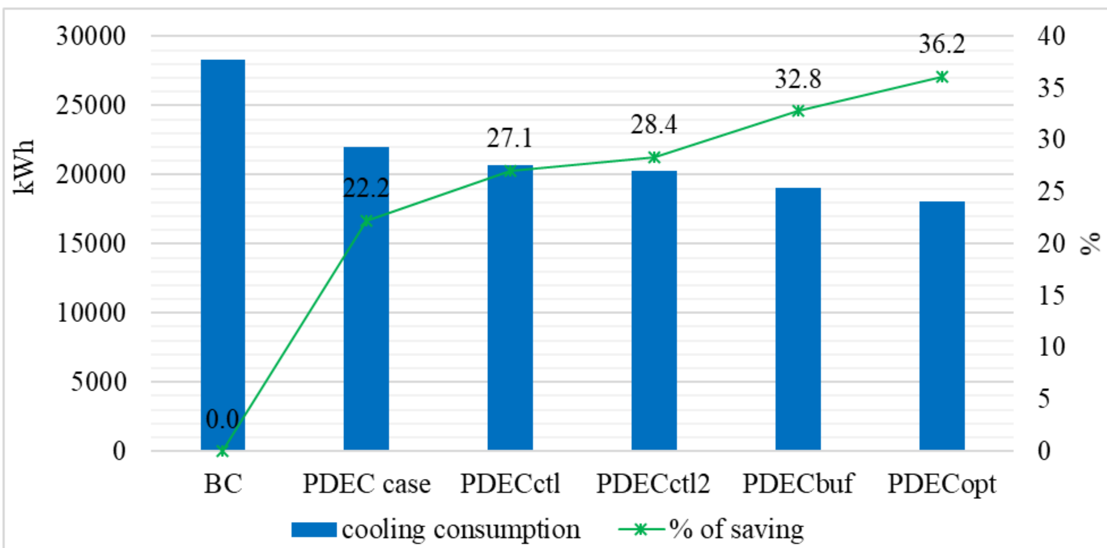


Figure 7-51: Cooling energy consumption and percentage of saving during the summer (PDEC running continuously)

7.5.5 Performance and Energy Consumption During Mixed-mode Cooling (Controlled PDEC)

Despite the amount of energy saved, the use of the PDEC tower must be stopped when temperatures declined significantly to cool and discomfort levels. This would require careful consideration to balance between energy consumption and required set-point temperature. As a result, the setup previously explained in Table 7-3 to Table 7-5 to control indoor temperatures and PDEC system were reconsidered. Based on these setups, the PDECctl2, PDECbuf, and PDECopt will run the PDEC system in line with the mechanical cooling (which is running during occupied hours only) to reach the required set-points only and prevent any excessive cooling. The operation of the spray system and supply opening of the PDEC tower were linked to the coupled spaces temperatures (set-point 24.5^{o}C). This set up would assure the running of the PDEC tower to below the mechanical cooling set-point and prevent any extra unwanted cooling. The best scenario discovered to control the external (exhaust) openings during the developing process was to link the external openings of the living spaces to room set-point (24.5^{o}C) while the MGR and MB were linked to occupancy profiles. Since the MGR and MB are used during night time when DBT is lower, it was not worthy to passively cool their spaces when they are not used. In addition, most of the higher prevailing wind speeds were occurring during day time. Consequently, saving the cooling capacity of the PDEC tower to the larger living room spaces during the warmer day time was more efficient. Because of the central protected location of the living rooms, it was found that the continuous air supply from the PDEC tower (linked with space temperature) was more energy-efficient as these spaces were linked to most of the other spaces in the house. The continuous cool temperatures of these spaces would make the surrounding spaces relatively cooler, which would ultimately minimize the energy consumption needed for cooling.

Figure 7-52 to Figure 7-55 show the percentage of hours in each degree Celsius during occupied times only for every space. Apart from PDEC case and PDECctl, it can be seen that most of the cases show similar results. This is because of the control applied to the PDEC system to maintain room temperatures at a certain level. In the cases of the controlled PDEC tower, more than 95% of the hours were falling within the range of set-point temperatures of the PDEC and mechanical cooling in all the spaces. However, the PDECopt case was the best case in terms of energy consumption.

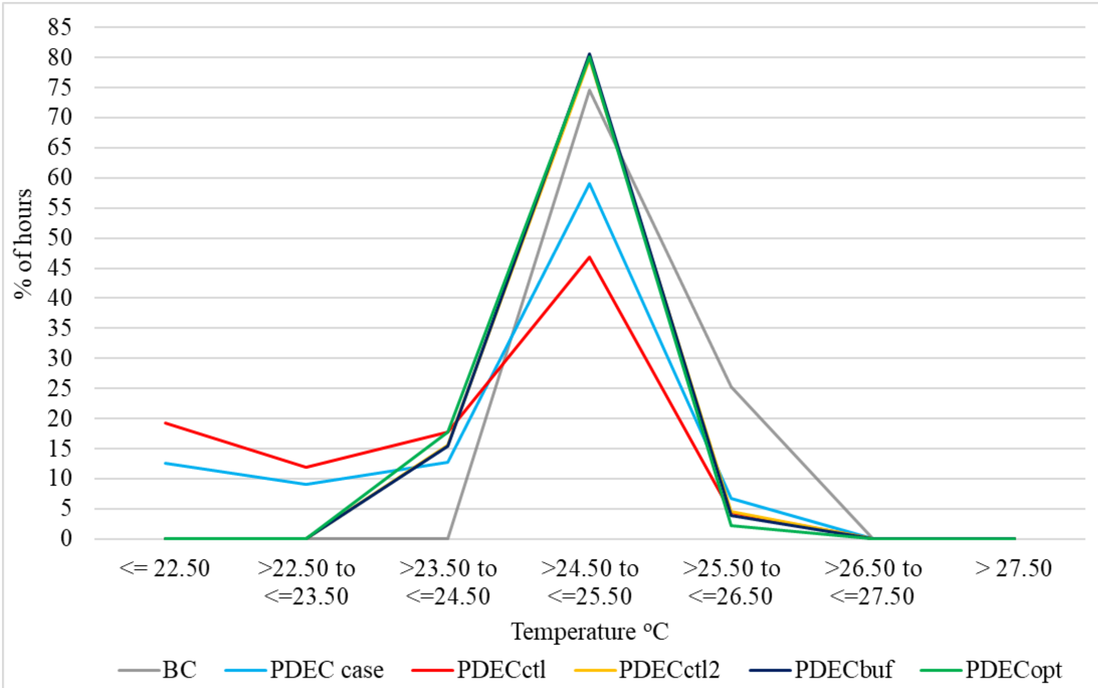


Figure 7-52: Persentage of hours in a temperature range for different cases in the GF living room during occupied hours (mixed-mode - controlled PDEC)

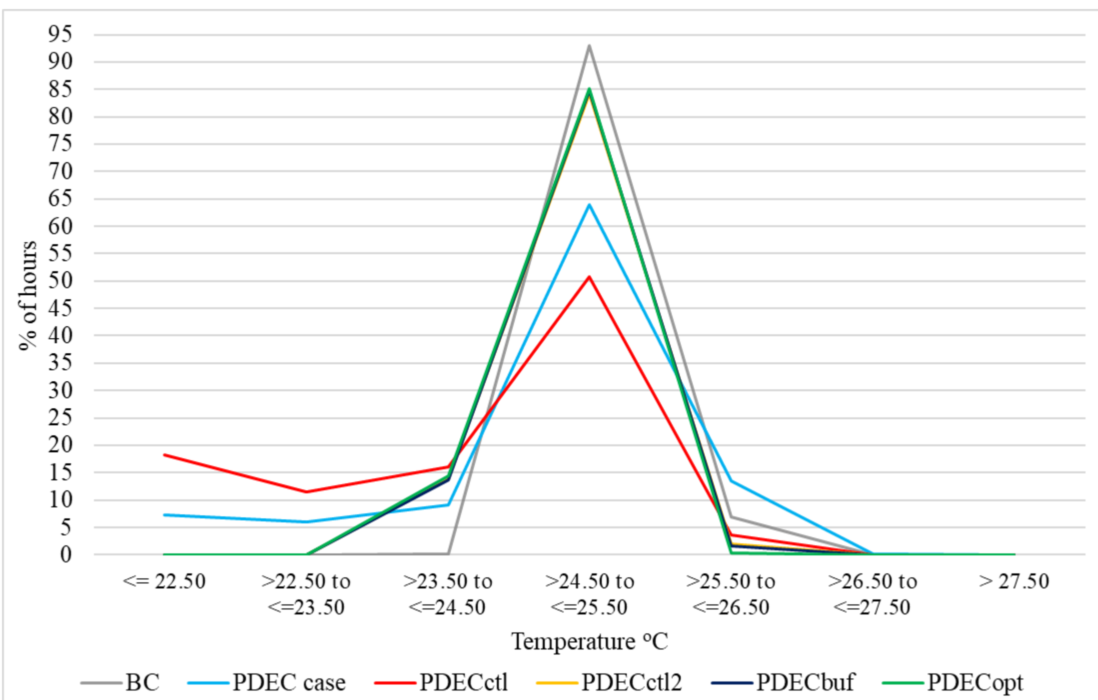


Figure 7-53: Persentage of hours in a temperature range for different cases in the FF living room during occupied hours (mixed-mode - controlled PDEC)

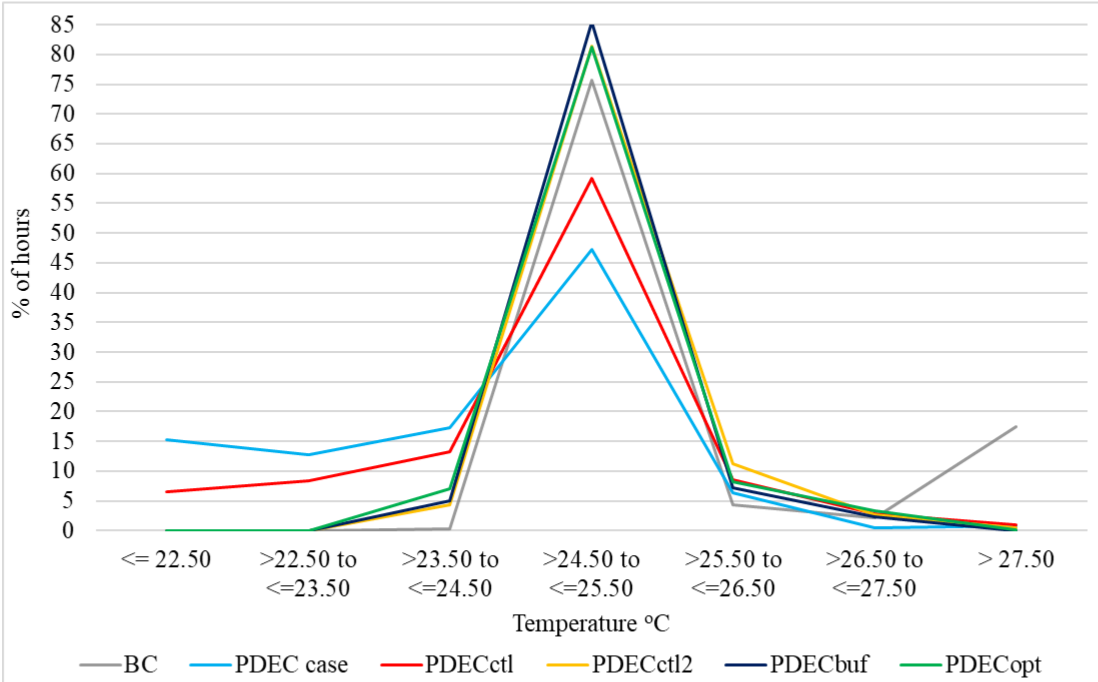


Figure 7-54: Persentage of hours in a temperature range for different cases in the MGR during occupied hours (mixed-mode - controlled PDEC)

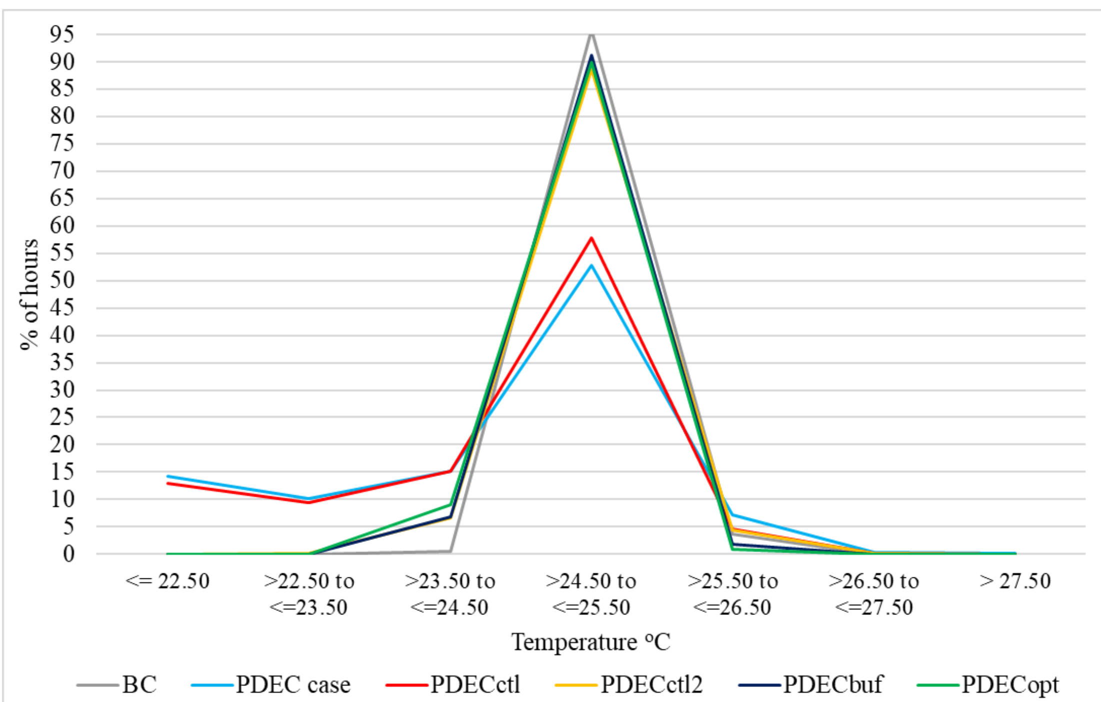


Figure 7-55: Persentage of hours in a temperature range for different cases in the MB during occupied hours (mixed-mode - controlled PDEC)

Based on the analysis discussed in the previous two sections, it was apparent that the PDECopt case would achieve the least energy consumption (see Figure 7-56). However, the energy consumption actually decreased in the cases of stage 1 while increased in the cases of the second stage. In fact, savings achieved in the PDECctl case became similar to that of PDECbuf. This increase is attributed to the fact that the MGR and MB external openings became closed during the day hours when the high-speed prevailing winds were mostly blowing. So, the negative effect of the wind was reduced by just closing the windows. The optimum case has shown less energy saving as the PDEC was not running continuously at this time. The total energy consumed for cooling reduced from 28337kWh in the BC to 18614kWh (34.3% saving) in the PDECopt, almost 2% less when compared to the PDEC running continuously. Nevertheless, the case would not be comparable as the indoor temperatures will be at required (comfort) levels. So, compensation in energy consumption must be considered to achieve that.

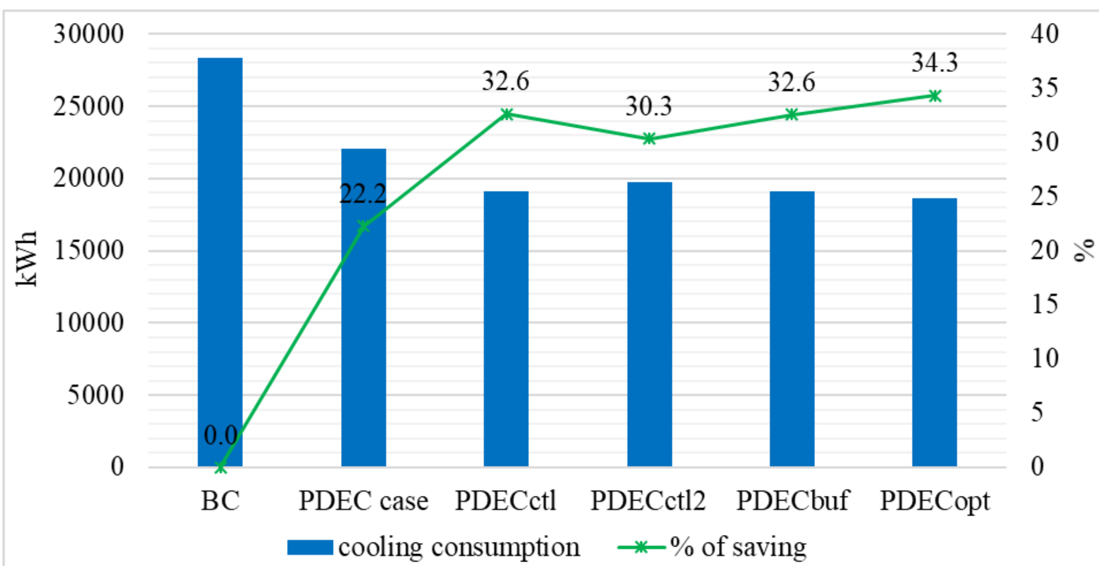


Figure 7-56: cooling energy consumption and percentage of saving during the summer (mixed-mode - controlled PDEC)

7.5.6 Wind Direction and Wind Speed Effects on the PDEC Case and PDECopt

In order to understand the level of improvement achieved throughout the development process, the analysis in section 7.3.5 was repeated, but by comparing the PDEC case with the PDECopt case. Figure 7-57 below shows the wind speed and direction effect in a comparison between the PDEC case, PDECopt (24/7), and PDECopt. It is obvious how the negative wind effect was minimised. The maximum simulated indoor temperature reduced from around 38^{o}C in the PDEC case to 31.5^{o}C in the PDECopt, and 29^{o}C when the PDEC was running continuously in PDECopt (24/7). It should be noted that the higher indoor temperatures in the MGR and MB in the PDECopt (24/7) and PDECopt cases were simulated during unoccupied hours. This significant reduction in wind effect was the main contributor to maximising the performance of the PDEC tower. However, it can be noticed that indoor temperatures in all spaces went down to as low as 17^{o}C during near calm conditions in the PDEC case and PDECopt (24/7). This issue was apparently solved in the PDECopt case by controlling the operation of the PDEC tower to maintain the internal temperature at acceptable levels during most of the time.

The proper design and operation of both the PDEC tower and the coupled building as one integrated design have advanced the overall performance of the PDEC tower. Special consideration and opening design for every passively cooled space based on the weather and space conditions have improved the cooling performance of the tower, maintained the room/space condition at required conditions, and ultimately decreased the energy consumption under most weather conditions.

Having developed and maximised the PDEC tower performance throughout the parametric analysis process, the next step was to analyse thermal comfort levels in every coupled space. This analysis is discussed in the following section.

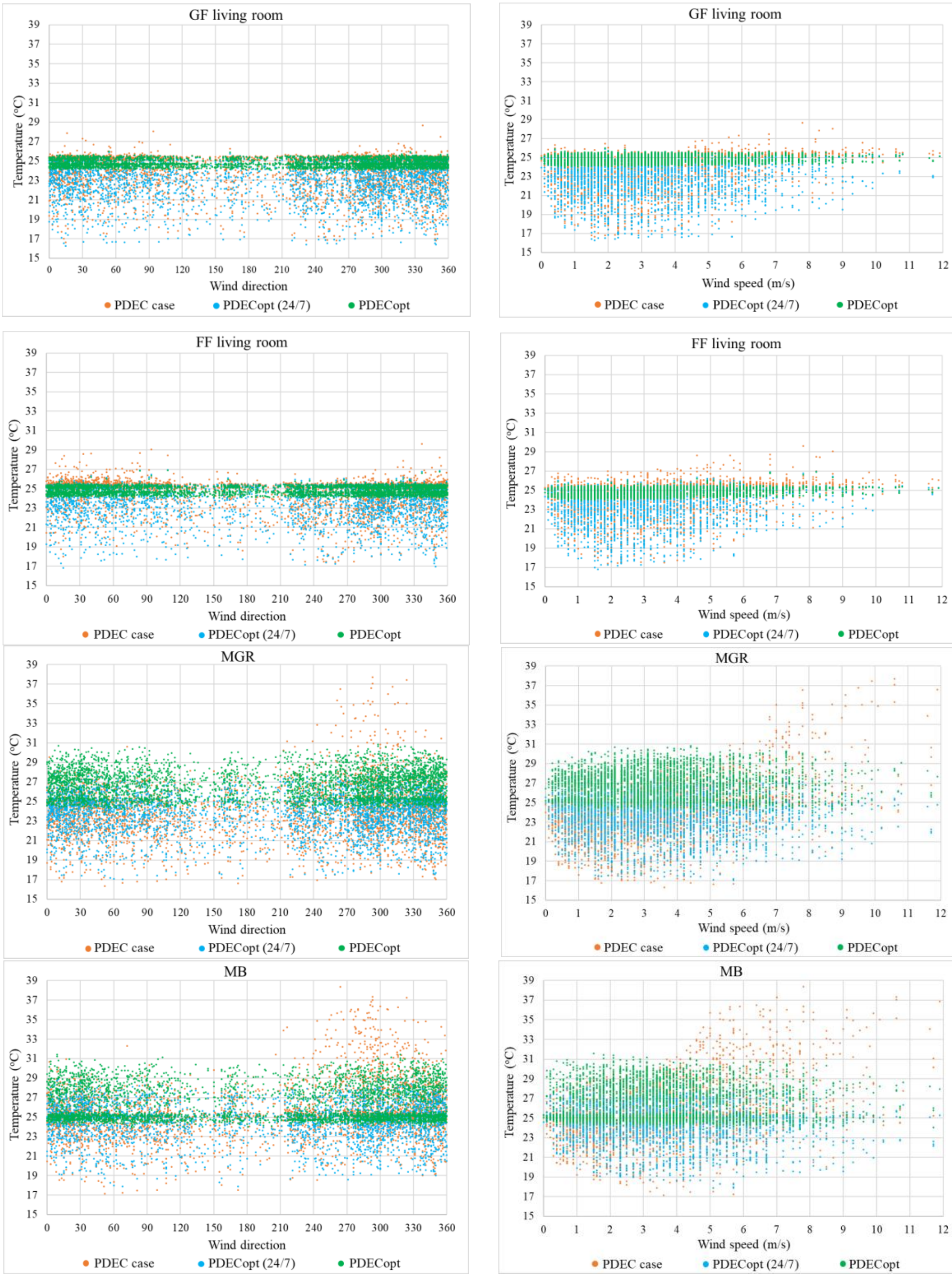


Figure 7-57: Wind direction effect (left) and wind speed effect (Right) on the four spaces – comparison between PDEC case, PDECopt (24/7), and PDECopt

7.6 THERMAL COMFORT

Maintaining an acceptable thermal comfort level in an occupied space is a significant aspect alongside performance and energy consumption during the design process. However, it is difficult to define specific thermal comfort limits for all occupants as each occupant prefers special environmental conditions based on several factors such as activity level, clothing, and variations in an indoor environment. In an extreme climate such as Saudi Arabia, as well as in mixed-mode conditioned buildings, the thermal comfort situation is even more complicated as there is no definitive comfort model that can be directly used to measure and analyse comfort level. As discussed in 4.7, the Adaptive Thermal Comfort Model (ATC) can be used when a building is naturally ventilated while the Predicted Mean Vote (PMV) is used for mechanically conditioned buildings. In mixed-mode cases, it might be said that the ATC model can be used during a passive cooling mode while the PMV model may be used when the building is mechanically conditioned. However, the different comfort ranges between the two models makes it difficult to apply this approach as, for example, the maximum comfort level in the ATC model could be out of the comfort range of the PMV model in such an extreme climate. As a result, both models were considered separately in this study when conducting a thermal comfort analysis for the passively cooled spaces.

To achieve that, the set-point temperature considered for mechanical cooling was set based on the analysis conducted in the Climate Consultant software. The 25.5^{o}C was a suitable temperature within the thermal comfort zone following the PMV calculation based on the ASHRAE standard. On the other hand, the minimum comfort temperature during the three hottest months was calculated using the ATC model (around 24.5^{o}C) and was set when operating the PDEC tower. This consideration would take into account that the indoor temperatures do not fall below the ATC lower comfort levels while maintaining acceptable comfort temperature at 25.5^{o}C when considering the PMV model calculation approach, when mechanical cooling is running. The analysis and discussion of comfort levels using each model are discussed below.

7.6.1 The Adaptive Thermal Comfort Model

As mentioned previously in section 4.7, recent studies have discovered that occupants showed a higher level of thermal comfort satisfaction in naturally conditioned spaces and extreme climates (Dear, Dear and Ph, 1998; Dear, 2001; Dear, Dear and Brager, 2002; Paul, John and Dear, 2012; Humphreys, 2015). The ATC equation developed by De Dear and used in ASHRAE Standard 55 was used to find out the comfort levels for each month. Figure 7-58 to Figure 7-61 show the simulated indoor temperatures during occupied hours only for each space. Using the ATC model, two comfort zones (80% and 90% acceptability limits) are represented for each month dependent on the monthly mean outdoor temperature. The lowest comfort level was found to be in May at 23^{o}C while the highest comfort level reached 31.7^{o}C in August.

Among all the four spaces, the majority of occupied hours fall within the 80% acceptability limits. In fact, most indoor temperatures can be seen at the lowest limit of the zone because of the mechanical cooling (25.5^{o}C) running during occupied hours. Since there was no temperature control for the PDEC tower in the PDEC and PDECopt (247) cases, the temperatures went below the comfort range in all the four spaces. May and September experienced the coolest temperature due to the relatively cooler weather. In the GF and FF living room, the temperatures decreased to below comfort levels even during the hottest three months. In May and September, the temperatures went below the lower acceptable level for more than 50% of the time in these two spaces. In the MGR and MB, the reduction in the indoor temperature below the lower 80% acceptability limit was less compared to the GF and FF living room. During the entire summer season, approximately 23% of the simulated indoor temperatures during the occupied time were below the lower comfort level in the MB and less than that in the MGR. However, these below comfort temperatures were significantly minimised when the PDEC tower was controlled in the PDECopt case. In this case, the PDEC tower was set to operate when room temperatures exceeded 24.5^{o}C in order to assure that the PDEC ran prior to the mechanical cooling and, in the same time, did not let indoor temperatures fall below the lower comfort acceptability limit. Consequently, the indoor temperature was kept within the ATC levels during occupied hours.

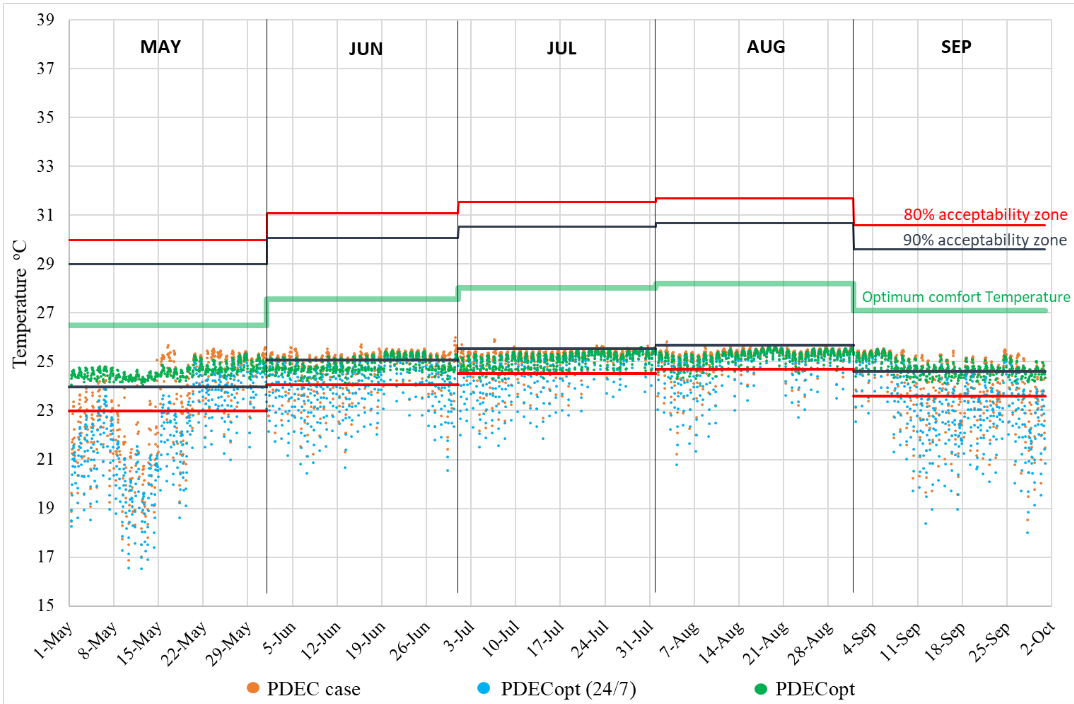


Figure 7-58: Comparasion between indoor temperatures for the PDEC case, PDECopt (24/7), and PDECopt within the ACM zones for the GF living room (occupied hours only)

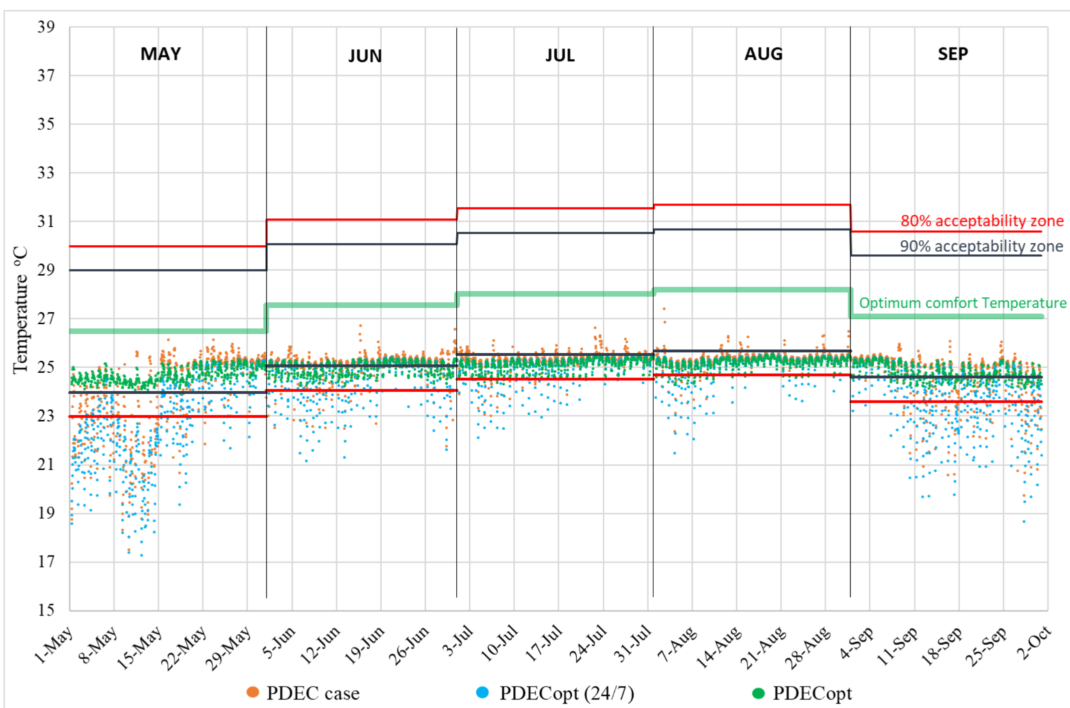


Figure 7-59: Comparasion between Indoor temperatures for the PDEC case, PDECopt (24/7), and PDECopt within the ACM zones for the FF living room (occupied hours only)

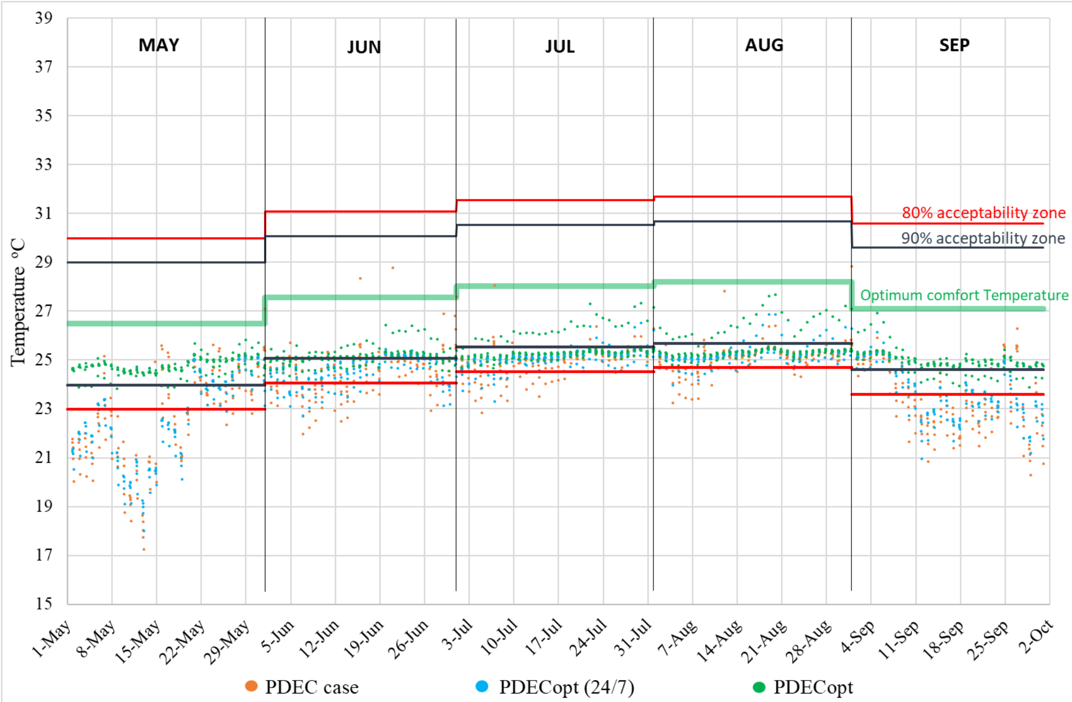


Figure 7-60: Comparasion between Indoor temperatures for the PDEC case, PDECopt (24/7), and PDECopt within the ACM zones for the MGR (occupied hours only)

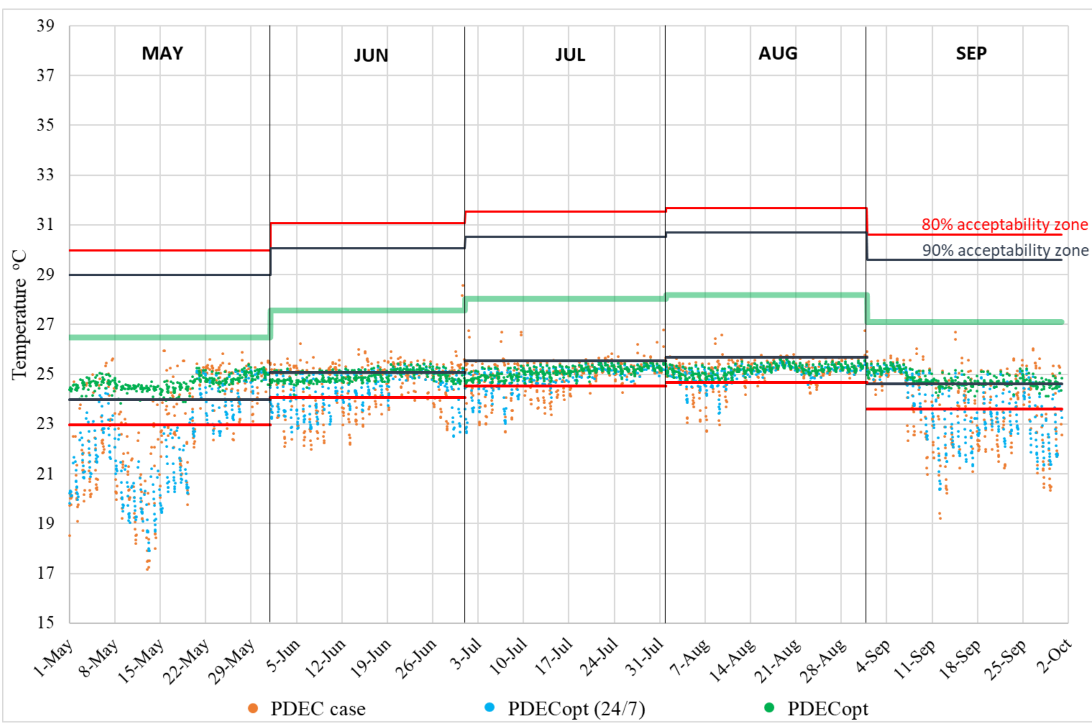


Figure 7-61: Comparasion between Indoor temperatures for the PDEC case, PDECopt (24/7), and PDECopt within the ACM zones for the MB (occupied hours only)

7.6.2 Fanger Model - The Predicted Mean Vote (PMV)

According to ASHRAE 55 (ASHRAE, 2010), the PMV model is used to determine thermal comfort by using a thermal sensation scale. The thermal sensation scale is developed to predict occupants' responses (votes) to thermal conditions on a 7-point scale: (-3) cold, (-2) cool, (-1) slightly cool, (0) neutral, (+1.0) slightly warm, (+2.0) warm and (+3.0) hot. This prediction is calculated based on six factors including (1) air temperature, (2) mean radiant temperature, (3) relative humidity, (4) air movement, (5) metabolic rate, and (6) clothing level. Values of -0.5 and +0.5 represent a Predicted Percent Dissatisfaction (PPD) of 10% while an unsatisfactory environment is considered when people are voting +3, +2, -2, and -3 on the PMV scale.

Given these inputs, IES-VE can report the values of PMV within a space according to the Fanger model. A PDEC tower will definitely impact on all the factors considered in the PMV model. Apart from air velocity, IES will consider the space's environmental factors based on the dynamic thermal simulation (DTS). Air velocity, metabolic rates, and clothing levels must be entered manually. The metabolic rates and clothing levels are considered based on the ASHRAE Handbook and are summarized in Table 7-6. Since the PDEC tower typically supplies a large amount of airflow, air velocity must be altered continuously for accurate prediction. However, due to the difficulty and complexity to find out an accurate prediction of air velocity values at hourly or sub-hourly basis, the air velocity was assumed to be 0.15m/s for each space.

Table 7-6: PMV inputs

	Clothing level (clo)	Metabolic rate (met)	Air velocity (m/s)
Guest and Living zone	0.59	1.2	0.15 (assumed), (ASHRAE, 2010)
Sleeping zone	0.57	0.9	

The results of the PMV values were then reported for each room and are illustrated in Figure 7-62 to Figure 7-65. The figures show the results during occupied hours for each space. Due to the specified set-point temperatures for cooling operation, the results indicate that the high satisfactory level is achieved in the BC and PDECopt case. The cases where the PDEC tower was running continuously reported an unsatisfactory result in May and September. In the GF and FF living room, and MGR, the results indicated a vote of nearly (-2), which is classified as a cool environment on the PMV scale. This level of dissatisfactorion was greatly minimised when controlling the PDEC tower in the PDECopt case. The MB represented the worst PMV values in all cases. The PMV values in the MB reached (-3) cold condition in the cases where the PDEC was not controlled. Although the results were improved in the PDECopt, the results still show values between (-1) slightly cool and (-2) cool conditions. This is due to the activity level (sleeping) and clothing insulation inputs specified in these spaces as the indoor conditions are nearly similar to the other spaces during occupied hours. Considering the energy saving achieved in the PDEC cases, the PDECopt case showed the best thermal comfort using PMV model with values that were very close to neutral.

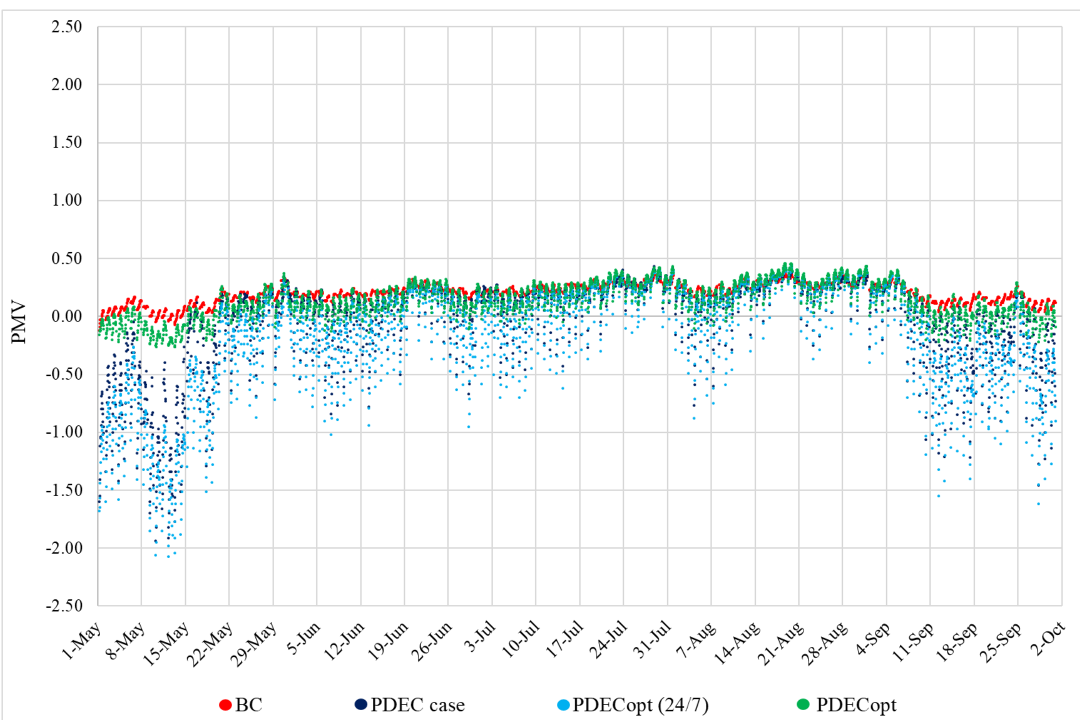


Figure 7-62: Variation of indoor PMV values for the BC, PDEC case, and PDECopt during the summer season (GF living room – occupied hours only)

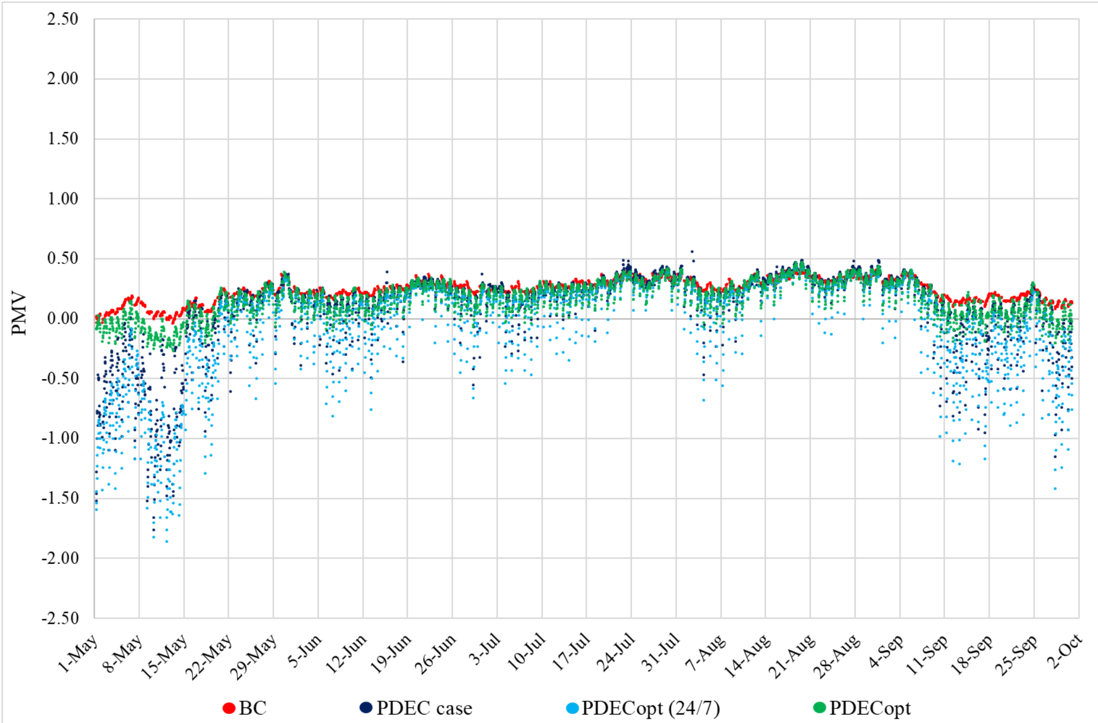


Figure 7-63: Variation of indoor PMV values for the BC, PDEC case, and PDECopt during the summer season (FF living room – occupied hours only)

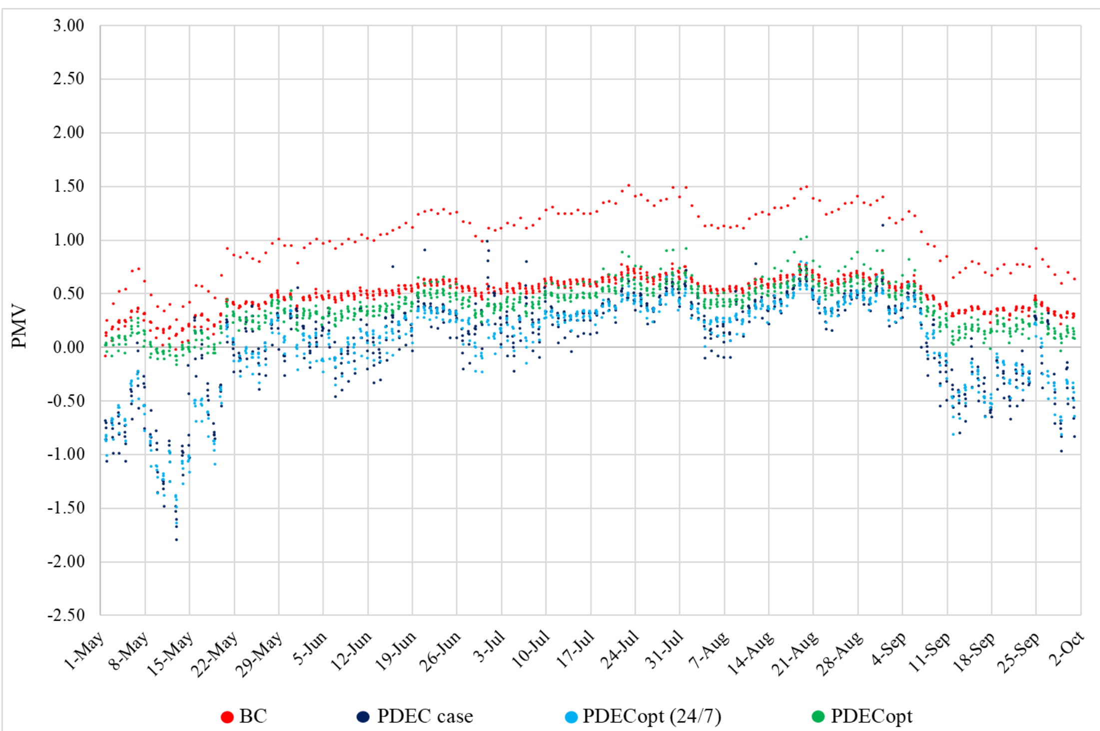


Figure 7-64: Variation of indoor PMV values for the BC, PDEC case, and PDECopt during the summer season (Guest room - occupied hours only)

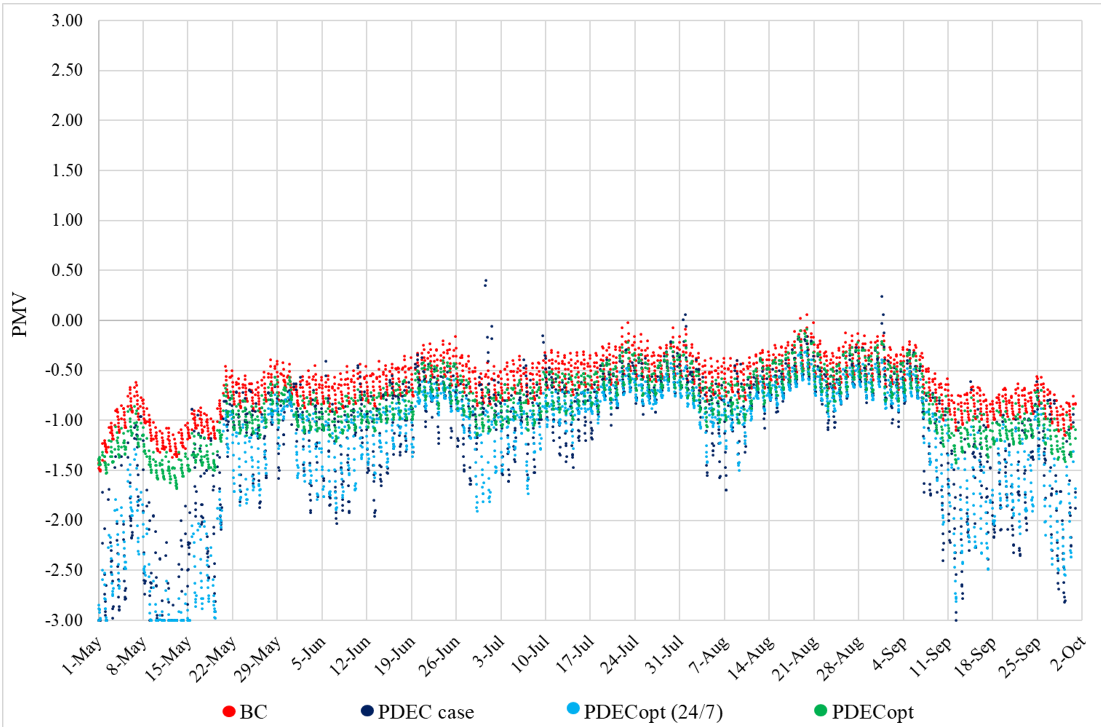


Figure 7-65: Variation of indoor PMV values for the BC, PDEC case, and PDECopt during the summer season (MB - occupied hours only)

7.7 CONCLUSION

Although many studies have shown improved PDEC performance based on technical control and engineering design of the PDEC system (Belarbi, Ghiaus and Allard, 2006; Kang and Strand, 2013, 2016; Alaidroos and Krarti, 2017), the architectural design of a PDEC building can also play a key role to enhance the indoor comfort level. The alteration and modification on the opening design of the spaces cooled by the PDEC tower have shown significant improvement of the PDEC cooling performance. This improvement resulted in better and acceptable thermal comfort levels with less energy consumption. Hence, one integrated design of a PDEC building could significantly improve thermal comfort levels and lower energy consumption.

CHAPTER 8. CONCLUSION AND DISCUSSION

8.1 OVERVIEW

This study primarily investigated the potential of reducing cooling energy consumption and maintaining thermal comfort from using passive downdraught evaporative cooling (PDEC) in Saudi housing.

Even though many successful applications of PDEC systems have been reported around the world, there is still a lack of reported studies about the actual applicability of PDEC towers in the extremely hot and arid climate of Saudi Arabia despite the emergence of such passive system in the Middle East. The assessment of an existing PDEC tower in Saudi Arabia was a critical stage of this research before considering its investigation to residential units. Furthermore, although many studies have investigated PDEC performance in terms of its technical and engineering aspects, there is a shortage of investigation about the significance of proper integration between the PDEC tower and the coupled building. Appropriate consideration of building / architectural design and air inlets and outlets position is as crucial as engineering for a successful building project. In addition, most of the previous research concentrated on the use of the PDEC system in non-domestic buildings. PDEC has demonstrated its viability, both technically and commercially, with respect to non-domestic buildings. However, there is a lack of research that assesses the potential applicability of such passive cooling technique in domestic buildings.

The monitoring and analysis of an existing PDEC performance in a building in the hot arid climate of Saudi Arabia will be an added value to the literature in this field. In addition, further investigation on the applicability of the PDEC towers for existing residential buildings in the extremely hot Saudi climate will be another important research opportunity. As a result, this study found it a valuable opportunity and a contribution to the knowledge to first, investigate the actual performance of PDEC in an existing building in the Kingdom of Saudi Arabia; second, model and analyse the applicability and performance of PDEC tower in a typical Saudi house. A residential building was an ideal selection to study the integration of a PDEC tower in this type of buildings and to analyse the effect of architectural design on the PDEC performance. The successful performance of such a system could be introduced as a viable solution to tackle the high energy demand required for cooling in the Saudi residential sector.

8.2 RESEARCH SUMMARY

It has been mentioned that the energy consumption for cooling and associated CO2 emissions have been significantly increasing for housing in Saudi Arabia in the last decades. The rapid population growth, the reliance of burning crude oil for power generation, and the extremely hot climate make the Saudi case even worse, indicating a serious challenge that the country could face in the near future. Nowadays, the use of air conditioning represents roughly 70% of all energy used in the Saudi residential sector. Several energy efficiency measures have been considered by the government of Saudi Arabia to reduce the demand for energy consumption (SASO, 2014; SEC, 2016; Al-Tamimi, 2017; SEEC, 2018). However, future energy demand is expected to increase in line with the increasing housing demand and population growth, which would require more mechanical air conditioning. This challenge requires greater attention and underlies the significance of this study, which investigate the viability and applicability of passive cooling. Passive cooling techniques have been used as a sustainable alternative to conventional AC systems. PDEC tower is considered one of the most efficient and cost-effective passive cooling techniques in hot arid climates, where it relies on the evaporation process as a heat sink in such dry climate (Ford, Schiano-Phan and Francis, 2010).

The research was carried out to address two primary aims: (1) investigating the effectiveness of an actual PDEC system in an existing building in the extremely hot dry climate of Saudi Arabia; (2) studying the applicability of a PDEC tower in a multi-space building, a typical Saudi villa, as one integrated design. In the beginning, four research questions were raised and asked to guide the researcher to meet the research objectives. To address and answer the research objectives and questions, this research was conducted in three main stages, as shown in Figure 1-6. The first stage involved the monitoring and assessment of an existing PDEC building in Saudi Arabia. The second stage included computational modelling and validation of a PDEC tower in IES-VE to initially study the performance of a spray PDEC tower and the coupled space as one integrated design. The third stage represented the modelling validation and analysis of a virtual integration of a PDEC tower to a typical Saudi villa. Based on the research findings, the research question asked in Chapter One can now be answered.

8.3 RESEARCH MAIN FINDINGS

This section describes, in brief, the main findings of the research by referring back to the main research questions asked initially in section 1.5. Below, the answers of the research questions are discussed by highlighting the findings that relate to each question.

> ***Research Question 1: What are the actual cooling efficiency and thermal performance of an existing PDEC tower in the extreme hot arid climate of Saudi Arabia?***

The answer to this question was provided within the first stage of this research in Chapter Four. In order to comprehend the cooling efficiency and thermal performance of a PDEC tower in Saudi Arabia, the researcher, in the beginning, considered the importance of monitoring and assessing an existing PDEC building in the Saudi climate. This step was considered for two main reasons: (1) due to the lack of studied PDEC buildings in the Middle East region, and (2) to raise the confidence of the applicability of the PDEC tower in such an extreme climate. This was a very important step and a question to answer before considering and investigating its applicability to residential buildings. To answer this significant research question, field measurements, analysis, and assessment of the performance of an existing PDEC building in Saudi Arabia were conducted. A small public library, Dar Al-Rahmaniah, located in the extremely hot central region of Saudi Arabia, was selected. Only the men's building was studied and assessed because of religious and privacy reasons. Fortunately, the men's section, which is mainly cooled by two PDEC towers, was representing the main part of the library. The building was monitored for more than 70 days during the summer of 2018. Tens of thousands measured weather data, both externally and internally, were recorded by installing several data-loggers inside and outside the towers and the occupied space. The assessed case study provided detailed information about cooling efficiency and thermal performance of the PDEC tower in the climate of Saudi Arabia. The results indicated that the PDEC towers could deliver significant cooling for library users considering that the mechanical cooling was working for only 72 hours of the recorded 1688 hours. The temperature difference between the external DBT and that delivered at the bottom of the PDEC towers ranged from 6°C in the early morning to 22.5°C during the hottest parts of the days (~3.00pm).

The hourly cooling efficiency for the entire monitored period for both towers was calculated. The results indicated that a high cooling efficiency rated was achieved, ranging from 16.5% during the closed cool night hours (when exhaust openings are closed) to 94% during peak times. However, it was noted that under certain weather conditions, the PDEC performance was less effective. Changes in wind conditions played a significant role in the overall performance of the PDEC. A parametric analysis of the wind effects was conducted by studying the relationship between wind speed and the amount of cooling achieved by the PDEC towers in terms of supply temperature and cooling efficiency. A similar process was performed to investigate the relationship with the external wind speed. It was revealed that the towers' effectiveness was influenced by changes in wind speed, and in a counter-intuitive way – stronger wind speeds tended to reduce the tower cooling efficiency, leading to offsetting the loss of PDEC cooling by mechanical air conditioning. The findings showed how the increase in wind speed increased the supply temperatures from as low as 17°C to as high as approximately 29°C. Hence, the maximum cooling efficiency reduced from above 90% to below 60%. This correlation analysis between the wind speed and the supply temperatures and cooling efficiency showed a strong negative relationship. As mentioned previously, the same process was repeated to discover the effect on PDEC tower air velocity. It was observed that air velocity within the tower decreased to below 0.15m/s during the periods of higher external wind speeds. In contrast, during calm or low wind speed conditions, the acquired air velocity data of the towers were mainly above 0.5m/s, with air velocity readings exceeding 1m/s at specific points.

Moreover, thermal comfort analysis investigated the acceptability limits of indoor temperature using two different thermal comfort models. Due to the lack of a definitive comfort model for mixed-mode buildings such as the case study assessed in this research, it was difficult to select a specific thermal comfort analysis approach. Hence, both the adaptive thermal comfort model (ATC) and Predicted Mean Vote model (PMV) developed by Fanger were considered separately. The analysis indicated that high levels of comfort could be delivered by the PDEC towers for most of the occupied time. The results also showed that the ATC model seems to be more appropriate when analysing such type of buildings. However, this analysis indicated the need for more appropriate thermal comfort limits/model for such an extreme climate as the results showed the need for mechanical cooling, at sometimes, even within ATC limits.

The case study analysis provided detailed information about the ability of the PDEC towers to provide effective passive cooling and adequate thermal comfort for most of the time, although the degree of cooling was affected by higher wind speeds.

> ***Research Question 2: How will the architectural design of a space coupled to a PDEC tower affect the performance of a PDEC?***

This question was answered during the second stage of this research in Chapter Five. By answering the first research question, and despite the impressive cooling performance of PDEC tower in Saudi Arabia, it was very important to determine the effect of the cooled space/s on the cooling efficiency of the towers. Appropriate consideration of building / architectural design elements and air inlets and outlets position is as crucial as engineering for a successful building project. The proper integration between the PDEC tower and the building to be cooled offers a great potential for maximising cooling efficiency by this type of passive cooling approach. To understand the importance of integrated design, and to initially identify the possible opportunities of a developed PDEC building, a PDEC tower was digitally modelled in IES-VE software and virtually integrated with a single-story open plan room. The selection of the software involved a literature review, self-training, personal communications with experts in the field, and direct contact with software companies. The tower was placed in the prevailing wind direction side (north) while the exhaust window opening was placed on the opposite side (south). Two days scenarios were analysed, a very hot day with northerly winds and a slightly cooler day with a southerly wind.

Answering this question was an introduction before considering the PDEC integration to a more complex building with multiple spaces (a house), and then answering the following research questions. Finding the answer to this question involved the modelling and validation of a PDEC tower, investigating the performance of a baseline case, and examining different window configurations of the coupled space to increase the cooling performance. The PDEC model was tested against experimental data derived from a European Union (EU) PDEC project. The results showed a close agreement of indoor temperatures and relative humidity between the actual and predicted results. Then, a current Riyadh weather file was obtained from Meteonorm and used for the analysis. As expected, the results demonstrated that PDEC towers could achieve significant cooling, but that their effectiveness was greatly reduced by changes in wind speed and direction linked to opening distributions in the room attached to the PDEC tower. The influence of wind speed and direction was then taken into account when developing the opening design. As a result, a double-skin type buffer zone corridor was then created on the exhaust window opening to test if the window could be protected from unwanted winds and the tower performance improved. The addition of the buffer zone followed by a number of developed opening design configurations. The parameters that have been considered included buffer depth buffer height, opening sizes, and opening placement. Many design configurations were investigated, but only three were presented where major improvements in the tower's cooling performance were observed. The first configuration had two openings located at the floor and ceiling of the buffer zone. The second configuration had two openings at the top North and south side of the buffer zone in addition to the floor opening. The floor opening was removed for the third configuration. The first configuration improved the performance during south wind conditions only while reduced it during higher wind speed. The performance has slightly improved in the second configurations, but the effect of wind speed remained apparent. The third configuration provided the best performance under different weather conditions and significantly improved cooling performance. It can be said that the top leeward openings decreased the pressure within the buffer zone cavity while the elimination of the bottom opening helped to create a stack effect, which enhanced the airflow within the tower and space.

The answers of the first two questions provided a good start to search the answer for the remaining two questions.

Research Question 3: How much cooling energy reduction could be achieved by applying a PDEC tower to a typical Saudi dwelling?

Following the optimistic findings of stage one and two, the next step was to identify the possible cooling energy saving achieved by the integration of a PDEC tower into a typical Saudi house. The monitoring, modelling, and assessment of a typical Saudi villa discussed in chapter six and seven (stage three) provided the answer to this question. The previous findings were brought together to study the virtual integration of a PDEC tower in an existing typical Saudi villa in IES-VE. A villa in Hail was the selected location of the study in this part for several reasons, including full accessibility to the selected case study, it being a recently built house, orientation and design geometry of the house, and building size. Moreover, the climatic characteristics of Hail and Riyadh are nearly similar, where both cities have extremely high DBT and low RH levels during the summer. These reasons have guided the researcher to identify this case study as a proper selection for a typical Saudi dwelling.

Answering this question was achieved through several steps. First, data of the villa, including architectural and construction details, systems details, and thermal performance monitoring, were collected during the summer of 2018. Second, the collected data were used to model and validate the house in IES-VE. Third, the baseline energy consumption for the summer season (May to September) was identified. These three steps were conducted in chapter six. After that, a PDEC tower was virtually integrated and linked to the main spaces of the house including the ground floor living room, first-floor living room, men guest room, and master bedroom (almost 50% of the functional space's area).

The base case energy consumption was found to be around 32415 kWh during the summer, while the cooling energy demand was representing approximately 88% of the total energy used (28337 kWh). By integrating the PDEC tower, the cooling energy consumption reduced by around 22.2%, from 28337 kWh to 22032 kWh, taking into account that the PDEC was operating continuously throughout the day. Despite the reduction in energy consumption, the cooling amount provided for each evaporatively cooled space was influenced by specific wind conditions based on the location of each space. The parametric analysis of the wind effect on every cooled space revealed the influence of the unwanted positive wind pressure on the exhaust opening under different climatic conditions, depending on the location and orientation of each space. This finding corresponds with previous findings in the case study analysis.

Research Question 4: Can the PDEC efficiency and thermal performance be improved by altering the architectural design of coupled spaces' openings?

The issues associated with this question were addressed in the third stage in chapter seven. The integration of a PDEC tower in a typical Saudi dwelling in IES-VE and the assessment of its performance indicated the possibility of further cooling energy reduction by reducing the unwanted wind pressure on the exhaust openings. Modifying and improving the window openings design of the cooled spaces could enhance the cooling performance of the PDEC tower, which would ultimately increase cooling energy-savings and thermal comfort levels. The analysis in stage one and two of this research were taken into account when answering this question. However, the case of the house required a more detailed analysis as every space linked to the PDEC tower had different characteristics in terms of size, design, and location. Hence, a parametric analysis of the window design for every space linked to the PDEC tower was performed.

The parametric analysis was conducted in two stages: (1) the PDEC case parametric analysis, and (2) the developed case parametric analysis. The PDEC case involved analysis and possible improvements of the existing window design openings without further modification. The parameters included an openable window area, opening operation control, and spray control (on/off). The room occupancy, wind effect, and indoor temperature were considered when assessing these parameters. The best-case scenario in terms of energy consumption and thermal performance was considered as the start point for the second stage of the analysis. Then, the second stage involved the addition of a X-shaped wind catcher layout, a buffer zone to the external windows, leeward openings, and roof openings. Five cases were discussed were major improvement was observed.

The analysis included the investigation of two different days scenarios followed by thermal performance and wind analysis effect for the entire period for every developed case. Opening area and control of opening schedule and PDEC in the analysis of the first stage improved the cooling performance for every space and achieved further cooling energy saving from 22.2% in the first PDEC case to 28.4% without modification to the window design. The addition extra architectural elements to the exhaust openings, such as the buffer zones, leeward openings, and roof 4-sided openings, significantly reduced the negative wind pressure for most of the summer. In the optimum case, a buffer zone with top leeward openings was added to the north side openings for the male guest room and master bedroom while the air in the living room was exhausted by the added roof 4-sided openings. This modification to the openings' designs led to better cooling performance and a maximum energy reduction of up to 36.2%, considering that the PDEC was connected to only 50% of the functional space's area and running continuously. To enhance the thermal comfort level, additional control to operation times of both the PDEC tower and windows was applied as indoor temperatures reached as low as 17^{o}C during night hours in May and September. This enhancement in thermal comfort led to a reduction in cooling energy saving of nearly 2%. However, the indoor temperature became more stable and comfortable. Thermal comfort was analysed using both the adaptive thermal comfort (ATC) model and Fanger Predicted Mean Vote (PMV) model. The results of the analysis indicated that high thermal comfort levels could be achieved for each room with significantly less energy consumption.

8.4 LIMITATION OF THE STUDY

The scope of this study was limited to the assessment of the PDEC performance in the context of Saudi Arabia. The analysis and assessment were restricted to three main indicators: cooling performance, energy consumption, and thermal comfort. The research was undertaken in three main stages and bounded by a number of limitations. Limitations of the study varied for each stage. During the first stage, limitations included that not all the library sections were accessible, such as the women’s section, due to privacy and religious reasons. In addition, all the library was operated on just one electricity meter. As a result, energy performance analysis was neglected due to the difficulty of acquiring the energy consumption of the monitored part of the library.

In the second stage, it was difficult to validate the PDEC model against real data from Saudi Arabia. All the existing and known PDEC buildings were using wetted-pads systems. So, it was not possible to use these case studies for the validation of the computational model as IES-VE simulates a spray system only. For that reason, the PDEC model was tested against experimental data derived from a European Union (EU) PDEC project obtained from Ford et al. (2010).

During the third stage, the selected case study villa was located in Hail rather than Riyadh, although the weather conditions are very similar in both Hail and Riyadh (see Figure 6-7). The selection of the specified case study villa was considered for several factors, including accessibility, building age, building geometry and design, building size (area). Despite the granted accessibility to install the data-loggers and acquire the architectural and construction details, it was not possible to engage with the house users and conduct a post-occupancy evaluation to collect data associated with their use of the house. As a result, several inputs were assumed, such as occupancy profiles, and household appliances usage. Moreover, considering the research method followed in this stage, other factors were assumed, such as people gain, clothing levels and metabolic rates. Hence, thermal comfort analysis was predicted based on assumptions considered according to the type of each occupied space.

Because of the significant amount of time consumed in the monitoring and analysis process, water consumption analysis was excluded and suggested as a future research opportunity. Moreover, the energy consumption issue and the need for cooling in the extremely hot climate of Saudi Arabia have driven the research to focus more on cooling and energy performance.

8.5 OPPORTUNITIES FOR FUTURE WORK

It is evident that new research studies are developed based on previous research and findings. In the field of passive cooling, particularly PDEC towers, there are many research opportunities worthy of investigation. The limited number of PDEC applications around the world, despite its successful performance, the advantages and disadvantages, and strength and weaknesses of cooling performance associated with its climatic dependency raise many other research questions that need answers. In terms of this research, the cooling performance, expected energy-saving and thermal comfort achieved by PDEC towers for Saudi housing had been investigated and discussed. The findings have revealed other opportunities for further studies. Future studies in this field could include:

- Water is a very significant resource as energy, particularly in environments where PDEC is mostly applicable, hot and arid. Due to the amount of time consumed to perform cooling and energy performance analysis in this study, water consumption analysis was excluded. Hence, it would be one of the most valuable opportunities and a contribution to the knowledge to conduct water studies and analysis in this field in the future.
- This research mainly concentrated on the bulk airflow of the PDEC performance on a building scale. The study was more focused to conduct a practical analysis of the effect of a building on the PDEC performance. The analysis revealed a significant influence of the buildings opening architectural design on the overall performance of the attached PDEC tower due to wind effects. As a result, it should be suggested that detailed computational fluid dynamics (CFD) analysis could provide a further understanding of the effect of wind on the PDEC and occupied spaces. Such analysis would provide detailed assessment and understanding of the airflow patterns on a small scale.
- Following a theoretical CFD analysis, a detailed full-scale experimental analysis could be performed to examine different design configurations of inlet and outlet openings of both the PDEC tower and the coupled space/building.
- Full and detailed monitoring and analysis of an existing and different PDEC case studies involving cooling performance and energy consumption in Saudi Arabia.
- Post-occupancy evaluation and thermal comfort analysis of users of PDEC buildings in Saudi Arabia.
- Since the PDEC analysis in this study was considered for the main functional spaces in the house, expanding the analysis of the PDEC to all the functional spaces in a house would provide a full perspective of the expected total energy saving achieved by PDEC systems in housing.

- Integrating PDEC towers with other passive, environmental, and energy-saving measures, such as thermal insulation, and renewable energy would be a good area of investigation.
- Considering the significant potential energy savings achieved by the PDEC tower in housing, the next steps could involve the focus on developing a zero-energy house, particularly when integrating the PDEC tower with other low energy measures.

Based on the different and specific research areas mentioned above, a key research opportunity would include the design of framework and strategies of the application and implementations of such energy-efficient and low carbon passive system. Such a project will require a multi-disciplinary research team supported by the cooperation of different organisations associated with the building industry.

REFERENCES

Abdul Mujeebu, M. and Alshamrani, O. S. (2016) ‘Prospects of energy conservation and management in buildings - The Saudi Arabian scenario versus global trends’, *Renewable and Sustainable Energy Reviews*. Elsevier, pp. 1647–1663. doi: 10.1016/j.rser.2015.12.327.

Al-Hassawi, O. D. S. (2017) *Advancing Performance of Passive Downdraft Cooling Towers*. ARIZONA STATE UNIVERSITY.

Al-Hassawi, O. D. S. (2020) ‘Advancing performance of passive downdraft cooling: results from built prototypes of single stage and hybrid downdraft cooling towers’, *Architectural Science Review*. Taylor & Francis, 0(0), pp. 1–11. doi: 10.1080/00038628.2020.1731677.

Al-hemiddi, N. A. M. (1995) *Passive Cooling Systems Applicable for Buildings in the Hot-Dry Climate of Saudi Arabia*. University of California, Los Angeles.

Al-Sanea, S. A. *et al.* (2016) ‘Optimum R-values of building walls under different climatic conditions in the Kingdom of Saudi Arabia’, *Applied Thermal Engineering*. Elsevier Ltd, 96, pp. 92–106. doi: 10.1016/j.applthermaleng.2015.11.072.

Al-Saud, K. A. M., & Al-Hemiddi, N. A. M. (1999) ‘Cooling Towers and their Effect on Mosque Thermal Performance Case Study: Al-Rahmania Mosque Al-Jouf’, in *the Symposium on Mosque Architecture.* Riyadh, Kingdom of Saudi Arabia: College of Architecture & Planning, King Saud University, pp. 25–40. Available at: https://cap.ksu.edu.sa/en/SMA_V6.

Al-Tamimi, N. (2017) ‘A state-of-the-art review of the sustainability and energy efficiency of buildings in Saudi Arabia’, *Energy Efficiency*, pp. 1129–1141. doi: 10.1007/s12053-017-9507-6.

Alaidroos, A. A. (2016) *THERMAL ANALYSIS OF VENTILATED WALL CAVITIES WITH SPRAY EVAPORATIVE COOLING SYSTEMS*. University of Colorado Boulder.

Alaidroos, A. and Krarti, M. (2016a) 'Experimental validation of a numerical model for ventilated wall cavity with spray evaporative cooling systems for hot and dry climates', *Energy and Buildings*. Elsevier B.V., 131, pp. 207–222. doi: 10.1016/j.enbuild.2016.09.035.

Alaidroos, A. and Krarti, M. (2016b) 'Numerical modeling of ventilated wall cavities with spray evaporative cooling system', *Energy & Buildings*. Elsevier B.V., 130, pp. 350–365. doi: 10.1016/j.enbuild.2016.08.046.

Alaidroos, A. and Krarti, M. (2017) 'Optimized controls for ventilated wall cavities with spray evaporative cooling systems', *Energy and Buildings*, 154. doi: 10.1016/j.enbuild.2017.08.076.

Alrashed, F. A. (2015) 'Design and application of zero-energy homes in Saudi Arabia'. Glasgow Caledonian University.

Alrashed, F. and Asif, M. (2015) 'Analysis of critical climate related factors for the application of zero-energy homes in Saudi Arabia', *Renewable and Sustainable Energy Reviews*. Elsevier, 41, pp. 1395–1403. doi: 10.1016/j.rser.2014.09.031.

Alvarez, S. *et al.* (1991) 'Full scale experiments in EXPO '92 the bioclimatic rotunda', in *PLEA Ninth Conference Proceedings*.

Amer, E. H. (2006) 'Passive options for solar cooling of buildings in arid areas', *Energy*, 31(8–9), pp. 1332–1344. doi: 10.1016/j.energy.2005.06.002.

Amer, O., Boukhanouf, R. and Ibrahim, H. G. (2015) 'A Review of Evaporative Cooling Technologies', *International Journal of Environmental Science and Development*, 6(2), pp. 111–117. doi: 10.7763/ijesd.2015.v6.571.

Amran, Y. H. A. *et al.* (2020) 'Renewable and sustainable energy production in Saudi Arabia according to Saudi Vision 2030; Current status and future prospects', *Journal of Cleaner Production*. Elsevier Ltd, 247, p. 119602. doi: 10.1016/j.jclepro.2019.119602.

Antinucci, M. *et al.* (1992) 'Passive and hybrid cooling of buildings - state of the art', *International Journal of Solar Energy*, 11(3–4), pp. 251–271. doi: 10.1080/01425919208909744.

ArchDaily (2014) *Spanish Pavilion Expo Zaragoza 2008 / Francisco Mangado | ArchDaily*. Available at: https://www.archdaily.com/479306/pabellon-de-espana-para-la-exposicion-internacional-zaragoza-08-francisco-mangado?ad_medium=widget&ad_name=navigation-next (Accessed: 3 April 2020).

ArchDaily (2020) *AD Classics: Frederick C. Robie House / Frank Lloyd Wright | ArchDaily*. Available at: https://www.archdaily.com/60246/ad-classics-frederick-c-robie-house-frank-lloyd-wright (Accessed: 23 February 2020).

ArchitectureAU (2020) *Interactive Learning | ArchitectureAU*. Available at: https://architectureau.com/articles/interactive-learning/ (Accessed: 1 April 2020).

ASHRAE (2009) ‘Handbook-Fundamentals’, *American society of Heating Refrigerating and Air-Conditioning Engineers*.

ASHRAE (2010) ‘Thermal environmental conditions for human occupancy, ASHRAE standard 55-2010’. Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Attia, S., Hensen, J. L. M., *et al.* (2012) ‘Selection criteria for building performance simulation tools: Contrasting architects’ and engineers’ needs’, *Journal of Building Performance Simulation*. doi: 10.1080/19401493.2010.549573.

Attia, S., Gratia, E., *et al.* (2012) ‘Simulation-based decision support tool for early stages of zero-energy building design’, *Energy and Buildings*. doi: 10.1016/j.enbuild.2012.01.028.

Awbi, H. B. (1996) ‘Air movement in naturally-ventilated buildings’, Renewable Energy 8, Issues 1–4, Pages 241-247

Bahadori, M. N. (1978) ‘Passive cooling systems in Iranian architecture’, *Scientific*

American. JSTOR, 238(2), pp. 144–155.

Bahadori, M. N. (1979) ‘Natural cooling in hot arid regions’, in *Solar energy application in buildings*. Elsevier, pp. 195–225.

Bahadori, M. N. (1985) ‘An improved design of wind towers for natural ventilation and passive cooling’, *Solar Energy*. doi: 10.1016/0038-092X(85)90002-7.

Bahadori, M. N. (1994) ‘Viability of wind towers in achieving summer comfort in the hot arid regions of the middle east’, *Renewable Energy*, 5(5–8), pp. 879–892. doi: 10.1016/0960-1481(94)90108-2.

Batty, W. J., Al-Hinai, H. and Probert, S. D. (1991) ‘Natural-cooling techniques for residential buildings in hot climates’, *Applied Energy*, 39(4), pp. 301–337. doi: 10.1016/0306-2619(91)90002-F.

Belarbi, R., Ghiaus, C. and Allard, F. (2006) ‘Modeling of water spray evaporation: Application to passive cooling of buildings’, *Solar Energy*, 80(12), pp. 1540–1552. doi: 10.1016/j.solener.2006.01.004.

Bowman. *et al.* (1997) ‘Application of Passive Downdraught Evaporative Cooling (PDEC) to Non-Domestic Buildings’, *Renewable Energy*, 10(2/3), pp. 191–196. doi: 10.1016/0960-1481(96)00062-6.

Bowman *et al.* (1997) *APPLICATION OF PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING (PDEC) TO NON-DOMESTIC BUILDINGS*.

Bowman, N. T. *et al.* (2000) ‘Passive downdraught evaporative cooling: I. Concept and precedents’, *Indoor and Built Environment*. doi: 10.1159/000057521.

BP (2020) Statistical Review of World Energy 2020, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

Buckley, L. (2014) ‘Simulating a Passive Downdraft Evaporative Cool Tower’.

Cain, A. *et al.* (1976) ‘Traditional Cooling Systems in the Third World’, *The Ecologist*, 6(2), pp. 60-.

Carew, P. and Joubert, G. (2006) ‘Shower tower, miele showroom, Johannesburg South Africa’, in *PLEA 2006 - 23rd International Conference on Passive and Low Energy Architecture, Conference Proceedings*.

CBE (2020) *Global Ecology Research Center | Center for the Built Environment*. Available at: https://cbe.berkeley.edu/livable-building/global-ecology-research-center/ (Accessed: 24 February 2020).

Chalfoun, N. V. (1997) ‘Design and Application of Natural Down-Draft Evaporative Cooling Devices’, *26th American Solar Energy Society (ASES) and the 22nd National Passive Solar Annual Conference*.

Chan, H. Y., Riffat, S. B. and Zhu, J. (2010) ‘Review of passive solar heating and cooling technologies’, *Renewable and Sustainable Energy Reviews*, 14(2), pp. 781–789. doi: 10.1016/j.rser.2009.10.030.

Chiesa, G. *et al.* (2017) ‘Passive Downdraught Evaporative Cooling System Integration in Existing Residential Building Typologies: A Case Study’, in *Energy Procedia*. doi: 10.1016/j.egypro.2017.03.222.

Chiesa, G. and Grosso, M. (2015) ‘Direct evaporative passive cooling of building. A comparison amid simplified simulation models based on experimental data’, *Building and Environment*. Elsevier Ltd, 94(P1), pp. 263–272. doi: 10.1016/j.buildenv.2015.08.014.

Choudhary, S., Thakur, M. S. and Dogne, N. (2014) ‘Passive Cooling Techniques , Design Concept and Ventilation Passive Cooling Techniques , Design Concept and’, (March), pp. 4–11.

CIBSE (2005) *Natural ventilation in non-domestic buildings, CIBSE Applications Manual AM10*. doi: 10.1002/9781119951773.

CIBSE (2013) ‘The limits of thermal comfort : avoiding overheating in European buildings The limits of thermal comfort : avoiding overheating in European buildings, CEBSE TM52: 2013’.

Climate Consultant (2019a) ‘Climate Consultant Software’. Available at: http://www.energy-design-tools.aud.ucla.edu/climate-consultant/request-climate-consultant.php (Accessed: 15 October 2019).

Climate Consultant (2019b) ‘Climate Consultant Software’.

Cook, J. (1989) *Passive cooling*. Arizona State Univ., Tempe, AZ (USA).

Cook, M. J. *et al.* (2000) ‘Downdraught Evaporative Cooling’, *Indoor and Built Environment*, pp. 325–334.

Crawley, D. B. *et al.* (2008) ‘Contrasting the capabilities of building energy performance simulation programs’, *Building and Environment*. doi: 10.1016/j.buildenv.2006.10.027.

Cuce, P. M. and Riffat, S. (2016) ‘A state of the art review of evaporative cooling systems for building applications’, *Renewable and Sustainable Energy Reviews*. Elsevier, 54, pp. 1240–1249. doi: 10.1016/j.rser.2015.10.066.

Cui, W. *et al.* (2011) ‘Measurement and prediction of undisturbed underground temperature distribution’, *ASME 2011 International Mechanical Engineering Congress and Exposition, IMECE 2011*, 4(PARTS A AND B), pp. 671–676. doi: 10.1115/imece2011-63311.

Cunningham, W. A. and Thompson, T. (1986) ‘Passive Cooling with natural draft cooling towers in combination with solar chimneys’, in *Passive and Low Energy Architecture (PLEA)*. Hungary.

Dear, D. (2001) ‘The adaptive model of thermal comfort and energy conservation in the built environment’. doi: 10.1007/s004840100093.

Dear, D., Dear, R. J. De and Brager, G. S. (2002) ‘Thermal comfort in naturally ventilated buildings : revisions to ASHRAE Standard 55’.

Dear, D., Dear, R. J. De and Ph, D. (1998) 'Developing an Adaptive Model of Thermal Comfort and Preference'.

Delzendeh, E. *et al.* (2017) 'The impact of occupants ' behaviours on building energy analysis : A research review', *Renewable and Sustainable Energy Reviews*. Elsevier Ltd, 80(May), pp. 1061–1071. doi: 10.1016/j.rser.2017.05.264.

ECRA (2018) *Statistical Booklets*, *Electricity and Co-generation Regulatory Authority*. Available at: https://www.ecra.gov.sa/en-us/MediaCenter/doclib2/Pages/SubCategoryList.aspx?categoryID=5 (Accessed: 24 April 2020).

EIA (2017) *Country Analysis Brief: Saudi Arabia*.

EIA (2019) *International Energy Outlook 2019*. Available at: www.eia.gov/ieo (Accessed: 21 April 2020).

Elements (2019) *Elements | Big Ladder Software*. Available at: https://bigladdersoftware.com/projects/elements/ (Accessed: 5 November 2019).

EnergyPlus (2020) *Weather Data for Simulatio*. Available at: https://energyplus.net/weather/simulation (Accessed: 20 May 2020).

EPA (2019) *Overview of Greenhouse Gases (GHG) Emissions*, *United States Environmental Protection Agency*. Available at: https://www.epa.gov/ghgemissions/overview-greenhouse-gases (Accessed: 23 April 2020).

Etzion, Y. *et al.* (1997) 'Adaptive architecture: Integrating low-energy technologies for climate control in the desert', *Automation in Construction*. doi: 10.1016/S0926-5805(97)00020-4.

Felimban, A. *et al.* (2019) 'Assessment of Current Energy Consumption in Residential Buildings in Jeddah, Saudi Arabia', *Buildings*. Multidisciplinary Digital Publishing Institute, 9(7), p. 163.

Florides, G. and Kalogirou, S. (2005a) 'Annual ground temperature measurements at various depths', *8th REHVA World Congress, Clima*, pp. 1–6.

Florides, G. and Kalogirou, S. (2005b) 'Annual ground temperature measurements at various depths', *8th REHVA World Congress, Clima*, pp. 1–6. Available at: http://ktisis.cut.ac.cy/handle/10488/844.

Ford, Brian and Schiano-Phan, R. (2003) *Passive Downdraught Evaporative Cooling using Porous Ceramic in Non- Domestic buildings – Development of Key Components (Evapcool)*.

Ford, B. *et al.* (1998) 'COOLING WITHOUT AIR CONDITIONING The Torrent Research Centre , Ahmedabad , India', 15, pp. 177–182.

Ford, B. (2002) 'Passive downdraught evaporative cooling : principles and practice environmental design Passive downdraught evaporative cooling : principles and practice', 5(January 2002), pp. 271–280. doi: 10.1017/S1359135501001312.

Ford, B. (2012) 'Downdraught cooling: An overview of current research and practice', *Architectural Science Review*, 55(4), pp. 237–240. doi: 10.1080/00038628.2012.724953.

Ford, B. *et al.* (2012) 'Passive downdraught evaporative cooling: Performance in a prototype house', *Building Research and Information*, 40(3), pp. 290–304. doi: 10.1080/09613218.2012.669908.

Ford, B. and Diaz, C. (2003) 'Passive downdraft cooling: hybrid cooling in the Malta Stock Exchange', in *Bustamante, WG, Collados, B., 20th Plea International Conference: Rethinking Development: Are We Producing a People Oriented Habitat. Santiago, Chile, November*, pp. 9–12.

Ford, B., Schiano-Phan, R. and Francis, E. (2010) *The architecture & engineering of downdraught cooling: a design sourcebook*. Bologna, Italy: PHDC Press.

Ford, B., Schiano-Phan, R. and Vallejo, J. A. (2019) *The Architecture of Natural Cooling*. 2nd edn, *The Architecture of Natural Cooling*. 2nd edn. New York. doi:

10.4324/9781315210551.

Galatà, A. and Sciuto, S. (1997) ‘Passive Evaporative Cooling : the PDEC project’, (June), pp. 2–6.

GASTAT (2018a) *Housing Bulletin Semi Annual 2018 Bulletins Housing Statistics 2018*. Available at: https://www.stats.gov.sa/sites/default/files/housing_bulletin_semi_annual_2018_en.pdf (Accessed: 25 April 2020).

GASTAT (2018b) *Water consumption in Saudi Arabia from 2014 to 2018*, *General Authorty of Statestics*. Available at: https://www.stats.gov.sa/sites/default/files/nsb_lmyh_ljwfy_gyr_lmtjdd_mn_jmly_lmyh_lmsthlk_2013-2017_m.pdf (Accessed: 17 September 2020).

GASTAT (2019) *Housing Statistics Bulletin*. Available at: https://www.stats.gov.sa/en/911-0.

Geetha, N. B. and Velraj, R. (2012) ‘Passive cooling methods for energy efficient buildings with and without thermal energy storage - A review’, *Energy Education Science and Technology Part A: Energy Science and Research*, 29(2), pp. 913–946.

Givoni, B. (1983) ‘Review of passive heating and cooling research’, in *Passive and Low Energy Architecture*. Elsevier, pp. 339–352.

Givoni, B. (1991) ‘Performance and applicability of passive and low-energy cooling systems’, *Energy and Buildings*, 17(3), pp. 177–199. doi: 10.1016/0378-7788(91)90106-D.

Givoni, B. (1994) *Passive and low energy cooling of buildings*, *Choice Reviews Online*. doi: 10.5860/choice.32-2759.

Givoni, B. (1995) *Passive and low energy cooling of buildings*, *Choice Reviews Online*. doi: 10.5860/choice.32-2759.

Givoni, B. (1997) ‘Performance of the “Shower” cooling tower in different climates’, *Renewable Energy*. doi: 10.1016/0960-1481(96)00059-6.

Givoni, B. (1998) ‘Climate considerations in building and urban design’, *Building*.

Google Maps (2019a) *Hail - Google Maps*. Available at: https://www.google.com/maps/place/Hail+Saudi+Arabia/@27.5211967,41.6054804,52254m/data=!3m1!1e3!4m5!3m4!1s0x157646e696d0faa3:0xa823a286278a8880!8m2!3d27.5114102!4d41.7208243 (Accessed: 15 October 2019).

Google Maps (2019b) *Hail - Google Maps*.

Gratia, E. and De Herde, A. (2007) ‘Guidelines for improving natural daytime ventilation in an office building with a double-skin facade’, *Solar Energy*, 81(4), pp. 435–448. doi: 10.1016/j.solener.2006.08.006.

Guerra-Santin, O. and Tweed, C. A. (2015) ‘In-use monitoring of buildings: An overview of data collection methods’, *Energy and Buildings*. Elsevier B.V., 93, pp. 189–207. doi: 10.1016/j.enbuild.2015.02.042.

Al Harbi, F. and Csala, D. (2019) ‘Saudi Arabia’s Electricity: Energy Supply and Demand Future Challenges’, in *Proceedings - 2019 IEEE 1st Global Power, Energy and Communication Conference, GPECOM 2019*. doi: 10.1109/GPECOM.2019.8778554.

Hassan, H. and Sumiyoshi, D. (2017) ‘Environmental Science and Sustainable Development Evaluation of Basement’s Thermal Performance against Thermal’, *International Journal of Environmental Science & Sustainable Development*, 1(2), pp. 24–38. doi: 10.21625/essd.v1i2.26.

Hens, H., Parijs, W. and Deurinck, M. (2010) ‘Energy consumption for heating and rebound effects’, *Energy and Buildings*, 42(1), pp. 105–110. doi: 10.1016/j.enbuild.2009.07.017.

Hong, T. *et al.* (2016) ‘Advances in research and applications of energy-related occupant behavior in buildings ☆’, *Energy & Buildings*. Elsevier B.V., 116, pp. 694–702. doi:

10.1016/j.enbuild.2015.11.052.

Humphreys, M. (2015) *Adaptive Thermal Comfort: Foundations and Analysis*, *Adaptive Thermal Comfort: Foundations and Analysis*. doi: 10.4324/9781315765815.

ICOS (2019) https://www.icos-cp.eu/global-carbon-budget-2019 (Accessed: 22 April 2020).

IEA (2018a) *Cooling - Fuels & Technologies - IEA, International Energy Agency*. Available at: https://www.iea.org/fuels-and-technologies/cooling (Accessed: 22 April 2020).

IEA (2018b) *Emissions – Global Energy & CO2 Status Report 2019 – Analysis - IEA, International Energy Agency*. Available at: https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions#abstract (Accessed: 22 April 2020).

IEA (2019) *Energy Atlas, International Energy Agency*. Available at: http://energyatlas.iea.org/#!/tellmap/1378539487 (Accessed: 23 April 2020).

IES (2015a) 'Apache-Tables User Guide'. Available at: http://www.iesve.com/support/userguides.

IES (2015b) 'ApacheView user guide'. Available at: https://www.iesve.com/downloads/help/VE2015/Thermal/ApacheView.pdf.

IES (2016) 'ApacheHVAC User Guide Part B: Equipment, Loops, Components, and Controls'.

IES (2019) *Software Validation and ApprovaL, IES Virtual Environment*. Available at: https://www.iesve.com/software/software-validation (Accessed: 18 May 2020).

IES (2020) *Integrated Environmental Solutions | IES*. Available at: https://www.iesve.com/ (Accessed: 14 May 2020).

IES Validation results (2019) *Software Validation and Approval | Integrated Environmental Solutions*. Available at: https://www.iesve.com/software/software-validation (Accessed: 5 November 2019).

IPCC (2019) *Global warming of 1.5°C, The Intergovernmental Panel on Climate Change*. Available at:

https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf (Accessed: 21 April 2020).

Jain, P. K. and Dewan, S. B. (1990) *A Performance Comparison of Full- and Half-Bridge Series Resonant Inverters in High-Frequency High-Power Applications*, *IEEE Transactions on Industry Applications*. doi: 10.1109/28.54258.

Jani, D. B. (2019) 'An overview on passive cooling systems in green building architectures', *Open Journal of Architectural Engineering*, pp. 1–15. doi: https://doi.org/10.36811/ojae2019.110001.

Jani, D. B., Mishra, M. and Sahoo, P. K. (2016) 'Solid desiccant air conditioning - A state of the art review', *Renewable and Sustainable Energy Reviews*. Elsevier, 60, pp. 1451–1469. doi: 10.1016/j.rser.2016.03.031.

Kamal, M. A. (2012) 'An Overview of Passive Cooling Techniques in Buildings: Design Concepts and Architectural Interventions', *Civil Engineering & Architecture*, 55(1), pp. 84–97.

Kang, D. (2011) *Advances in the Application of Passive Down-Draft Evaporative Cooling Technology in the Cooling of Buildings*. University of Illinois at Urbana-Champaign.

Kang, D. and Strand, R. K. (2009) 'Simulation of passive down-draught evaporative cooling (pdec) systems in energyplus', in *IBPSA 2009 - International Building Performance Simulation Association 2009*.

Kang, D. and Strand, R. K. (2013) 'Modeling of simultaneous heat and mass transfer within passive down-draft evaporative cooling (PDEC) towers with spray in FLUENT', *Energy and Buildings*, 62. doi: 10.1016/j.enbuild.2013.02.039.

Kang, D. and Strand, R. K. (2016) ‘Significance of parameters affecting the performance of a passive down-draft evaporative cooling (PDEC) tower with a spray system’, *Applied Energy*, 178. doi: 10.1016/j.apenergy.2016.06.055.

Kassir, R. M. (2016) ‘Passive downdraught evaporative cooling wind-towers: A case study using simulation with field-corroborated results’, *Building Services Engineering Research and Technology*, 37(1), pp. 103–120. doi: 10.1177/0143624415603281.

Kavanaugh, S. P. and Rafferty, K. (1997) ‘Ground-source heat pumps: Design of geothermal systems for commercial and institutional buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers’, *Inc., Atlanta, GA*.

Krarti, M., Dubey, K. and Howarth, N. (2017) ‘Evaluation of building energy efficiency investment options for the Kingdom of Saudi Arabia’, *Energy*. Elsevier Ltd, 134, pp. 595–610. doi: 10.1016/j.energy.2017.05.084.

Lechner, N. (2015) *Heating, Cooling, Lighting : Sustainable Design Methods for Architects*, *Wiley*. doi: 10.1109/28.54258.

Lewis Thompson, T., Chalfoun, N. V. and Yoklic, M. R. (1994) ‘Estimating the performance of natural draft evaporative coolers’, *Energy Conversion and Management*. doi: 10.1016/0196-8904(94)90022-1.

Maile, T., Fischer, M. and Bazjanac, V. (2007) ‘Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective’, *Center for integrated facility engineering*.

De Melo, A. C. M. and Guedes, M. C. (2006) ‘Passive Downdraught Evaporative Cooling applied on existing fabric: Using traditional chimney as case study in Portugal’, *PLEA 2006 - 23rd International Conference on Passive and Low Energy Architecture, Conference Proceedings*, (September), pp. 6–8.

Meteonorm (2019a) *Meteonorm (en)*. Available at: https://meteonorm.com/en/ (Accessed: 15 October 2019).

Meteonorm (2019b) *Meteonorm (en)*.

MOH (2018) *Completion Reports | Ministry of Housing, Ministry of Housing*. Available at: https://www.housing.gov.sa/en/reports (Accessed: 25 April 2020).

MOMRA (2019) *Statistics - Portal of the Ministry of Municipal and Rural Affairs, CONSTRUCTION PERMITS*. Available at: https://www.momra.gov.sa/ar/open-data/70 (Accessed: 25 April 2020).

Monawar, A. H. (2001a) 'A Study of Energy Conservation in the Existing Apartment Buildings in Makkah Region , Saudi Arabia', *PhD Thesis, School of Architecture, Planning & Landscape, University of Newcastle upon Tyne, United Kingdom.* Available at: https://theses.ncl.ac.uk/dspace/handle/10443/950.

Monawar, A. H. (2001b) 'A Study of Energy Conservation in the Existing Apartment Buildings in Makkah Region , Saudi Arabia', *PhD Thesis, School of Architecture, Planning & Landscape, University of Newcastle upon Tyne, United Kingdom.*

Nadarajan, M. and Kirubakaran, V. (2016) 'Simulation tools for residential buildings-A review on concepts and technologies', *ARPN Journal of Engineering and Applied Sciences*, 11(5), pp. 2998–3007.

Paul, M., John, R. and Dear, D. (2012) 'Mixed-mode buildings : A double standard in occupants ' comfort expectations', *Building and Environment*. Elsevier Ltd, 54, pp. 53–60. doi: 10.1016/j.buildenv.2012.01.021.

Pearlmutter, D. *et al.* (1996) 'Refining the use of evaporation in an experimental down-draft cool tower', *Energy and Buildings*, 23(3), pp. 191–197. doi: 10.1016/0378-7788(95)00944-2.

Pearlmutter, D., Erell, E. and Etzion, Y. (2008) 'A multi-stage down-draft evaporative cool tower for semi-enclosed spaces: Experiments with a water spraying system', *Solar Energy*. doi: 10.1016/j.solener.2007.12.003.

Pearlmutter, D., Etzion, Y. and Erell, E. (2006) 'A multi-stage down-draft evaporative cool tower for semi-enclosed spaces. Part II: Water spraying system', in *PLEA 2006 - 23rd International Conference on Passive and Low Energy Architecture, Conference Proceedings*.

Peel, M. C., Finlayson, B. L. and McMahon, T. A. (2007) 'Updated world map of the Köppen-Geiger climate classification', *Hydrology and Earth System Sciences*, 11(5), pp. 1633–1644. doi: 10.5194/hess-11-1633-2007.

Qiu, J., Li, B. F. and Qiu, Y. (2013) 'Review of passive downdraught evaporative cooling technique and its application', *Applied Mechanics and Materials*, 390, pp. 691–695. doi: 10.4028/www.scientific.net/AMM.390.691.

Raja, I. A. *et al.* (2001) 'Thermal comfort: Use of controls in naturally ventilated buildings', *Energy and Buildings*, 33(3), pp. 235–244. doi: 10.1016/S0378-7788(00)00087-6.

Robinson, D. *et al.* (2004) 'Passive Down-Draught Evaporative Cooling: Thermal Modelling of an Office Building', *Indoor and Built Environment*, 13(3), pp. 205–221. doi: 10.1177/1420326X04043816.

Salmerón, J. M. *et al.* (2012) 'Analysis of a PHDC (Passive and Hybrid Downdraft Cooling) experimental facility in Seville and its applicability to the Madrid climate', *International Journal of Ventilation*, 10(4), pp. 391–404. doi: 10.1080/14733315.2012.11683964.

Santamouris, M. (2007) *Advances in passive cooling*, *Advances in Passive Cooling*. doi: 10.4324/9781849773966.

Santamouris, M. and Asimakopolous, D. (1996) *Passive Cooling of Buildings*. London: James & James Ltd.

SASO (2014) *Thermal transmittance values for residential buildings based on SASO 2856 / 2014-Saudi Standards Metrology and Quality Organization*. KSA.

Saudi Vision 2030 (2020). Available at: https://vision2030.gov.sa/en (Accessed: 21

September 2020).

Schiano-Phan, R. and Ford, B. (2003) ‘Evaporative cooling using porous ceramic evaporators: product development and generic building integration’, in *PLEA 2003: the 20th conference on passive & low energy architecture*. Santiago, Chile,: PLEA.

Schiano-phan, R. (2004) ‘The Development of Passive Downdraught Evaporative Cooling Systems Using Porous Ceramic Evaporators and their application in residential buildings’, in *Conference on Passive and Low Energy Architecture*.

Schiano-Phan, R. (2010) ‘Environmental retrofit: Building integrated passive cooling in housing’, *Architectural Research Quarterly*. doi: 10.1017/S1359135510000758.

Schiano-Phan, R. (2012) ‘Post-occupancy evaluation of non-domestic buildings using passive downdraught evaporative cooling in south-west USA’, *Architectural Science Review*. doi: 10.1080/00038628.2012.725535.

Schiano-Phan, R. and Ford, B. (2008) ‘Post occupancy evaluation of non-domestic buildings using downdraught cooling: Case studies in the US’, in *PLEA 2008 - Towards Zero Energy Building: 25th PLEA International Conference on Passive and Low Energy Architecture, Conference Proceedings*.

Schiano-phan R (2010) ‘Integrated passive cooling in housing’, *Architectural Research Quarterly*, 14(2), pp. 139–151.

SEC (2016) *THERMAL INSULATION IN BUILDINGS-Saudi Electricity Company*.

SEC (2019) *Saudi Electricity Company*. Available at: https://www.se.com.sa/en-us/Pages/home.aspx (Accessed: 24 October 2019).

SEEC (2018) *BUILDINGS | Saudi Energy Efficiency Center*, *Saudi Energy Efficiency Center*. Available at: https://www.seec.gov.sa/en/blog/buildings (Accessed: 24 April 2020).

Al Surf, M. S. and Mostafa, L. A. (2017) ‘Will the Saudi’s 2030 Vision Raise the Public

Awareness of Sustainable Practices?', *Procedia Environmental Sciences*, 37, pp. 514–527. doi: 10.1016/j.proenv.2017.03.026.

SWCC (2017) *Annual Statestical Booklet for Operation and Maintenance Sector*, *CorporationSaline Water Conversion*. Available at: https://www.swcc.gov.sa/Arabic/MediaCenter/SWCCPublications/PUBLICATION FILES/SWCC ANNUAL REPORT 20167D50FCD7-D599-493B-8B42-D24BBEACF444.PDF (Accessed: 17 September 2020).

Taleb, H. M. and Sharples, S. (2011) 'Developing sustainable residential buildings in Saudi Arabia : A case study', *Applied Energy*. Elsevier Ltd, 88(1), pp. 383–391. doi: 10.1016/j.apenergy.2010.07.029.

Ten, A. (2020) *The Earth Centre Galleries – Atelier Ten*. Available at: https://www.atelierten.com/projects/the-earth-centre-galleries/ (Accessed: 25 February 2020).

Thomas, L. and Baird, G. (2006) 'Post-occupancy evaluation of passive downdraft evaporative cooling and air-conditioned buildings at Torrent Research Centre, Ahmedabad, India', *Australian and New Zealand Architectural Science Association (ANZAScA) Annual Conference - Challenges for Architectural Science in Changing Climates*, (February 2015).

Torcellini, P. a *et al.* (2004) 'Lessons Learned from Field Evaluation of Six High-Performance Buildings', *ACEEE Summer study on energy efficiency in buildings*, (July).

Torcellini, P., Judkoff, R. and Hayter, S. (2002) 'Zion National Park visitor center: significant energy savings achieved through a whole-building design process', (July).

UCS (2017) *Each Country's Share of CO2 Emissions*, *Union of Concerned Scientists*. Available at: https://www.ucsusa.org/resources/each-countrys-share-co2-emissions (Accessed: 22 April 2020).

UCS (2018) *Climate Impacts*, *Union of Concerned Scientists*. Available at: https://www.ucsusa.org/climate/impacts (Accessed: 23 April 2020).

Watt, J. R. (1986) *Evaporative Air Conditioning Handbook, Evaporative Air Conditioning Handbook*. doi: 10.1007/978-1-4613-2259-7.

Webster-mannison, M. (2003) 'Cooling rural Australia: passive downdraught evaporative cooling', *The Official Journal of the Australian Institute of Refrigeration, Air Conditioning and Heating*.

Weytjens, L. *et al.* (2011) 'The "architect-friendliness" of six building performance simulation tools: A comparative study', *International Journal of Sustainable Building Technology and Urban Development*. doi: 10.5390/SUSB.2011.2.3.237.

World Bank (2014) *CO2 emissions (metric tons per capita) - Saudi Arabia, European Union, United Kingdom, United States | Data*. Available at: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?contextual=default&end=2014&locations=SA-EU-GB-US&name_desc=false&start=1998&view=chart+%28Accessed%3A+31+January+2020%29. (Accessed: 24 April 2020).

World Architecture (2018) *A Tribute To Nimish Patel - A Noted Indian Architect & Conservationist*. Available at: https://worldarchitecture.org/article-links/epfnm/a_tribute_to_nimish_patel__a_noted_indian_architect_conservationist.html (Accessed: 6 April 2020).

Yan, D. *et al.* (2015) 'Occupant behavior modeling for building performance simulation: Current state and future challenges', *Energy and Buildings*. Elsevier, 107, pp. 264–278.

APPENDICES

Appendix (A). Published papers

PLEA 2018 HONG KONG

Smart and Healthy within the 2-degree Limit

Investigating the Impact of Architectural Form and Wind Direction on the Performance of a Passive Downdraught Evaporative Cooling Tower in Saudi Arabia

MOHAMMAD A. ALSHENAIFI[1], STEVE SHARPLES[1]

[1]University of Liverpool, Liverpool, UK

ABSTRACT: Buildings in Saudi Arabia consumes approximately 80% of the electricity generated in the country. Saudi Arabia's hot, arid climate, with summer temperatures frequently exceeding 45°C, means that air conditioning uses nearly 50% of the country's electricity, and virtually all the electricity is generated from fossil fuels. Passive cooling techniques could be a sustainable alternative to conventional air-conditioning systems when integrated properly within a building. A Passive Downdraught Evaporative Cooling (PDEC) tower is considered as one of the most efficient passive systems and was investigated in this study. A single storey open plan room with a PDEC tower was digitally modelled and then changes in wind direction and architectural form were simulated to see the effect on the PDEC performance. IES VE software was selected for the simulations as it can conduct a dynamic thermal simulation for PDEC systems. A weather file for Riyadh was obtained from the software Meteonorm. The study demonstrated that significant cooling can be achieved by PDEC towers, but that their effectiveness was greatly reduced by changes in wind direction linked to opening distributions in the room attached to the PDEC tower.

KEYWORDS: Passive Cooling, Passive Downdraught Evaporative Cooling, Cool Towers, Buffer Zone

1. INTRODUCTION

In 2016 Saudi Arabia was the largest oil consuming nation in the Middle East, and 10th in the world, with a total consumption of approximately 3.9 million barrels per day (b/d). The average direct burn of crude oil for power generation is more than 700,000 b/d during the summer months [1]. Buildings consume approximately 80% of the total electricity generated, and air conditioning represent most of that consumption [1]. It is obvious that buildings play a substantial role in Saudi Arabia's energy consumption. Passive cooling systems can significantly reduce cooling demand for buildings. This study investigated one such cooling system – the Passive Downdraught Evaporative Cooling (PDEC) tower – and assessed how architectural form and wind direction affect the performance of a PDEC system in a Saudi summer.

2. LITERATURE AND BACKGROUND

The term 'passive cooling' describes a process that relies on a natural environmental heat sink to achieve cooling. Passive cooling strategies can be classified to four major types based on the natural heat sinks: (i) Natural ventilation (night ventilation), (ii) night sky radiation, (iii) ground cooling, (iv) evaporative cooling [2]. Passive Downdraught Evaporative Cooling (PDEC) towers are categorized as a direct evaporative cooling technique. When hot dry air passes through a water medium, the evaporation of the water occurs as sensible heat is converted into latent heat, and the air temperature decreases as the relative humidity level increases. A PDEC tower consists of a wind catcher at the top of a tower, an evaporative/water medium, and a shaft to deliver the caught, cooled air to an occupied space via openings at the bottom of the tower. Hot and arid climatic regions provide an ideal environment for PDEC systems, and an up to 80% reduction of wet bulb depression (WBD) can be produced, which would ultimately lead to a significant reduction in cooling energy consumption [3]. Contemporary applications of PDEC towers can be classified as four different types based on the evaporation method [3]:

Cool towers (wetted pads).
Shower towers (large droplets of spray)
PDEC with wetted porous ceramic
Misting towers (misting nozzles)

In this study, the PDEC with misting approach was used. The flexibility to control water pressure and droplet size in this technique makes it the most efficient among the various options [3]. A smaller droplet size increases the evaporation rate, which leads to a higher amount of cooling.

Due to the climatic dependency of the PDEC system, several factors can affect PDEC performance. These factors include climate, the tower geometry, the tower height, water droplet size, water flow rate and the evaporation technique. Several recent studies have investigated, analytically and experimentally, some of these factors [4,5]. However, most studies have treated the PDEC tower as a standalone structure. In

294

this study the tower was coupled to a large room and openings in the room were altered to see the influence of the attached building's architectural form on PDEC performance.

2.1 PDEC case study with misting nozzles

The Torrent Research Centre in Ahmadabad, India involved the first large application of misting nozzles spraying in to the top of a tower inlet. The Centre had incorporated the PDEC system in to four buildings. In each building the PDEC system was located above a central atrium separating offices from laboratories. When the outside temperature reached its maximum, the PDEC could reduce the interior temperature by between 10 to 15°C. The system has achieved a 64% energy savings in cooling demand when compared to a conventional air conditioning system [6].

2.2 Climate of Riyadh, Saudi Arabia

Riyadh, latitude 24.65°N, in the central region of Saudi Arabia, was the chosen site for this study. Its climate is characterized as hot and arid, with external dry bulb temperatures (DBT) in summer reaching 45°C (Fig. 1). The average DBT and wet bulb temperatures (WBT) are 36.5°C and 18.8°C, respectively. The daytime relative humidity is below 20% during the same period. The prevailing wind directions during the summer season are north and north-west (Fig. 2). The high potential for PDEC systems in Riyadh is because of the significant difference between dry-bulb and wet-bulb temperature (WBD).

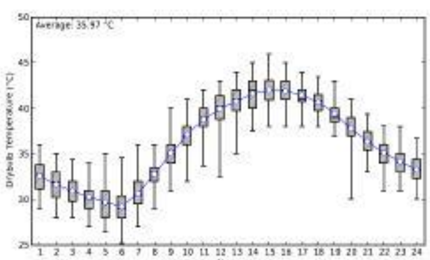


Figure 65: Range of mean hourly summer dry bulb temperatures, Riyadh. Source: epw.klimaat.ca

3. RESEARCH METHODOLOGY

This study aimed to evaluate the effect of the architectural design of a space linked to a PDEC tower. The purpose of the research was to maximize the performance of the PDEC tower in Saudi Arabia by improving the architectural design of the coupled building to act as one integrated design.

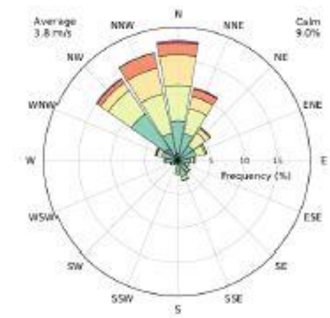


Figure 66: Frequency of wind direction and speed in summer, Riyadh. Source: epw.klimaat.ca

This study evaluated how wind direction and the addition of a buffer space to a room impacted on PDEC performance. A PDEC tower was located centrally and internally against the rear north wall of a single storey room connected to the tower (Fig. 3). The developed computer model applied the typical construction/material details of Saudi Arabia. The model construction specification is described in Table 1, and the tower specifications in Table 2. Most of the literature considers either 4:3 or 3:2 as a suitable aspect ratio for a rectangular tower. The dimensions of this study's tower cross-section were 1.6m x 2.5m, following the 3:2 aspect ratio. The width of the tower was parallel to the direction of the prevailing wind direction.

A previous study recommended a tower height of double to triple the width of the tower [5]. As a result, a tower height of 5m was initially set for this study. At the base of the tower three openings faced the room and had a total opening area of 3.43 m^2. A horizontal clerestory window was placed in the room's south façade with an opening area of 3.55m^2 (i.e. slightly larger than the tower's supply openings). This model was used as the base case design for the computer study (Fig. 3). Other opening configurations were also tested (shown in Fig. 13).

IES VE software was selected for the study as it can simulate PDEC systems that use misting nozzles and changeable cooling efficiency rates [7]. A current epw weather file for Riyadh was produced from Meteonorm, which is a commercial weather reference software tool [8]. Two different weather scenarios were tested in the simulations – (i) a very hot July day with northerly winds and (ii) a slightly cooler August days with some southerly winds.

Table 1: Construction specifications for the building
Table 2: PDEC tower parameters and specifications

	Construction Specifications
Building Height	3.5m
Floor dimensions	7.5m x 9m
Floor area	63.75 m^2
External walls	25mm external cement plaster + 100mm hollow concrete block + 50mm expanded polystyrene + 150mm hollow concrete block + 25mm internal cement plaster
Roof	gravel + 100mm expanded polystyrene + membrane+ 200mm concrete slab
Glazing	6mm outer pane + 12mm cavity + 6mm inner pane
South opening area	3.55 m^2

	PDEC tower specifications
Assumed cooling efficiency	80%
Tower Height	5m
Tower cross-section Dimensions	1.5m x 2.5m
Wind Catcher	Four sides louvres with 80% openable area (total area: 5.76 m^2)
Supply openings	Three openings facing the room (total area: 3.43 m^2)

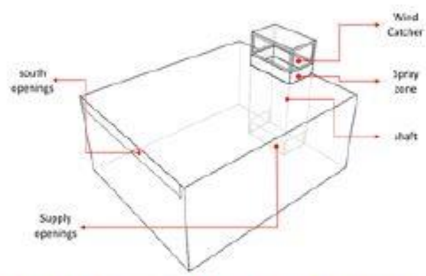


Figure 3: Base case building model and PDEC tower geometry

3.1 Model Validation

To check that the IES model had been configured correctly, the model was tested against experimental data derived from a European Union (EU) PDEC project [9]. The experimental building, shown in Fig. 4, was built in Catania, Italy, and consisted of a tower with two rooms attached to the north and south sides of the tower [9]. The PDEC tower dimensions were 4.1m x 4.4m x 10.7m. The wind catcher had two openings, each measuring 1.7m x 3.7m, and facing the east and west, which represented the prevailing wind direction. Data loggers were placed outside and within the building. The outdoor data recorded included solar radiation, air temperature, relative humidity, wind direction, and wind speed. Air temperatures and relative humidities were measured at different locations within the tower and the room.

A model of the Catania tower was created in IES VE. All the building details and opening profiles were considered when running the simulation. The simulation was run for 24 hours for the 30th July at a two minute time step.

The IES results for the north-coupled room were compared with average measured data. Figs. 5 and 6 show the good agreement between the measured and predicted data for the internal DBT and relative humidity, which gave confidence to develop an IES model for the Riyadh tower and room.

Figure 4: Experimental PDEC tower built in Catania [9].

4. RESULTS AND DISCUSSION

For the Riyadh tower the efficiency of the PDEC system was set in the IES model to be approximately 80% of the dry bulb to wet bulb temperature (wet bulb depression). Two days (scenarios) were considered. For scenario (i) on July 29th the maximum external air temperature peaked around 46°C mid-afternoon while the maximum external wet bulb temperature was around 21.5°C. The average external relative humidity was 14%.

Fig. 7 shows the wind speed and wind direction for July 29th generated from the weather file using IES software. The right vertical line represents the wind speed. The left vertical line refers to the wind direction, with the convention that a wind direction from the North is 0°, East 90°, South 180° and West 270°.

Figure 5: Comparison between measured and predicted internal air temperatures in room in Catania PDEC tower

Figure 6: Comparison between measured and predicted internal relative humidities in room in Catania PDEC tower

The sharp fluctuation in the wind direction line does not necessarily mean a big change in the wind direction. For instance, in Fig. 7, the wind direction was approximately between 250° and 325° (WNW) for most of the day, and then suddenly swung around to 15° (NNE) at 14:00. This means the wind direction has only moved from WNW to NNE although the change looks more dramatic on the graph. Thus, for scenario (i), the winds were mostly from the north (i.e. directly on to the tower) with a maximum wind speed of 4.6m/s (Fig. 7). Fig. 8 shows the hourly external dry bulb and wet bulb air temperatures and the PDEC-generated internal air temperatures in the room. Fig. 8 shows how effective the PDEC system was, with a peak internal temperature around 27.2°C compared to an outdoor peak around 46°C. The internal relative humidity dramatically increased to around 60% during the day (Fig. 9). This is attributed to the stable weather conditions and lower humidity levels during the day (Figs. 7 and 9).

For scenario (ii) on August 2nd the day was slightly cooler, with a maximum external DBT and WBT of around 40°C and 18.7°C respectively, and a mean relative humidity around 15%. The wind direction was mostly from the north west but changed to the south and south east from 14.30 to 16.30 and 20.00 to 21.00 and so struck the building before reaching the tower (Fig. 10). The wind speed was higher compared to scenario (i), increasing through the day and reaching 9.2m/s around 16.00 (Fig. 10).

Figure 7: Wind speed and wind direction, July 29th.

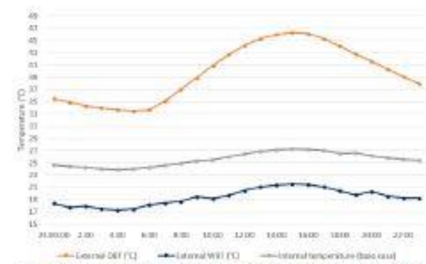


Figure 8: External and internal air temperatures, July 29th.

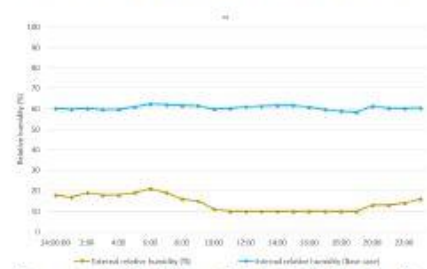


Figure 9: External and internal relative humidity, July 29th.

The results for scenario (ii) were not as expected when compared to those from scenario (i), with a reduction in the PDEC effectiveness being observed that was related to the unstable weather conditions. Figs. 10 and 11 show how the change in wind direction greatly reduced the effectiveness of the PDEC tower between 14.30 and 16.30 and between 20.00 and 21.00, when the wind direction became southerly. Internal temperatures peaked around 35.5°C and stayed higher than in the July scenario. The internal relative humidity had dramatically decreased when the winds were southerly (Fig. 12). This suggests that the clerestory window opening in the south façade was allowing a positive pressure to be generated in the room that acted against the ingress of cool air from the tower.

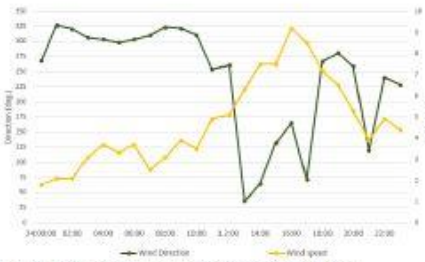


Figure 10: Wind speed and wind direction, Aug 2nd.

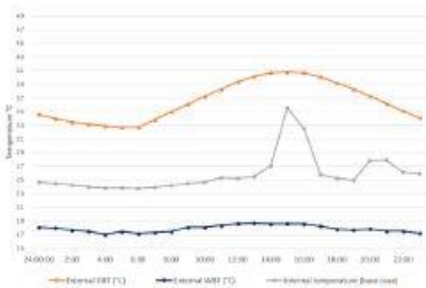


Figure 11: External and internal air temperatures, Aug 2nd.

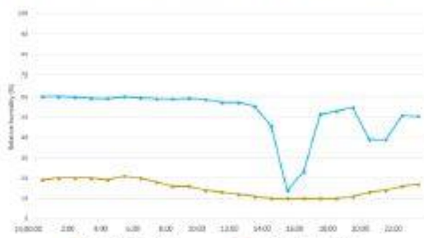


Figure 12: External and internal relative humidity, Aug 2nd.

Since wind direction played an important role in the performance of the PDEC tower, a double-skin type buffer zone corridor was then created on the south façade to test if the window could be protected and the tower performance improved for southerly winds. The buffer zone and the further improvements were developed based on recommendations from the literature [10]. The parameters that have been considered included buffer depth, buffer height, opening sizes, and opening placement. The investigation included many different configurations to improve the air movement of the PDEC within the space. Several cavity depths were tested, and it was found out that this parameter had no large influence on the overall performance of the PDEC tower. So, a cavity depth of 0.4m was chosen for this study. Three configurations were chosen for this study in addition to the base case (Fig. 13). These three configurations represented the major changes that has been discovered during the research modelling process. The first configuration had two openings located at the floor and ceiling of the buffer zone. The second configuration had two openings at the top north and south side of the buffer zone in addition to the floor opening. The floor opening was removed for the third configuration.

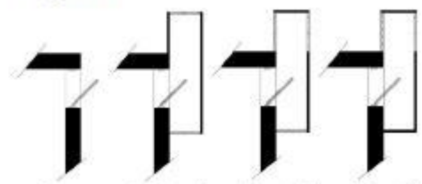


Figure 13: Base case and the three different configurations

Fig. 14 shows the internal air temperatures for the July 29th (northerly wind) conditions for the base case without the buffer zone and the three different zoned configurations. The addition of the buffer zone had little impact on the July tower performance, which might be expected for northerly low speed winds. However, Fig. 15 shows the positive impact of the buffer zones on the August tower performance during southerly wind conditions between 14.30 and 16.30 and between 20.00 and 21.00, but there was a negative impact after the wind changed direction. An interesting finding was that the internal temperature went up between 12.00 and 14.00, and between 16.30 and 18.30 when winds were blowing from north. The only logical explanation for this change was the higher wind speed as this scenario was working properly during steady wind conditions. The pressure increases on the buffer openings due to higher wind speeds has affected the performance negatively. So, the first configuration would provide better results only for southerly winds and lower wind speed conditions, otherwise, the base case performed better most of the time as the prevailing wind direction was northly.

For the second configuration, the top opening was replaced with two openings at the top north and south side of the buffer zone. This was developed to minimize the positive pressure of the wind speed, so the leeward side opening could negatively pressurize the buffer zone. Although the results showed that the situation had improved, the negative effect of the wind speed still had an impact on this configuration (Fig. 15).

The bottom opening was then eliminated for the third configuration. The purpose behind this was to create a stack effect within the buffer zone. The results showed that significant improvement was achieved during this scenario (Fig. 15). This configuration gave the best results compared with the other scenarios for most of the time and during different weather conditions. The two upper openings had decreased the pressure within the buffer zone cavity while the elimination of the bottom opening helped to create a stack effect.

Figure 14: Comparison between results of the base case and the three buffer zone configurations, July 29th

Figure 15: Comparison between results of the base case and the three buffer zone configurations, Aug 2nd

Although many summertime simulations have been made, the two scenarios presented here give a good representation of how the PDEC system performed for a range of summer wind speeds and wind directions. Due to a limitation on number of pages, it was not possible to represent more analyses here for the whole summer. However, it should be mentioned that the findings that were observed in the second scenario (Aug 2nd) occurred during many other days (e.g. Jun 4th, Jun 6th, Jul 2nd, Aug 8th etc.), and under similar weather conditions. Overall, the PDEC tower performed well as Riyadh has a climate that is generally dry and hot throughout the summer. Full season analysis and representation in the future is highly recommended to better understand the overall performance of the PDEC system and will be presented in future work.

4. CONCLUSION

This paper has investigated the impact of architectural form on the performance of a PDEC tower. The tower was virtually created and linked to a room. The software IES VE was used to conduct the simulation of the PDEC system, and the tower's predicted performance was impressive in Saudi Arabian climatic conditions. However, the performance was affected by changes in wind direction and wind speed. A buffer zone was added to the south side of the coupled space to minimize the negative effect of the winds. By assessing many configurations of the suggested solution, the performance was improved significantly. Further analysis, involving modelling and monitoring, will be conducted to better understand the relationships between the tower and room factors. Other architectural elements, such as roof openings might improve the performance of the PDEC system and provide more architectural design options. Detailed analysis including CFD would also provide a deeper understanding of the findings.

REFERENCES

1. Electricity & Cogeneration Regulatory Authority (ECRA Statistical Booklets 2016, [Online], Available at: http://www.ecra.gov.sa/ [10 Nov 2017].

2. Lechner, N., (2014) *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*. 4th ed., John Wiley & Sons.

3. Ford, B. and R. Schiano-Phan, (2010). *The Architecture and Engineering of Downdraught Cooling*. PHDC Press, Bologna, Italy.

4. Belarbi, R., Ghiaus, C. and F. Allard, (2006). Modeling of water spray evaporation: application to passive cooling of buildings. Solar Energy, 80: p. 1540–1552.

5. Kang, D. and R. K. Strand, (2016). Significance of parameters affecting the performance of a passive downdraught evaporative cooling (PDEC) tower with a spray system. *Applied Energy*, 178: p. 269-280.

6. Ford, B., Patel, N., Zaveri, P. and Hewitt, M., (1998). Cooling without air conditioning: The Torrent Research Centre, Ahmedabad, India. *Renewable Energy*, 15: p. 177-182.7.

7. Buckley, L., (2014) Simulating a Passive Downdraft Evaporative Cool Tower. In *Proceedings eSim 2014*. Ottawa, Canada, May 8-9

8. Meteonorm: [Online]. Available at: http://www.meteonorm.com/ [29 Nov 2017].

9. Galatà, A and S. Sciuto, (1997). Passive Evaporative Cooling : the PDEC project. In *International Thermal Energy and Environment Congress*. Marrakesh, Morroco, June.

10. Gratia, E. and A. de Herde, (2007). Guidelines for improving natural daytime ventilation in an office building with a double-skin façade. *Solar Energy*, 81: p. 435-448.

Monitoring the performance of a passive downdraught evaporative cooling (PDEC) system – a case study of a library in Saudi Arabia

Mohammad Abdullah Alshenaifi and Steve Sharples

School of Architecture, University of Liverpool, Liverpool, UK
E-mail address: m.alshenaifi@liverpool.ac.uk

Abstract: This paper presents field measurements and analysis from the performance monitoring of a Passive Downdraught Evaporative Cooling (PDEC) building in Saudi Arabia. Summer temperatures in Saudi Arabia frequently exceeding 45°C, and daytime relative humidities can be below 20% during the same period. The case study building, Dar Al-Rahmaniah, is a small public library located in the central region of Saudi Arabia. The library consists of three main parts, which include separate sections for men, women and children, and an auditorium. The men's section was chosen for the monitoring process as it represents the largest part of the library. Two PDEC towers are used to cool the large open space of the library. Central and leeward clerestory openings in the roof exhaust the stale air, allowing the evaporatively cooled air coming down the towers to circulate within the space. The primary aim of this study was to investigate the applicability and effectiveness of the PDEC system in the hot and arid climate of Saudi Arabia. For over 70 days during the summer of 2018, a range of data loggers were installed in the case study building to collect data. Different types of data loggers were used to record various parameters inside and outside the towers and the building, including external and internal dry-bulb temperatures, wet-bulb temperatures, relative humidity and external wind speed and wind directions. The case study provided detailed information about the performance of the PDEC tower in the climate of Saudi Arabia. The results indicated that PDEC Towers can achieve significant cooling for most of the time, but that their effectiveness was influenced by changes in wind direction and wind speed. Some reasons for this loss of effectiveness are discussed.

Keywords: Passive cooling; cooling Tower; PDEC systems.

1. Introduction

In Saudi Arabia, buildings use around 75% of the country's total electricity generation, with air conditioning being responsible for most of that consumption (Abuhussain et al, 2018). The majority of electric power generation comes from the direct burning of crude oil, with up to 900,000 barrels per day being used during the summer months (EIA, 2017). If air conditioning use in buildings might be reduced by substituting passive cooling systems, then this could have a significant impact on Saudi Arabia's energy consumption and greenhouse gas emissions. This study investigated one such cooling system – the Passive Downdraught Evaporative Cooling (PDEC) tower – by monitoring the performance of the system in a real building. The analysis of collected data revealed that this passive system did provide cooling, although the system's performance was negatively affected by the wind.

2. Literature and Background

The term 'passive cooling' describes a process that relies on a natural environmental heat sink to achieve cooling. Passive cooling strategies can be classified to four major types based on the natural heat sinks: (i) Natural ventilation (night ventilation), (ii) night sky radiation, (iii) ground cooling, (iv) evaporative cooling (Lechner, 2009). Passive Downdraught Evaporative Cooling (PDEC) towers are categorized as a direct evaporative cooling technique. When hot, dry air passes through a water medium, the evaporation of the water occurs as sensible heat is converted into latent heat, and the air temperature decreases as the relative humidity level increases. A PDEC tower consists of a wind catcher at the top of a tower, an evaporative/water medium, and a shaft to deliver the caught, cooled air to an occupied space via openings at the bottom of the tower. Hot and arid climatic regions provide an ideal environment for PDEC systems, and an up to 80% reduction of wet bulb depression (WBD) can be produced, which would ultimately lead to a significant reduction in cooling energy consumption (Alshenaifi et al, 2018). Contemporary applications of PDEC towers can be classified as four different types based on the evaporation method (Ford et al, 2010):

- Shower Towers (large droplets of spray)
- PDEC with wetted porous ceramic
- Cool Towers (wetted pads).
- Misting Towers (misting nozzles)

2.1. PDEC case study with wetted pads

Zion National Park's Visitors' Centre in south-west Utah, USA has two cooling towers incorporated in to the building, and air is cooled naturally by evaporation using four wet pads at the top of the towers. The outdoor summer daytime temperatures range between 35°C and 37°C. Clerestories are designed in the roof to maximise daylighting and improve the air movement with the cooling towers. The building envelope is well insulated to minimise heating and cooling loads. The building was assessed over two years (Torcellini et al, 2004). Results showed that the PDEC towers met most of the cooling requirements and that they contributed significantly in eliminating the use of conventional cooling. In the summer of 2017, the maximum external air temperature in Zion was recorded as around 42°C, while the internal temperature did not exceed 27°C (Ford et al, 2010).

2.2. PDEC case study with misting nozzles

The Torrent Research Centre (TRC) in Ahmadabad, India was the first large scale application of misting nozzles spraying into the top of the tower inlet. TRC has six laboratory buildings and some administrative spaces. In each building, the PDEC system is positioned above a central atrium that separates the offices from the laboratories. On the major axis of each building, shafts are built to maximise air circulation and exhaust the warm air out of the building. When the outside temperature reaches its maximum, the PDEC drops the interior temperature by between 10 and 15°C. The system has achieved 64% energy savings in cooling demand when compared to a conventional air conditioning system (Ford et al., 1998).

3. Case study of Dar Al-Rahmaniah library: Location and Climate

The PDEC building chosen in this study was the Dar Al-Rahmaniah library, which has two PDEC towers. The PDEC towers use the wetted pads approach to cooling. The library is situated in Alghat city, latitude 26.03°N, in the central region of Saudi Arabia. The city is in the north-western part of Riyadh province. Its climate is characterised as hot and arid, with external dry bulb temperatures (DBT) in summer reaching 45°C. The annual average DBT and wet bulb temperatures (WBT) are 36.5°C and 18.8°C, respectively. The library was monitored for over 70 days during the summer of 2018. The daytime relative humidity was typically below 20% during the same period, and the prevailing wind directions during the summer season are north and north-west. Figure 1 shows the library and its two PDEC towers.

Figure 1: The main entrance of Dar Al-Rahmaniah library and the two PDEC towers

4. Building Information

It is apparent that the designer of the Library tried to reflect the surrounding environment in the building. The use of construction elements from the same environment, such as straw bale walls covered with earthen plaster and wooden roof structure, gives a clear expression of how the building belongs to its land. The high thermal mass of the used material could provide a cooler internal temperature of the occupied spaces. The main entrance is located on the north-west side of the building between two PDEC towers, with the left-hand tower designated as Tower A in this study and B on the right side of the entrance (Figure 1). It is apparent from the location of the Tower that the design concept is to capture the prevailing summer winds and direct them into the building. The two towers are approximately 10m high with four openings on the top. At the bottom of each Tower, there is one large opening to deliver the cool air to the occupied space. The library is mainly a large open room cooled by the two PDEC towers. Clerestories are placed in the centre of the roof facing north-eastern and south-western side. The leeward clerestory openings in the roof were designed to assure the circulation of the air inside the building. Tables 1 and 2 show the architectural details and construction specifications for the building and the Towers.

Table 1: Construction specifications for the building

	Construction Specifications
Space height	4.4m
Library floor area	443 m^2
External walls	112cm total thickness: earthen plaster finish + straw bales (average size: 95 x 48 x 30cm) + earthen plaster finish
Roof	10cm light clay straw plaster + 7cm heavy clay plaster + 2cm lime plaster finish
column	Cast in place concrete column

Table 2: PDEC Tower specifications and details for Tower A (B similar)

	PDEC tower specifications
Tower Height	10m
Tower cross-section Dimensions	3.7m x 3.4m (become narrower at the top)
Wind Catcher	Four sides openings at the top (1.5m height x 2m width each)
Supply openings	One supply opening at the bottom of each tower (2m width x 1.8m height)
walls	46cm total thickness (20cm concrete masonry + 20cm stone block)

5. Work schedule

Data loggers were installed in the library for more than 70 days from 21st June to the 30th Aug 2018. The recordings were set for 24 hours continuous logging each day with a logging interval of 10 minutes. The library working time is divided into two shifts from Sunday to Thursday. The first shift starts from 09:00 to 12:00 while the second shift is from 16:00 to 20:00. The PDEC Towers were set to work for 24 hours each day.

6. Monitoring Equipment

Four different data logging equipment were used for the monitoring of the building. The recorded parameters included external and internal dry-bulb and wet-bulb temperature, external and interior relative humidity, external wind speed and wind direction, and internal air velocity. The data logger types used in the monitoring process are explained as follows:

6.1. Kestrel 5500

The Kestrel 5500 is a weather meter that can read and record a wide range of parameters. These parameters include wind speed, wind direction, dry-bulb temperature, RH and wet-bulb temperature. The meter is easy to set up and install. This mini weather station was installed above the library roof to record different weather parameters.

6.2. Kestrel 5200

The Kestrel 5200 is like the Kestrel 5500. The most apparent difference is that the 5200 meter does not contain a compass, so it cannot read and record wind direction. However, it can record extra parameters such as evaporation rate and moisture content. The Kestrel 5200 could be used to measure internal or external weather parameters. Two Kestrel 5200 were installed at the Tower supply openings to collect the supply air conditions.

6.3. EXTECH SDL350 Thermo-Anemometer

The EXTECH SDL350 consist of two parts - the meter and a probe that contains the sensors. The meter is featured by its sensitive sensors, which can record temperature and air velocity readings at low values. The EXTECH SDL350 was chosen to record air velocity readings from within the PDEC Tower.

6.4. Rotronic HL-1D

The Rotronic HL-1D is a compact and easy to install data logger. It can record air temperature and relative humidity for a long period. Seven data loggers of this type were installed within the PDEC Tower B and the occupied spaces.

7. **Accuracy**

The specifications of the sensors are summarized in Table 3. All the loggers were new and unused, and so the factory calibrations were valid. However, to check consistency between the loggers they were all, before installation in the library, run in a closed room environment for 24 hours. Note that the minimum starting speed for the Kestrel loggers is 0.6m/s. This means that external wind speeds below 0.6m/s will be recorded as zero.

Table 3: Data loggers and sensors specifications

	Measurement range	Accuracy	Reporting interval
Kestrel 5500	Temp: -29 to 70°C RH: 10 to 90%, WS: 0.6 to 40m/s	Temp: ±0.5°C RH: ±2% WS: ±3%, compass: ±5°	10 minutes
Kestrel 5200	Temp: -29 to 70°C RH: 10 to 90% V: 0.6 to 40m/s	Temp: ±0.5°C RH: ±2% V: ±3%	10 minutes
EXTECH SDL350 Thermo-Anenometer	Temp: 0 to 50°C V: 0.2 to 25m/s	Temp: ±0.8°C V: ±5%	10 minutes
Rotronic HL-1D	Temp: -20 to 70°C RH: 0 to 100%	Temp: ±0.3°C RH: ±3.0%	10 minutes

8. **Installation**

The data loggers mentioned above were installed in different locations in the library and the PDEC towers (Figure 2, 3 and 5). All the data loggers were labelled and numbered to simplify and organise the process of installation. The schematic drawings show the position of the sensors. The mini weather station (Kestrel 5500) was installed centrally above the roof of the library. The meter was raised above the roof by approximately 1.2m. Besides, the meter was shaded as recommended by the manufacturer (Figure 4). Two Kestrel 5200 were installed at the supply openings of Tower A and B at a roughly 1.4m height from the floor. Four temperature and humidity data loggers (H1-1D) were nailed on walls in different locations within the library. These locations include near supply opening of Tower A (computer zone), near supply opening of Tower B (administration zone), the middle of the Library, and the back of the library. The height of the sensors was 1.6m, which provides an ideal position within the occupied spaces. One more H1-1D meter was installed on near the supply opening of an AC unit to collect data of the working hours of the mechanical cooling units. Two H1-1D meters were also installed within Tower B. one was at the top, 2.3m below pads, while the other was at the bottom at a 1.6m height from the floor. The anemometer was installed inside Tower B. The probe sensors were positioned centrally inside the Tower at 2.9m above the floor.

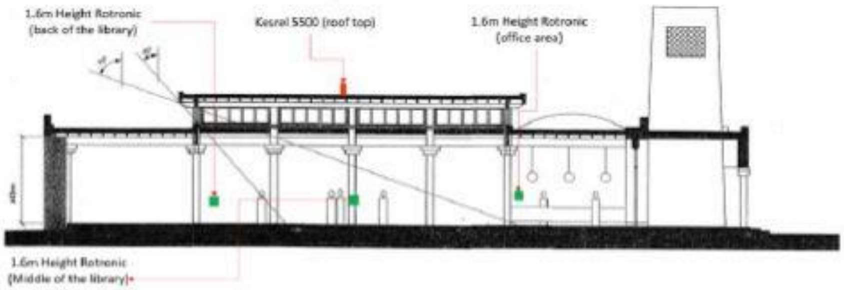


Figure 2: Section A-A

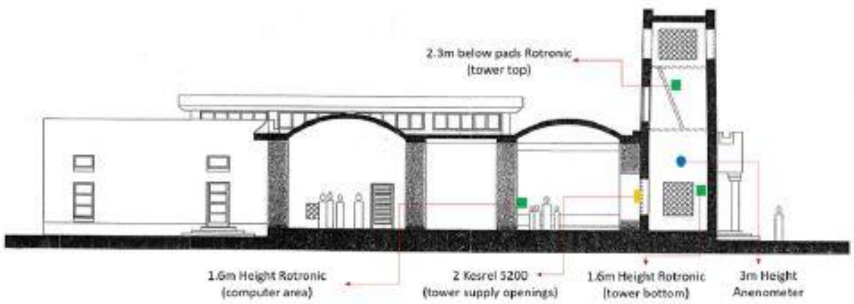


Figure 3: Section B-B

Figure 4: Pictures taken during the installation of the data loggers

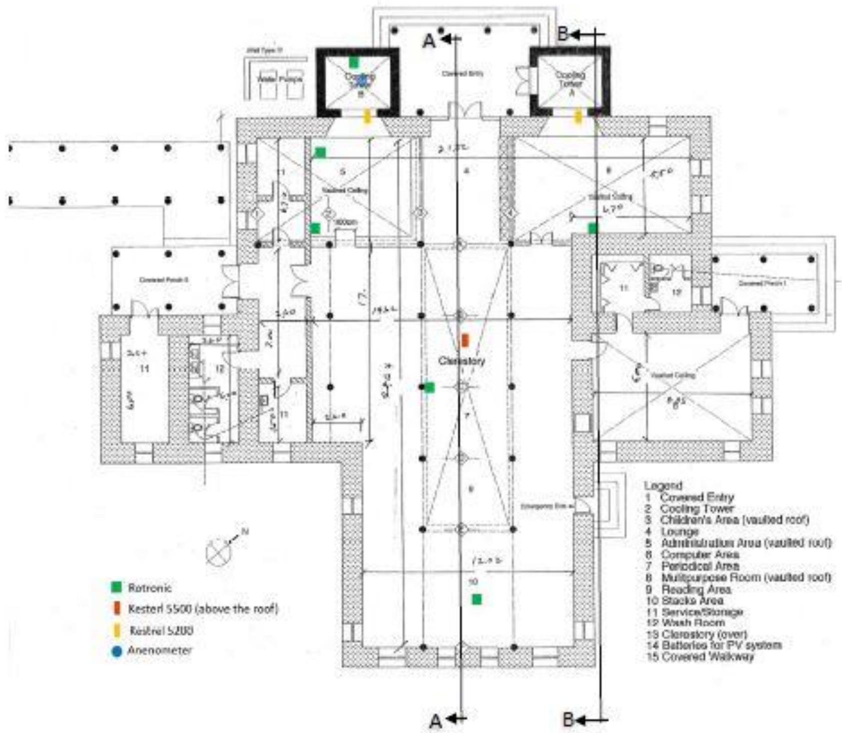


Figure 5: Library floor plan showing the location of the data loggers installed

9. Results and Analyses

For the hot, dry climate of Saudi Arabia, the monitored performance demonstrated the ability of the PDEC system to cool the incoming air. The temperature difference between the external air and that delivered at the bottom of the PDEC towers ranged from 6°C in the early morning to 16°C during the hottest parts of the days (~3.00pm). Despite the PDEC towers providing cooling for most of the time, there was still a need for mechanical cooling as the PDEC towers could not provide enough cooling all the time. It was noted that under certain weather conditions the performance was less effective. The wind speed and wind direction played significant roles in the overall performance of the PDEC.

9.1. Wind Speed

It was apparent from the logged data that the wind speed had a direct influence on the performance of the PDEC towers. Figures 6, 7 and 8 show that the lower the wind speed then the higher the humidity levels and the greater the temperature reductions achieved. On 8th and 9th August, and during a time when the wind speed went above 4m/s, the performance of the two PDEC towers became unstable, leading to fluctuations in the supply air temperature, higher internal air temperatures, and lower humidity levels. As a result, the loss of PDEC cooling had to be offset by mechanical air conditioning, which was running during work hours. This scenario happened frequently during the 26th/27th July and 7th August. A possible explanation for this is that turbulence increased around the tower inlet opening at the top due to the higher wind speeds, as discussed by Kang and Strand (2016). This situation can be seen in the supply air velocity, which decreased during the periods of higher external wind speeds. On the other hand, during calm wind conditions, the towers performed better, leading to lower supply air temperatures.

9.2. Wind Direction

Although the PDEC towers produced cooled air for most of the time, specific wind directions reduced the size of the cooling of one or both PDEC towers. One finding was that the south and south-west winds had a negative influence on cooling for Tower A. It was observed that the temperature at the tower at the supply opening went up while humidity levels dropped when winds came from south and south-west directions. This suggests that the south-western clerestory openings in the roof were allowing a positive pressure to be generated in the room that acted against the ingress of cool air from Tower A.

In Figures 9, 10 and 11, Tower B can be seen to have performed better than Tower A at specific times during the 23rd and 24th of June. The supply temperature increased, and humidity levels decreased below 50% for Tower A while Tower B was performing better, with supply temperatures going down to below 20°C at some times. This situation occurred during similar weather conditions where the wind direction bearing was approximately between 140° to 270° (SW). The same situation occurred for several days during the monitoring. These days include 11th, 12th, 13th, 17th, 21st, 22nd, and 24th July, and 2nd, 7th, 9th, 22nd August.

During calm weather, and when winds become north or north-north-west (i.e. directly on to Tower A), Tower A performed better. For these ambient conditions, Tower B's performance dropped compared to Tower A, and the temperature at the zone near the supply opening of Tower A (computer zone) became lower than the temperature at the Tower B supply opening. Possibly, Tower B could be acting as an exhaust shaft at some points. This scenario happened during weekends or after work hours, which suggests that clerestory openings might have been closed at these times. This situation occurred on the 27th July and 8th August.

9.3 Overall Performance

The overall capacity of the PDEC towers to provide useful levels of cooling performance in the hot, arid climate of Saudi Arabia was demonstrated. Although both towers performed well most of the time, it was apparent that Tower B was more effective than Tower A (Figure 12). This finding could be linked to a couple of reasons. First, the W and SW wind direction has played a role as it was explained previously. Secondly, the layout of the Library could be a reason for that. It can be seen in the floor plan layout that the supply opening of Tower A is facing a wall that creates the computer zone within the Library main space. These obstructions could minimise the airflow from Tower A, which would lead to less performance under certain circumstances. On the other side, Tower B has a direct connection with the library open space with no obstructions.

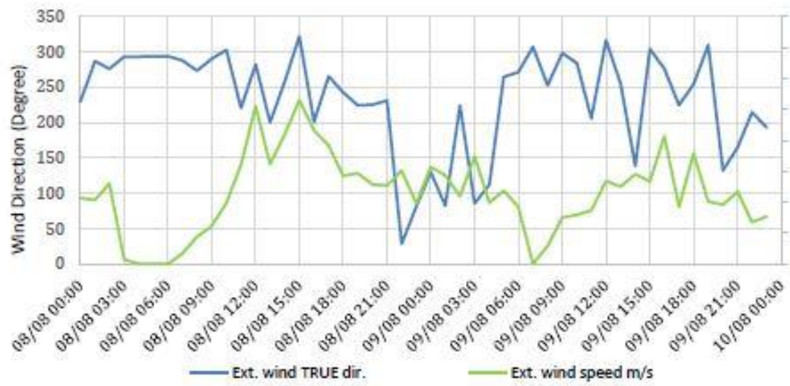


Figure 6: Wind speed and wind direction for the 8th and 9th August.

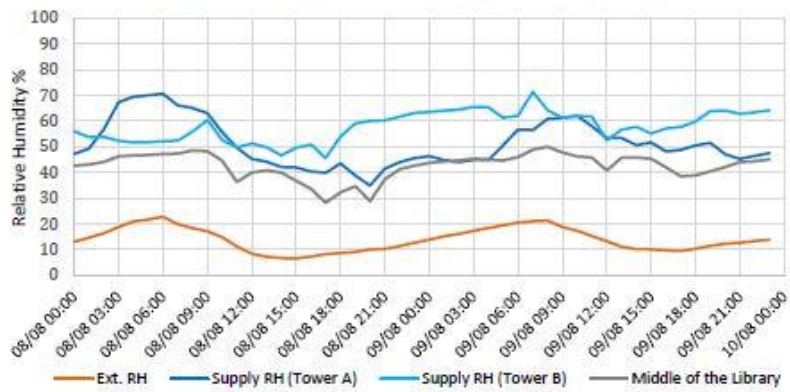


Figure 7: External and Internal Relative Humidity during the 8th and 9th August

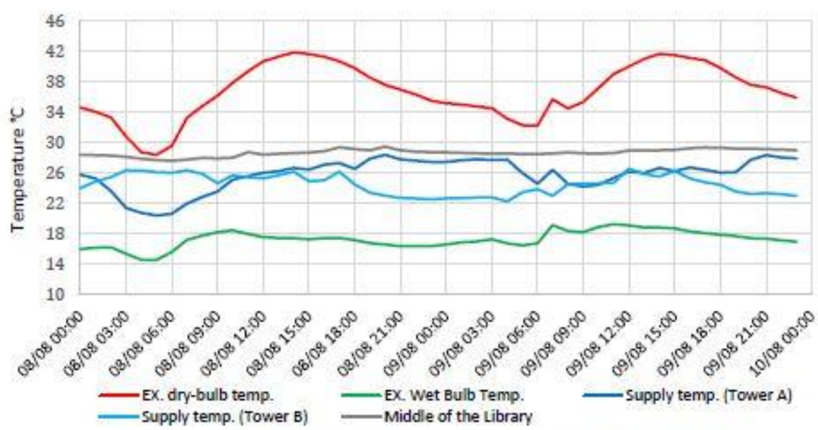


Figure 8: External DBT, WBT, and internal temperatures for the 8th and 9th August

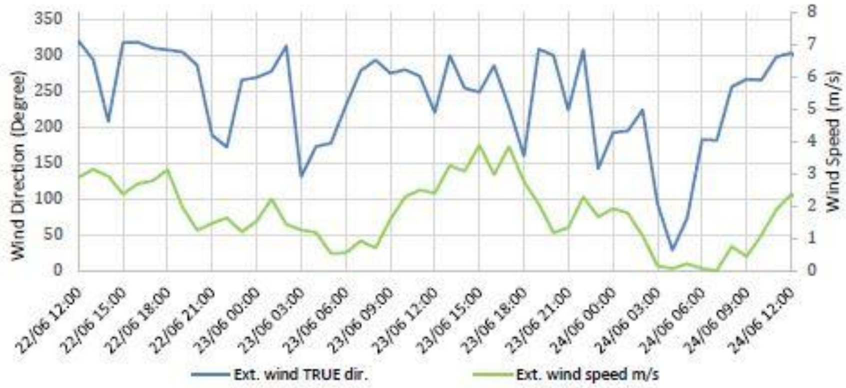


Figure 9: Wind speed and wind direction for the 22nd - 24th June

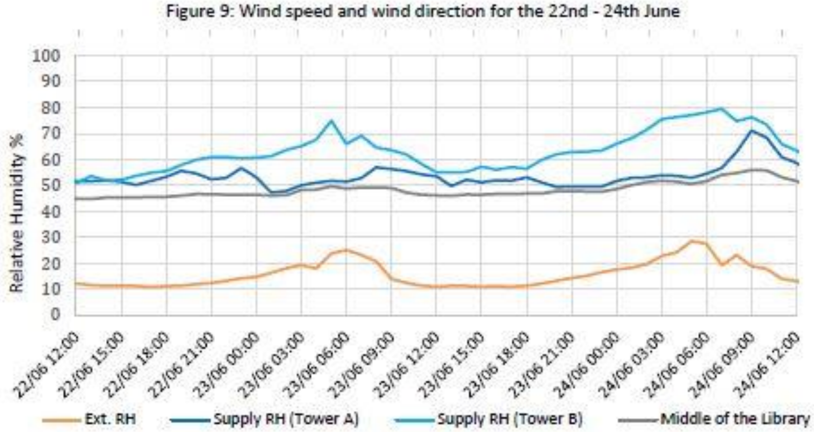


Figure 10: External and Internal Relative Humidity for the 22nd – 24th June

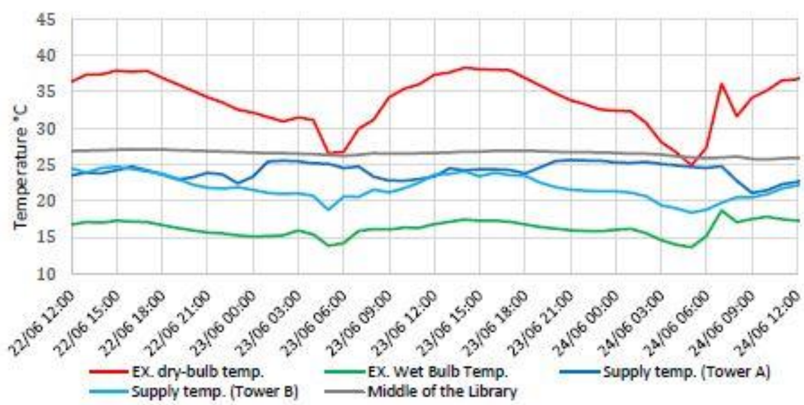


Figure 11: External DBT, WBT, and internal temperatures for the 22nd – 24 June

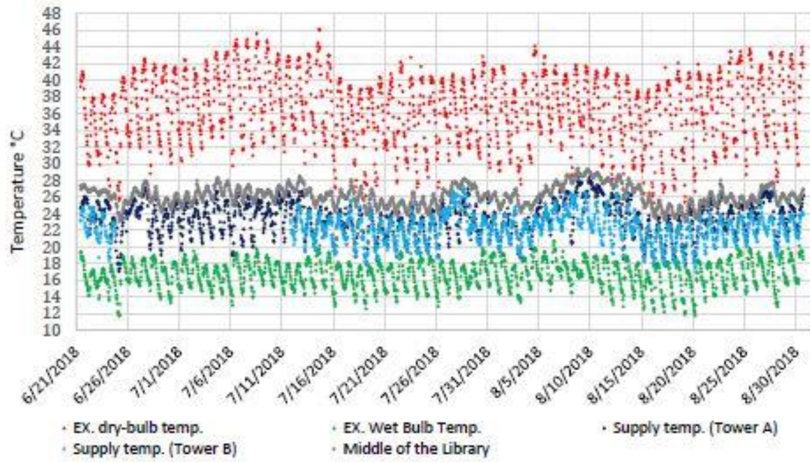


Figure 12: External DBT & WBT, and internal temperatures at Tower A and Tower B supply openings and the middle of the library during the whole monitoring period (70 days)

10. Conclusion

This paper has presented the analysis and results of the performance of an existing PDEC building – the Dar Al-Rahmaniah Library in Saudi Arabia. The primary objective of this case study was to quantify the actual level of cooling performance of real PDEC towers. The case study provided detailed information about the applicability of the PDEC Tower in the climate of Saudi Arabia. The findings showed that the two PDEC towers provided cooling to the building, although the degree of cooling was affected by prevailing wind speeds and directions. Limitations of the current study include the one season (summer) nature of the measurements (meaning that most winds blew from a narrow range of directions) and the fact that very low wind speeds could not be measured as the weather logger only recorded speeds above 0.6 m/s. Future work will include computer modelling of the Library and the validating of the model against the measured data. If that is successful, then detailed parametric analyses of the case study will be undertaken to provide a better understanding of PDEC performance and contribute to the future design and development of PDEC towers.

11. References

Abuhussain, M., Chow, D. and Sharples, S., 2018. Assessing the adaptability of the Saudi residential building`s energy code for future climate change scenarios. In: PLEA 2018, 34th International Conference on Passive and Low Energy Architecture. Hong Kong, pp. 73–78.

Alshenaifi, M. and Sharples, S., 2018. Investigating the Impact of Architectural Form and Wind Direction on the Performance of a Passive Downdraught Evaporative Cooling Tower in Saudi Arabia. In: PLEA, 34th International Conference on Passive and Low Energy Architecture. Hong Kong, pp. 294–299.

Ford, B. and Schiano-Phan, R., 2010. The Architecture and Engineering of Downdraught Cooling. PHDC Press, Bologna, Italy.

Ford, B., Patel, N., Zaveri, P. and Hewitt, M., 1998. Cooling without air conditioning: The Torrent Research Centre, Ahmedabad, India. Renewable Energy, 15: pp. 177-182

Kang, D., Strand, R.K., 2016. Significance of parameters affecting the performance of a passive down-draft evaporative cooling (PDEC) Tower with a spray system. Appl. Energy 178.

Lechner, N., 2009. Heating, Cooling, Lighting Susutainable Design Methods for Architects.

Torcellini, P. a, Deru, M., Griffith, B., Long, N., Pless, S., Judkoff, R., 2004. Lessons Learned from Field Evaluation of Six High- Performance Buildings. ACEEE Summer study energy Effic. Build.

U.S. Energy Information Adminstration (EIA), 2017. Country Analysis Brief: Saudi Arabia.

IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

A parametric analysis of the influence of wind speed and direction on the thermal comfort performance of a Passive Downdraught Evaporative Cooling (PDEC) system – field measurements from a Saudi Arabian library

To cite this article: M A Alshenaifi and S Sharples 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **329** 012042

IOP Conf. Series: Earth and Environmental Science **329** (2019) 012042 doi:10.1088/1755-1315/329/1/012042

A parametric analysis of the influence of wind speed and direction on the thermal comfort performance of a Passive Downdraught Evaporative Cooling (PDEC) system – field measurements from a Saudi Arabian library

M A Alshenaifi[1,2] and S Sharples[1]

[1]School of Architecture, University of Liverpool, Liverpool, UK
[2]Corresponding Author: m.alshenaifi@liverpool.ac.uk

Abstract: Building energy consumption in the desert climate of Saudi Arabia is dominated by cooling demand. Electricity for this cooling is generated predominantly from finite fossil fuel reserves. To improve resource efficiency and decrease carbon emissions, reducing this demand by using more passive cooling approaches is desirable. One system is the passive downdraught evaporative cooling (PDEC) tower. PDEC captures hot, dry winds at the top of a tower and then cools the air by passing it through or over water. This cooler air then flows out from the base of the tower into the building. In this study, a PDEC system in a small Saudi public library was monitored for two summer months. A key aim of this study was to investigate the relationship between local wind speed and direction and the performance of the PDEC towers. A thermal comfort analysis investigated the acceptability limits of indoor temperature using the adaptive thermal comfort model. A parametric analysis of the wind effects was conducted by grouping wind data in to ranges of wind speed and direction and then correlating them against environmental conditions in the library. The results indicated that the PDEC towers could deliver significant cooling for library users. However, the towers' effectiveness was influenced by changes in wind speed, and in a counter intuitive way – stronger wind speeds tended to reduce the tower cooling efficiency.

1. Introduction

In Saudi Arabia, around 75% of the country's total electricity generation is used in buildings, with air conditioning being accountable for most of that consumption [1]. Most electricity generation is from the burning of crude oil - around 900,000 barrels/day in the summer months [2]. Reducing or replacing air conditioning use in buildings with passive cooling systems could have a major influence on Saudi Arabia's energy consumption and greenhouse gas emissions. This study investigated one such cooling system – the Passive Downdraught Evaporative Cooling (PDEC) tower. The performance of an actual PDEC system was monitored in a real building. The analysis of collected data revealed that this passive system did provide cooling, although the system's performance was negatively affected by the wind.

2. Literature and Background

Passive Downdraught Evaporative Cooling (PDEC) towers is a direct evaporative cooling technique. When hot, dry air passes through a water medium, sensible heat is converted into latent heat, by the evaporation of the water, and the air temperature decreases as the relative humidity increases. A PDEC tower contains a wind catcher located at the top of a tower, an evaporative/water medium, and a shaft to deliver the caught, cooled air to an occupied space via openings at the bottom of the tower. Hot and arid climatic regions provide an ideal environment for PDEC systems, which could create a significant decrease in cooling energy consumption [4]. Contemporary applications of PDEC towers may use shower towers (large droplets of spray); wetted porous ceramic; wetted pads or water misting nozzles [5].

2.1. PDEC Case Studies

The Torrent Research Centre (TRC) in Ahmadabad, India was the first large scale application of a misting PDEC system, which was positioned above a central atrium that separated the offices from the laboratories. PDEC reduced the interior temperatures compared to outside by between 10 and 15°C, with a 64% savings in cooling demand, compared to full air conditioning, was achieved [5]. The Zion National Park's Visitors' Centre is in Utah, where the outdoor summer daytime temperatures range between 35°C and 37°C. The Centre incorporates two cooling towers and clerestories to circulate the cooled air within the spaces. The evaporation method used in this case study is wetted pads. The building was monitored over two years and its energy consumption was found to be approximately 70% less compared with a similar building built to the applicable Federal codes[6][7].

3. Thermal comfort models

Two dominant thermal comfort models have been developed. The Fanger heat balance model considers occupants as a passive recipient of thermal stimuli, while the adaptive model recognizes occupants as active users interacting with their environment. In the Fanger model heat balance principles are defined by several factors including metabolic rate, clothing insulation and environmental conditions. Controlled climate chamber studies led to the formulation of the average comfort score (on a seven-point scale from hot to cold) that a group of people would choose – the Predicted Mean Vote (PMV) [8], [9]. The adaptive model was developed by conducting field-studies in 160 buildings from 9 countries [8]. To apply the adaptive model, the investigated building (occupied space) must be exposed to the outdoors, conditioned naturally, and mechanical cooling/heating should be avoided. However, if the mean monthly outdoor temperature is less than 10°C or greater than 33.5°C, this model may not be used and the only model available is the PMV [8]. A thermal comfort model for mixed-mode buildings, with both passive and active cooling systems (as was the case in this study) is difficult to choose. Researchers have suggested using the adaptive model in mixed-mode, saying that the occupants have some control over some local thermal conditions, which is an adaptive feature [10], [11]. People with some control over their building conditions have been found to tolerate a wider comfort temperature range, which is similar to the adaptive model range in naturally ventilated buildings [10].

4. Case study of Dar Al-Rahmaniah library

4.1. The Studies Building and its PDEC towers Characteristics

The PDEC building assessed in this study was the Dar Al-Rahmaniah library, which has two PDEC towers that use wetted pads. The library is in Alghat city, central Saudi Arabia. Its climate is hot and arid, with external dry bulb temperatures (DBT) in summer reaching 45°C. The annual average DBT and wet bulb temperatures (WBT) are 36.5°C and 18.8°C respectively. The library was monitored for over 70 days during the summer of 2018. The daytime relative humidity was typically below 20% during this period, and the prevailing wind directions during the summer season were north and north-west. Figure 1 shows the library and its two PDEC towers. The design of the Library respects the traditional architecture of the surrounding environment. The main entrance is located on the north-west side of the building between two PDEC towers, with the left-hand tower designated as Tower A in this study and Tower B on the right side of the entrance. The two towers are approximately 10m high with four openings around the top. The bottom of each Tower has a large opening to provide the cool air to the occupied space. Clerestories are placed in the centre of the roof facing north-eastern and south-western side. The leeward clerestory openings in the roof were designed to assure the circulation of the air inside the building. Data loggers were installed in the library from 21st June to 30th August 2018, recording for

24 hours a day with a logging interval of 10 minutes, giving a total of 1688 recorded hours. The library working time is divided into two shifts from Sunday to Thursday. The first shift starts from 09:00 to 12:00 while the second shift is from 16:00 to 20:00. The PDEC Towers worked 24 hours each day.

Figure 1. The main entrance of Dar Al-Rahmaniah library and the two PDEC towers.

4.2. On-site monitoring

Four different data logging equipment were used for the monitoring of the building. The recorded parameters included external and internal dry-bulb and wet-bulb temperatures, external and interior relative humidities, external wind speed and wind direction, and internal air velocity. The data logger used were a Kestrel 5500, Kestrel 5200, EXTECH SDL350 thermo-anemometer, and Rotronic HL-1D. The Kestrel 5500 mini weather station was installed on the roof of the Library to record the outdoor weather conditions. Two Kestrel 5200 data loggers were installed at the towers supply air openings to measure the conditions of the delivered air. The thermo-anemometer was used to measure temperature and air velocity within the tower. Seven compact Rotronic HL-1D were installed at different locations inside the building and the tower to record temperature and relative humidity (RH). All the loggers were new and unused. Factory calibrations were checked by running the loggers in a controlled space for 12 hours to ensure consistent readings. Note that the minimum starting speed for the Kestrel loggers is 0.6m/s, which meant that external wind speeds below 0.6m/s will be recorded as zero. The data loggers were installed in the library and the PDEC towers as shown in Figure 2.

5. Results and discussion

5.1. Cooling impact

The temperature difference between the external DBT and that delivered at the bottom of the PDEC towers ranged from 6°C in the early morning to 22.5°C during the hottest parts of the days (~3.00pm). The hottest recorded period, from 5th to 15th July, is shown in Figure 3, and describes the measured hourly external dry-bulb temperature (DBT), external wet-bulb temperature (WBT), and the indoor temperature (Tin) observed by a Rotronic HL-1D data logger placed in the middle of the library. The PDEC towers provided a significant amount of cooling to the space, considering that the mechanical air conditioning was on for only 4 hours from 16:00 to 20:00 on the 11th July. On July 14th, the maximum external DBT peaked around 46°C mid-afternoon while the WBT was around 20°C. The supply air temperatures for Tower A (Ta) and B (Tb) were recorded at 24.2°C and 23.5°C respectively at the same time while the internal temperature Tin was around 25.8°C. At the same peak hour, the indoor relative humidity (RH) increased rapidly when compared to the external RH due to the evaporation process occurring within the PDEC tower. The recorded external RH was around 8% while the internal RH was approximately 65% at tower A, 70% at tower B, and 61% in the middle of the library. Despite the PDEC

IOP Conf. Series: Earth and Environmental Science **329** (2019) 012042 doi:10.1088/1755-1315/329/1/012042

towers providing cooling for most of the time, there was still a need for mechanical cooling as the PDEC towers could not provide enough cooling all the time. For instance, the maximum DBT reached around 43°C on July 11th. The WBT was around 18°C while the external RH was 7% during the same time. Given these suitable conditions for such a passive cooling system, the result, however, shows a higher indoor temperature although with the relatively lower DBT compared to the previous case. The Tin was observed around 28°C at 15:00 while the indoor RH was about 43%. The total reduction from the DBT to delivered temperatures was around 16°C, while it was around 22.5°C in the first case, leading to the mechanical cooling being used after 16:00 when the building was occupied in line with the PDEC towers. It was noted that under certain weather conditions, the performance was less effective. The wind speed played significant roles in the overall performance of the PDEC. As a result, analyses of wind direction and wind speed effects were undertaken.

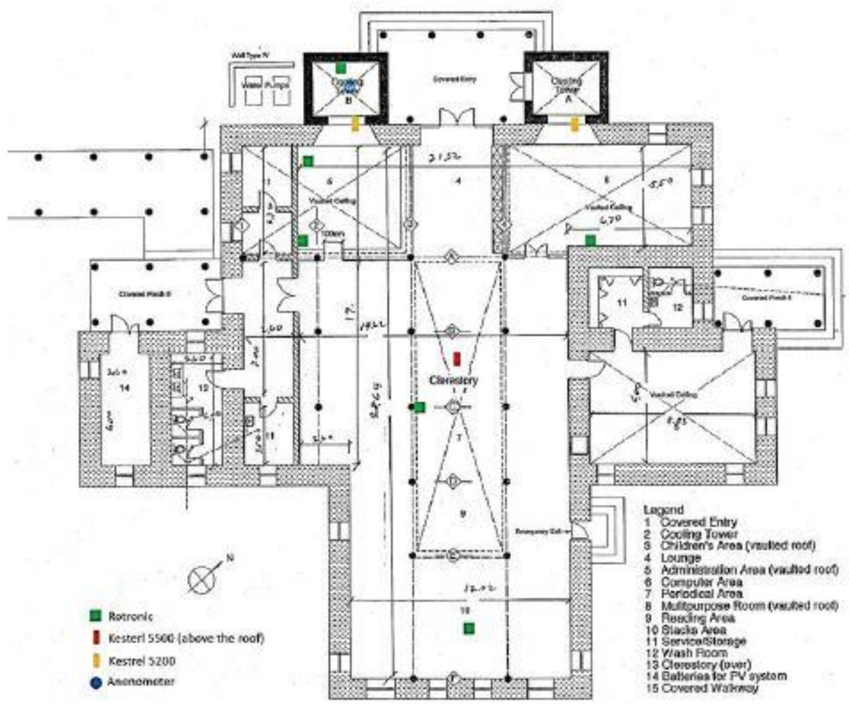


Figure 2. Library floor plan showing the location of the data loggers.

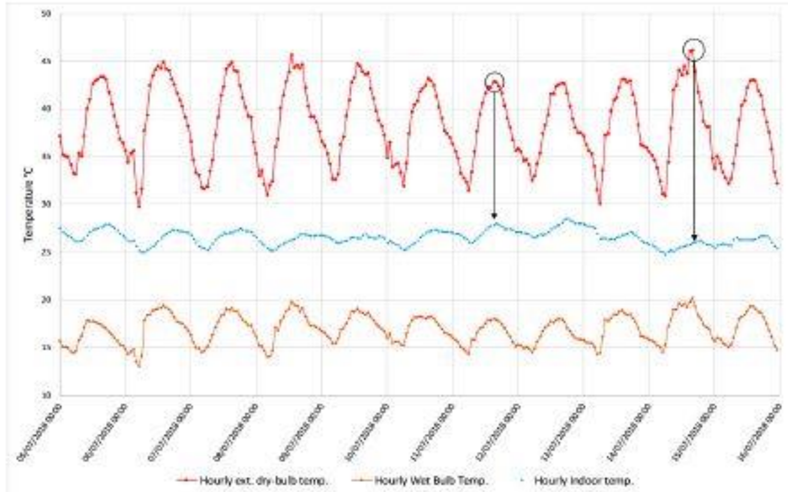


Figure 3. 10 days from 5th to 15th July, representing the hottest days of the recorded period.

5.2. *Wind direction effect*

In this case study, it was observed that the wind direction has a minimal impact on PDEC performance. This is attributed to four main reasons. First, the building was oriented in a way that placed the two cooling towers towards the prevailing wind direction, which was north-west. This minimised the effect of wind direction for most of the time. Secondly, it is strongly expected that the design and placement of the leeward clerestory openings within the roof significantly minimised the effect of other wind directions, which agrees with a previous computational study conducted by the authors [12]. Third, the wind catcher, at the top of each tower, was designed with four openings facing each direction. Then, an X-shaped wind barrier was placed inside the wind catcher directing the coming winds form any direction towards the airstream within the tower. Last, most of the collected data were at low wind speed while the data that was during higher wind speed was mostly coming from the prevailing wind direction. As a result, the impact of wind direction was neglected when investigating the wind speed effect.

5.3. *Wind speed effect*

It was apparent from the collected data that the wind speed had a direct influence on the performance of the PDEC towers. Hence, a parametric analysis of the wind speed was conducted by grouping wind data into ranges of wind speed and then correlating them against environmental conditions in the library. The investigation was performed for hours from 9:00-18:00 daily. This was the time of the day representing the higher DBT when there was a big difference between the DBT and WBT, known as wet-bulb depression (WBD). Another justification was that the higher wind speeds were recorded during daytime while nighttime was mostly calm. The results indicated that the PDEC towers' effectiveness was influenced by changes in wind speed, but in a counter-intuitive way as stronger wind speeds tended to reduce the efficiency of the towers. These findings from measured data support previous PDEC simulation analyses by the authors [12]. Figure 4 shows the observed average temperature reduction (external-internal air temperature difference ΔT) plotted against wind speed for the PDEC towers (A and B). ΔT ranged from approximately 18°C during near calm conditions to 13.5°C at the highest wind speed recorded. A simple linear correlation analysis between the ΔT and wind speed showed a strong negative relationship. A possible explanation for this is that turbulence increased around the tower inlet opening at the top due to the higher wind speeds, as discussed by [13].

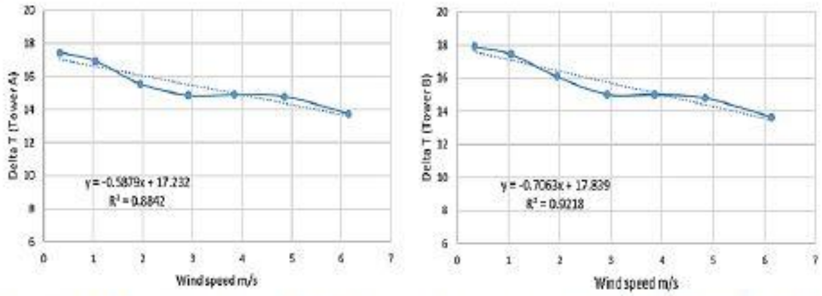


Figure 4. Influence of wind speed on the temperature reduction in Tower A (left) and B (right).

5.4. Overall Performance

The measured data from the PDEC towers demonstrated their ability to provide useful levels of cooling. Both towers performed well, but it was clear that Tower B was generally more effective than Tower A. This could be because the W and SW wind directions played a role, as discussed previously, or the layout of the Library could be a factor. It can be seen in the floor plan (Figure 2) that the supply opening of Tower A is facing a partition wall that forms a computer zone within the main area of the Library. This obstruction could hamper the airflow from Tower A, which would lead to reduced performance under certain circumstances. On the other side, Tower B has a direct unobstructed connection with the Library's open space.

6. Thermal comfort analysis

6.1. Passive cooling mode - adaptive comfort model

Of the 1688 monitored hours in the Library, the building was occupied for 410 hours. The mechanical cooling was working in conjunction with the PDEC towers (mixed-mode) for about 19% of the total occupied time, while the remaining 81% of the occupied time was just in PDEC passive cooling mode (i.e. a mixed-mode arrangment). Following the recommendation of [10] for mixed-mode buildings, the thermal comfort performance of the PDEC towers was analysed using the adaptive approach during the 410 occupied hours and the entire 1688 monitored hours (~70 days). The adaptive comfort model, as developed by de Dear and Brager [8] uses the following equation to calculate the comfort temperature:

$$Tcomf = 0.31Tm + 17.8 \quad (1)$$

Where Tcomf is the comfort temperature, and Tm is the monthly mean outdoor temperature. The model can represent two comfort zones – an 80% acceptability limit is used for typical applications, whilst a 90% acceptability limit is used when a higher standard of thermal comfort is desired. These two ranges can be defined by adding ±3.5°C to the comfort temperature to determine the 80% acceptability or ±2.5°C for the 90% acceptability [6][8]. Following the adaptive comfort model limits stated in the ASHRAE Standard [8], the higher end point of the mean monthly outdoor temperature (33.5°C) was considered in Equation (1), giving a Tcomf of 28.2°C. Consequently, the 90% acceptability limits were 25.7°C and 30.7°C while the 80% acceptability limits were between 24.7°C and 31.7°C. Using these comfort levels, the number of comfort hours experienced in the Library can be derived from the measured data.

IOP Conf. Series: Earth and Environmental Science **329** (2019) 012042 doi:10.1088/1755-1315/329/1/012042

6.2. Comfort hours using the adaptive comfort model

The adaptive model was used to predict thermal comfort hours during both the occupied working hours (410 hours) and the total recorded hours (1688 hours) - see Table 1 and Figure 5. Most recorded indoor temperatures fall within the comfort zone, ranging from 71% of acceptable temperatures within the narrower *90%* range of the total monitored period to 98% for the wider *80%* range during occupied hours only. 1606 hours where recorded during the passive cooling mode only, including occupied and non-occupied hours. Approximately 92% of the recorded indoor temperatures fell within the 80% thermal comfort range. Within the 90% comfort range, it was found that 70% of the monitored period was considered thermally comfortable. The rest of the measurements were recorded below this limit.

Table 1. Thermal comfort analysis using the adaptive comfort model for both occupied hours only and the total monitoring period for 80% and 90% acceptability limits.

	PDEC + mixed-mode (hours)	Comfort range 80% (°C)	No. of Comfort hours 80%	Comfort hours 80% (%)	Comfort range 90% (°C)	No. of Comfort hours 90%	Comfort hours 90% (%)
Occupied hours	410	24.7-31.7	401	97.8%	25.7-30.7	357	87.1%
Total monitored hours	1688	24.7- 31.7	1565	92.7%	25.7-30.7	1203	71.3%

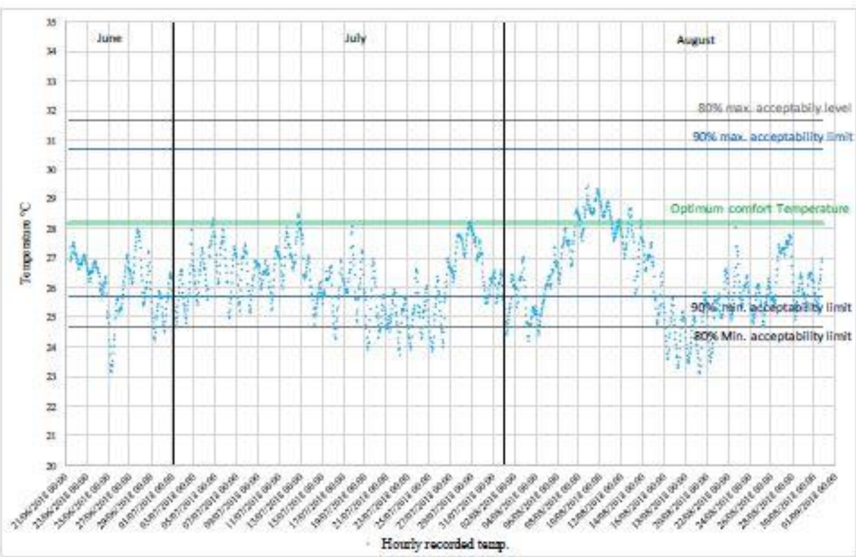


Figure 5. Measured summer internal air temperatures and 80% and 90% adaptive comfort ranges.

7. Conclusion

This paper has analysed the performance of an existing PDEC building – the Dar Al-Rahmaniah Library in Saudi Arabia. The case study provided detailed information about the ability of the PDEC towers to provide effective passive cooling, although the degree of cooling was affected by prevailing wind speeds. It was apparent from the finding that higher wind speeds had a negative impact on the performance of the towers, leading to higher supply air temperatures. The effect of wind direction was found to be minimised by the overall design and form of the library. Limitations of the current study include the fact that very low wind speeds could not be measured as the weather logger only recorded speeds above 0.6 m/s. The second part of the analysis used the adaptive comfort approach to determine levels of thermal comfort in the library. Results indicated high levels of comfort could be delivered by the PDEC towers for most of the occupied time. Further work could include detailed further parametric analysis of wind speed effect by linking the external wind speed to the tower and supply air velocities.

Acknowledgments
The authors acknowledge Abdulrahman Al Sudairy Cultural Centre for providing full access to Dar Al-Rahmaniah library and sharing all the information and documents needed to conduct this research.

References

[1] Abuhussain M, Chow D and Sharples S Assessing the adaptability of the Saudi residential building's energy code for future climate change scenarios *Proc.PLEA 2018*, p 73
[2] U.S. Energy Information Adminstration (EIA), Country Analysis Brief: Saudi Arabia 2017.
[3] Lechner N *Heating, Cooling, Lighting Sustainable Design Methods for Architects* 4th ed. 2009.
[4] Ford B, Schiano-Phan R and Francis E *The Architecture and Engineering of Downdraught Cooling*. Bologna, Italy: PHDC Press, 2010
[5] Ford B, Patel N, Zaveri P and Hewitt M Cooling without air conditioning: the Torrent Research Centre, Ahmedabad, India *Renewable Energy* **15**, pp. 177–182, 1998
[6] Torcellini P, Judkoff R, and Hayter S Zion National Park visitor center: significant energy savings achieved through a whole-building design process *ACEEE Summer Study on Energy Efficiency in Buildings* July, 2002
[7] Torcellini P, Deru M, Griffith B, Long N, Pless S, and Judkoff R, Lessons learned from field evaluation of six high-performance buildings *ACEEE Summer Study on Energy Efficiency in Buildings* July, 2004
[8] ASHRAE Thermal environmental conditions for human occupancy, ASHRAE Standard 55-2010. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia, 2010
[9] CIBSE The limits of thermal comfort : avoiding overheating in European buildings, CIBSE TM52: 2013
[10] de Dear, R. and G. S. Brager G S Thermal comfort in naturally ventilated buildings : revisions to ASHRAE Standard 55, 2002
[11] Paul M, John R, and de Dear R Mixed-mode buildings : a double standard in occupants ' comfort expectations *Build. Environ*. **54**, pp. 53–60, 2012.
[12] Alshenaifi M and Sharples S Investigating the impact of architectural form and wind direction on the performance of a passive downdraught evaporative cooling tower in Saudi Arabia *Proc. PLEA, 34th International Conference on Passive and Low Energy Architecture*, 2018, p 294
[13] Kang D and R. K. Strand R K Significance of parameters affecting the performance of a passive down-draft evaporative cooling (PDEC) tower with a spray system *Appl. Energy*, **178**, pp 269-280, 2016.

Appendix (B). Permession letter from Abdulrahman Al-Sudairy Cultural Centre to install the data-loggers

مركز عبدالرحمن السديري الثقافي
ABDULRAHMAN AL-SUDAIRY CULTURAL CENTRE

التاريخ: ٢١ / ٠٥ / ١٤٣٩هـ
الموافق: ٢٠١٨/٠٢/٠٦م

المكرم/ محمد بن عبدالله الشنيفي المحترم

السلام عليكم ورحمة الله وبركاته،

إشارة إلى طلبكم إجراء دراسة ميدانية على أبراج التبريد في مبنى مكتبة دار الرحمانية بالغاط، خلال الفترة من ٢ يونيو ولغاية ٣٠ أغسطس ٢٠١٨م، ضمن دراستكم لمرحلة الدكتوراه، وبحثكم المعنون: " تأثير التصميم المعماري للمبنى على فعالية وأداء ملاقف الهواء (أبراج التبريد) في المملكة العربية السعودية ".

نفيدكم بموافقتنا على طلبكم، ويمكنك التواصل مع أمين مكتبة دار الرحمانية، محمد الغنيم لتسهيل مهمتكم.

مع أمنياتي لكم بالتوفيق،،،

مساعد المدير العام

سلطان بن فيصل بن عبدالرحمن السديري

Abdulrahman Al-Sudairy Foundation | Royal Decree No. A/442, on 9/9/1403h (1983)
Al-Jouf 42421 P.O.Box 458 Tel: 014 6245992 - Fax 014 6247780
Al-Ghat 11914 P.O.Box 63 Tel: 016 4422497 - Fax 016 4421307
Riyadh 11614 P.O.Box 94781 Tel: 011 2817094 - Fax 011 2811357
Kingdom of Saudi Arabia | www.alsudairy.org.sa

Appendix (C). External and enternal measured temperatures for the entire monitored period of Dar Al-Rahmaniah library