# 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

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**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 5$^{th}$ to 15$^{th}$ 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 11$^{th}$ July. On July 14$^{th}$, 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 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.

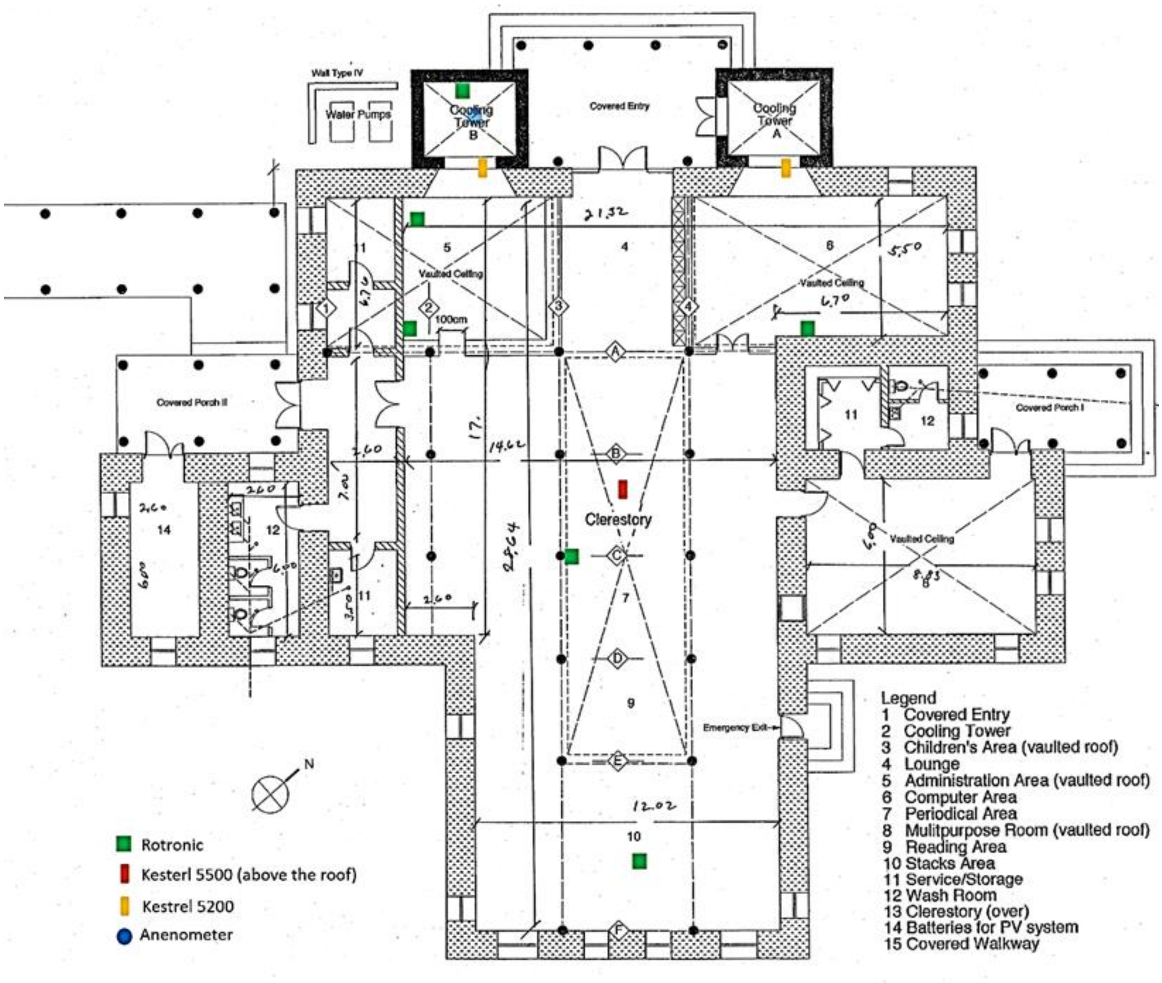


**Figure 2.** Library floor plan showing the location of the data loggers.

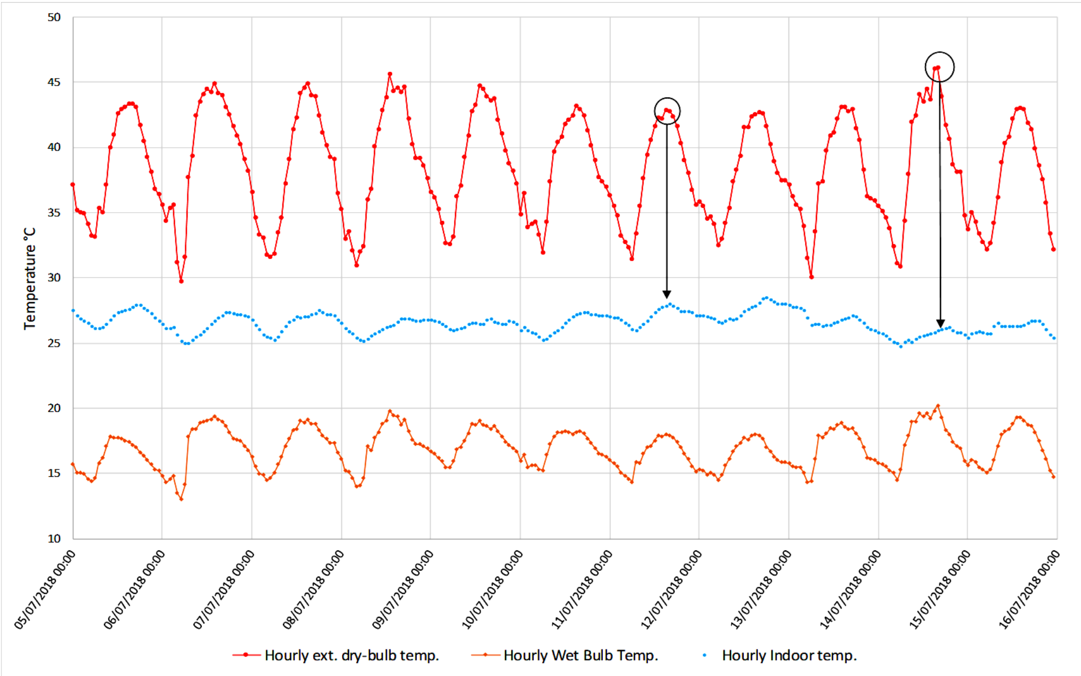


**Figure 3.** 10 days from 5th to 15th July, representing the hottest days of the recorded period.

### *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].

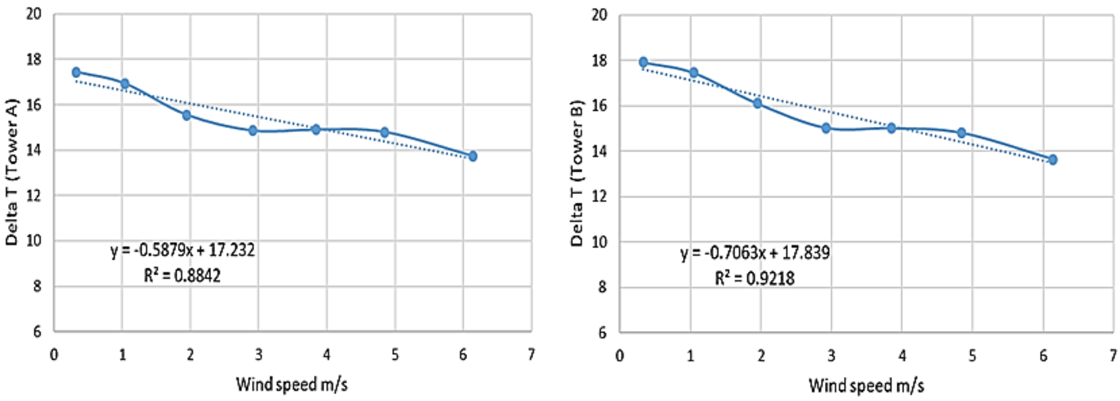


**Figure 4.** Influence of wind speed on the temperature reduction in Tower A (left) and B (right).

### *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.

### *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% |

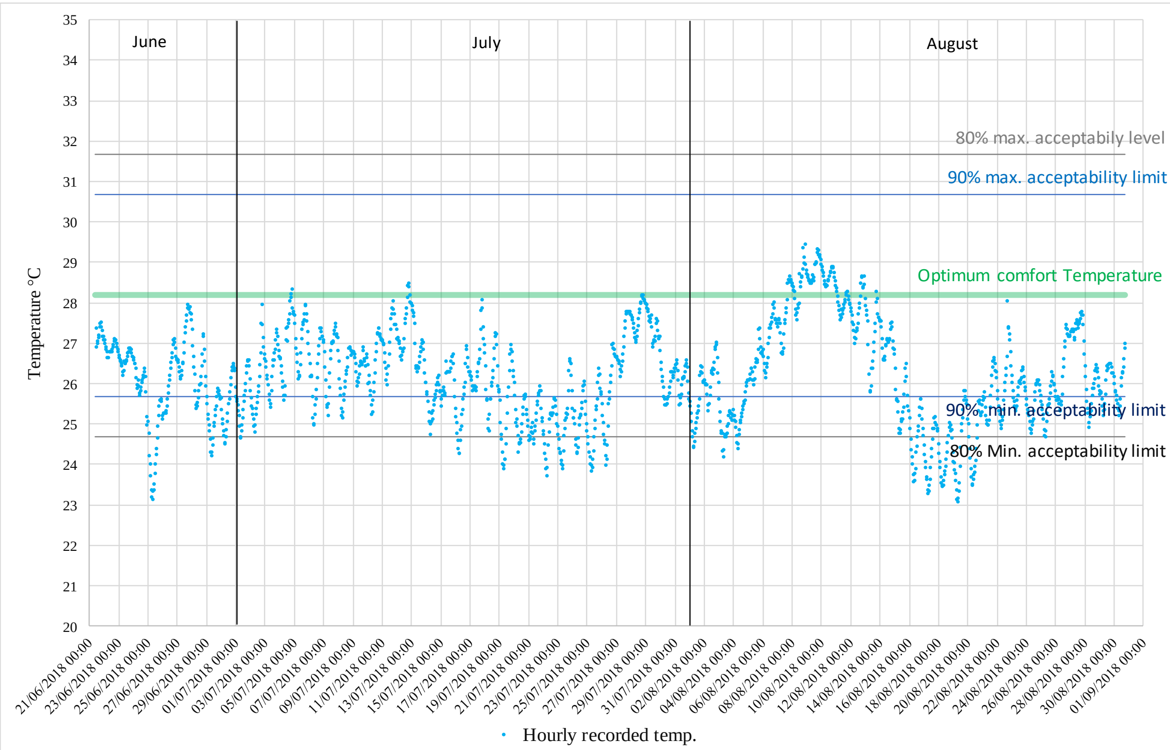


**Figure 5.** Measured summer internal air temperatures and 80% and 90% adaptive comfort ranges.

## *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.

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