Modelling the impact of ground temperature and ground insulation on cooling energy use in a tropical house constructed to the Passivhaus Standard

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Modelling the impact of ground temperature and ground insulation on cooling energy use in a tropical house constructed to the Passivhaus Standard

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Abstract. In tropical climates ventilation introduces high levels of moisture into dwellings, leading to raised values of indoor relative humidity and air temperatures, creating occupant thermal discomfort. The Passivhaus standard, by creating a super insulated and air-tight envelope, reduces heat losses and provides low energy comfort. This approach in tropical housing might be effective but could potentially increase mechanical cooling demand. This research investigated the effect of ground temperatures on thermal comfort and energy-saving in a tropical dwelling. Terraced houses in Jakarta, Indonesia were chosen as this a popular house type. IES VE software was used to study building energy use, and the Passivhaus software PHPP examined the application of Passivhaus criteria. Field measurements of air temperature and relative humidity were used to validate the software model. Analysis revealed that the building's predicted air temperatures were affected by the assumed ground temperature models in IES. Good agreement between the measured and modelled values was achieved only when a particular ground model was chosen. Having validated the IES model, dwelling insulation and air-tightness levels were incrementally changed until they met the Passivhaus standard. Finally, the feasibility of meeting the Passivhaus energy standard for cooling in the modified tropical house was tested.

1. Introduction

Low-density housing demand in Indonesia has contributed significantly to uncontrolled urban sprawl around the edges of Indonesia's major cities [1]. This unplanned development is characteristic of contemporary Asian Urbanization [2]. Many of these dwellings are badly constructed, being poorly insulated and not well-sealed. The air conditioning (AC) that is employed to achieve thermal comfort for residents is used inefficiently and expensively. Indonesia's hot and humid climate, coupled with rapid urbanisation and economic growth, means the demand for cooling energy in residential buildings will increase sharply in the coming decades [3]. In 2017, the three largest energy user sectors in Indonesia were transport (47%), industry (30%) and housing (16%) [4]. It is forecast that, by 2020, building energy consumption in South East Asia countries will exceed that of developed countries, with 56% of total building energy demand being used for air-conditioning [5]. Therefore, it is desirable to investigate low energy cooling systems that could help reduce the need for electric air conditioning.

Radiant cooling is one such strategy to cool buildings. Concrete Core Temperature Control (CCTC), for example, pumps cool water around pipes cast inside the floor [6]. In tropical climates, ground soil temperatures range from around 15°C to 25°C, and so can be much cooler than the ambient air temperature [7]. Floor slabs in contact with the ground can, therefore, be effective in cooling a building.

The use of ventilation to try and cool buildings can transfer high amounts of moisture in to rooms, resulting in poor internal thermal and health conditions in which the optimum humidity levels of 40% to 60% [5] are exceeded. It is, therefore, necessary to create design approaches to building design that can keep indoor air humidity low while still reducing cooling energy consumption. One radical alternative solution is to apply the German Passivhaus standard [8], with its very high levels of insulation and air tightness, to Indonesian dwellings.

This paper presents the validation and testing of a house model developed using the commercial dynamic thermal simulation software IES. Monitored air temperature and relative humidity data from a real dwelling were used to validate the IES software model before Passivhaus concepts were applied to the house model. This paper describes the development of a Passivhaus standard for housing built in Indonesia that works for both thermal comfort and energy efficiency. The energy advantages from cool ground temperatures and no floor insulation were observed in the development of the house model.

1.1. The Passivhaus standard

The requirements for the Passivhaus standard, which originated in Germany, are shown in Table 1 [8]. These requirements are principally performance-based, using passive measures, minimal thermal bridging and a whole house mechanical ventilation system with highly efficient heat recovery [9]. Even though the initial developments were made within the relatively mild climate of Central and Northern Europe, studies have suggested that Passivhaus could be a feasible option in other climate types [10]. The Passive-On study forecast a number of issues related to Passivhaus criteria for warmer climate, including the introduction of a limit for summer cooling energy demand, a higher infiltration rate and an indoor comfort temperature that coincided with adaptive thermal comfort standards [11]. The application of the Passivhaus standard must also properly consider moisture balances and latent loads for buildings in a hot and humid climate.

Table 1. Passive House Criteria.

			Criteria[1]			Alternative Criteria[2]
Heating						
Heating demand	[kWh/(m^{2}a)]	≤	15			-
Heating load[3]	[W/m^2]	≤	-			10
Cooling						
Cooling + dehumidification demand	[kWh/(m^{2}a)]	≤	15 + dehumidification contribution[4]			variable limit value[5]
Cooling load[6]	[W/m^2]	≤	-			10
Airtightness						
Pressurization test result n_{50}	[1/h]	≤	0.6			
Renewable Primary Energy (PER)[7]			Classic	Plus	Premium	
PER demand[8]	[kWh/(m^{2}a)]	≤	60	45	30	±15 kWh/(m^{2}a) deviation from criteria...
Renewable energy generation[9] (with reference to projected building footprint)	[kWh/(m^{2}a)]	≥	-	60	120	...with compensation of the above deviation by different amount of generation

1.2. Thermal Comfort

Thermal comfort assessment is an important tool to assess energy usage and measurement thermal satisfaction achievement. The term ‘thermal envelope’ used here refers to the shell of the dwelling as a barrier to unwanted heat or mass transfer between the interior of the building and the outside conditions [12]. In hot climates, the effect of air movement and humidity are particularly important because heat lost by evaporation dominates [13]. The impact of the external temperatures on perceived comfort has to some extent also been incorporated in to design standards such as ASHRAE Standard 55. The finding on the ASHRAE adaptive comfort standard study was the difficulty of creating generalization for areas that have mean outdoor temperatures above 23°C. The research indicated that buildings in this zone were unable to maintain thermal comfort for many hours of the day [14]. This is consistent with other research that found some climatic differences between cities in the lowland and highland in Indonesia, which could lead difference in people's comfort temperature due to physical adaptation [15]. However, the Indonesia National Standardization Agency (SNI) still issues standards whereby the comfort temperature is set at 25°C ± 1 °C and comfort relative humidity at 60% ± 10% [16]. The result from a study of comfort temperatures for people in the Depok area (a Jakarta satellite town) indicated that the comfort temperature was higher than this national standard, at 27.6°C [17].

2. Research methodology

This paper investigated the impact of ground temperature model on a simulated Passivhaus building. A row (terraced) house of the type that is commonly found in the Jakarta Metropolitan Region was chosen for the study. IES VE 2018 software was used to predict the dwelling's indoor temperatures, relative humidity and energy use. The building model in IES VE was built by inserting building information such as building materials, cooling systems, lights and appliances, and a presupposed occupancy schedule. The selected monitored house had a floor area between 50m^2 to 69m^2 floor area in which form most of the existing urban housing stock for housing in the Jakarta Metropolitan Region [18]. Empirical validation compared the computer simulation results with monitored data from the house. Analysis was done by investigating the typical housing characteristic, building performance and energy consumption.

3. Case study monitoring

The dwelling was in the major housing development area of Bogor, Jakarta Metropolitan Region. The dwelling measured 6m x 10m in plan, with a total floor area of 55m^2, and a floor-to-ceiling height of 2.85m. The building's main axis orientation was northerly; it was not insulated, being constructed from a single layer of brick, and with single glazing windows (Figure 1 and Figure 2).

Figure 1. Exterior of the row house.

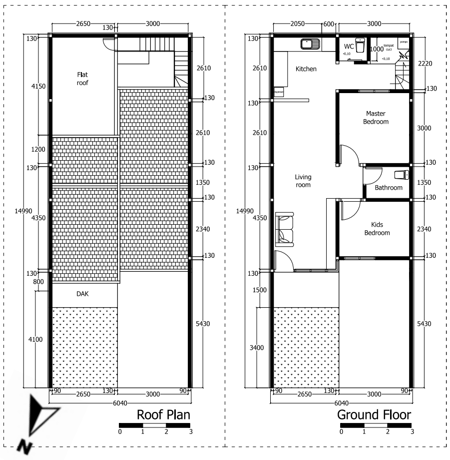


Figure 2. Floor plans of the row house.

The monitoring of the case study building was undertaken during a period of consistent occupation over two selected periods, one in January – February for the rainy season, and the other in September – November for the hot season. Air temperature and relative humidity values were collected at 30 minute intervals using Tinytag and Rotronic data loggers placed at a height of 1.5m in the living room, master bedroom and a sheltered outdoor area. Because of space limitations, only the living room results are presented in this paper.

4. Validation of the IES VE 2018 software

A three-dimensional dwelling model in IES VE software was built using the data obtained from field measurements. The IES VE simulation result was compared with measured period data, in this paper in mid-September, which has comparatively high weekly air temperature and a larger gap of temperature differences between maximum and minimum temperature compared to all the measured data. The dwelling model in this software was using plan provided by the home owner as a guidance, building materials information was based on the contractor specification, and the occupant activity schedule was gained from field observations. The building elements used to build the base model in IES VE 2018 can be seen in Table 2.

Table 2. Building elements.

Building Element	Constructional layers
External and internal walls	25 mm thick cement plaster + 100 mm thick clay brick + 25 mm thick cement plaster
Party wall	25 mm thick cement plaster + 100 mm thick clay brick + 25 mm thick cement plaster
Floor	8 mm thick ceramic tile + 22 mm thick cement screed + 100 mm thick concrete slab + soil layer
Window	6 mm thick single layer glass
Ceiling	6 mm thick gypsum board
Pitched roof	20 mm thick roof tile + 25 mm thick timber batten
Ceiling slab	22 mm thick cement screed + 100 mm thick concrete slab + 20 mm thick cement plaster

4.1. The ground temperature model used in the simulation

Figure 3 shows the detailed analysis of the air temperature and relative humidity measured data compared with simulation results for the living room. A large divergence between measured and modelled values was evident for daytime results, with simulation data showing internal air temperatures similar to the external temperatures. Undertaking a series of parametric studies of the IES model indicated that the assumed ground temperatures were creating the divergence. The default setting in IES VE sets the ground temperature equal to the external air temperature, but this may not be appropriate for tropical weather and soil conditions. To find out the setting for the ground temperature, the research continued by looking at ground temperatures in tropical countries, particularly Jakarta, Indonesia.

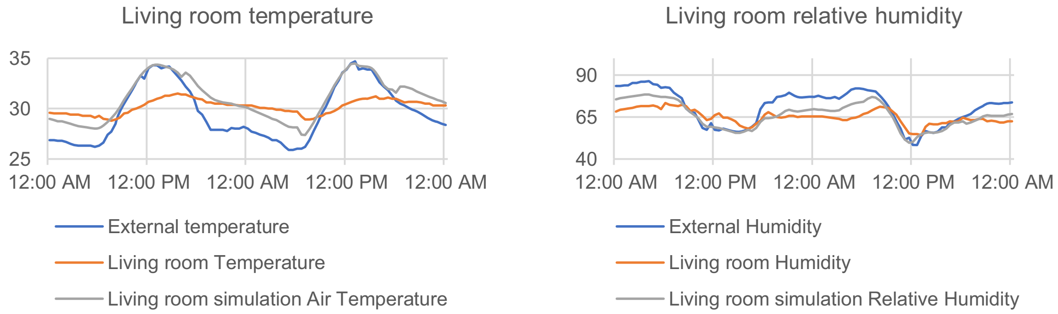


Figure 3. Comparison of measured and modelled air temperatures and relative humidities.

Soil properties are difficult to generalize because of local heterogeneity and the lack of broad based data; also, soil condition is not a standard variable collected at most weather stations [20]. Available literature indicates that underground soil temperatures can vary from 8°C to 27°C in some parts of the world, especially in cold-dominated areas (North America), and between 15°C and 25°C in tropical climates [7]. The average monthly ground temperature in Jakarta, based on the weather analysis software Climate Consultant, is 26°C [20]. Because soil temperature responds to the net effect of the daily surface energy balance, it can be estimated by computing a running average of air temperature, with progressively longer integration times as soil depth increases [21].

By using the literature information about ground temperature above, the setting on the IES VE simulation was set using outside air with an offset temperature profile. The analysis method for ground construction setting in IES VE software is based on EN-ISO 13370 [22]. The software analysis indicated that an offset temperature profile set at - 5°C from the external temperature was appropriate for this simulation. The graph in Figure 4 is ground temperature that was estimated by offsetting measured external temperature by -5°C following analysis above. The graph indicated that there was more than 75% of the time when the ground temperatures were below the adaptive comfort level.

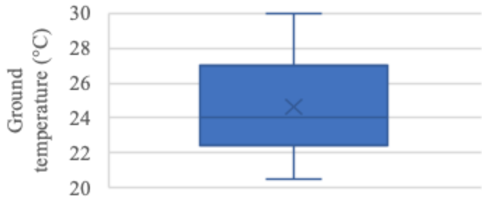
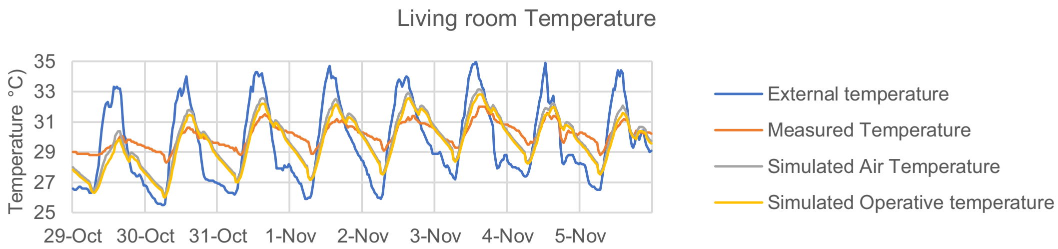


Figure 4. Box plot of ground temperatures during a one-week period.

4.2. The validation results

Figure 5 shows the air temperature and relative humidity for the living room after applying the adjusted ground temperature model. The results indicate that the simulations were satisfactory in displaying the same trends as the measured data. Living room results in Figure 5 suggest that the differences between the measured and modelled air temperature values were around 1 to 2°C, and the differences for relative humidity were around 10%.



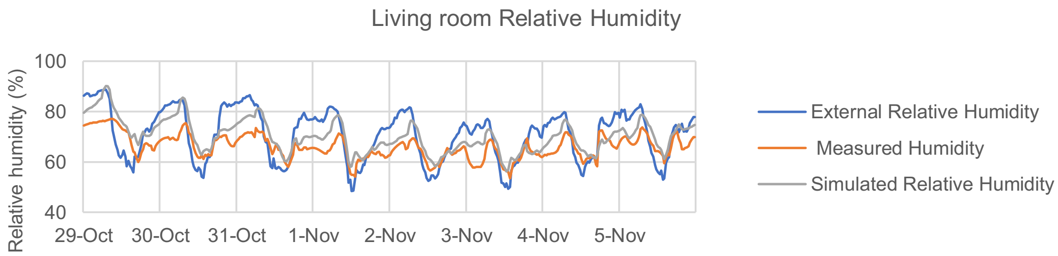


Figure 5. Measured and simulated data comparison in the living room.

To ensure that the IES dwelling model was statistically valid, an analysis was conducted in accordance with ASHRAE Standard 14-2002 [23]. As an indication of the mean ratio of relative error between two values (measured and modelled), the mean bias error MBE and Coefficient of Variation of the Root Mean Square Error CVRMSE were calculated. ASHRAE Standard 14 defines the acceptable limits for calibration to hourly data as within ±10% MBE (hourly) and ≤30% CVRMSE (hourly) measured at a utilities level [23]. The evaluation results for this study showed relative humidity and temperature MBE values for the living room of -5.9% and +0.3% respectively and CVRMSE values of +7.5% and +3.1% respectively. Therefore, it can be concluded that the IES simulation can model satisfactorily the studied house in the tropical climate and produce relatively similar results compared with the field measurement data.

5. The impact of ground temperature impact on a Passivhaus building in a tropical climate

To study the effect of ground temperature on a tropical Passivhaus building, the validated IES building model had Passivhaus elements applied to it. Table 3 indicates the materials that were used in the building model to follow the Passivhaus concept. This performance of the Passivhaus model will be compared with a Passivhaus model that had the floor insulation removed to let the ground floor act as a thermal sink and potentially provide radiant cooling. The house with its original building elements was also included in the comparison to look at the performance of the building with the Passivhaus standard to study the energy saving to reach thermal comfort. All three scenarios used the same HVAC system (AC and dehumidifier) that was located in the living room, master bedroom, and children's bedroom. For the simulation, the AC temperature set point in IES was 26°C, and relative humidity controller was set at 60%.

Table 3. Passivhaus building elements.

Building Element	Constructional layers
External and internal walls	25 mm thick cement plaster + 100 mm thick clay brick + 100 mm XPS Extruded Polystyrene + 25 mm thick cement plaster
Party wall	25 mm thick cement plaster + 100 mm thick clay brick + 100 mm XPS Extruded Polystyrene + 25 mm thick cement plaster
Floor	8 mm thick ceramic tile + 22 mm thick cement screed + 100 mm thick concrete slab + Urea Formaldehyde Foam + soil layer
Window	6 mm thick double layer glass
Ceiling	6 mm thick gypsum board
Pitched roof	20 mm thick roof tile + 25 mm thick timber batten + 100 mm MW Glass Wool (rolls)
Ceiling slab	22 mm thick cement screed + 100 mm thick concrete slab + 20 mm thick cement plaster

The loggers used in this study recorded air temperature. Operative temperature is often considered a better indicator of thermal comfort as it combines both air and mean radiant temperatures in a space but is not easy to measure in real building situations. The IES software was run to test for any significant differences between predicted air and operative temperatures in the house. However, as shown in Figure 5, there were only minor difference between simulated air temperatures with simulated operative temperature and so it was feasible to use air temperature for the validation and the comfort analysis.

6. Result and discussion

With the application of the Passivhaus standard to the IES dwelling model, simulation results for the living room showed that the Passivhaus building model provided stable air temperatures (Figure 6), although the air temperatures were mostly above 27.6°C (the adaptive comfort level). For the original building elements scenario, the air temperature was still fluctuating and following the external air temperature, with a few hours being above 27.6°C. Meanwhile, the Passivhaus application without floor insulation always maintained room air temperatures below 27.6°C. Relative humidity for the original house scenario tracked outside relative humidity and, for most of the time, was above 60%. On the other hand, the Passivhaus model and Passivhaus without floor insulation indicated low relative humidities, with relative humidity staying below 60% by using the AC + Dehumidifier system. With the same building HVAC system and occupancy schedule, the IES simulation predicted an annual cooling energy use of 11.41 MWh for the original layout, 10.89 MWh for the house with Passivhaus application, and 8.61 MWh for the Passivhaus without floor insulation (Figure 7).

From this study, the application of Passivhaus into a tropical dwelling provided stable interior air temperatures and relative humidities. The building airtightness reduced cooling energy slightly, and by removing floor insulation significant energy savings were made. The floor can be seen to act as a radiant cooling source for the dwelling built in tropical climate since the ground temperature that below room adaptive comfort level.

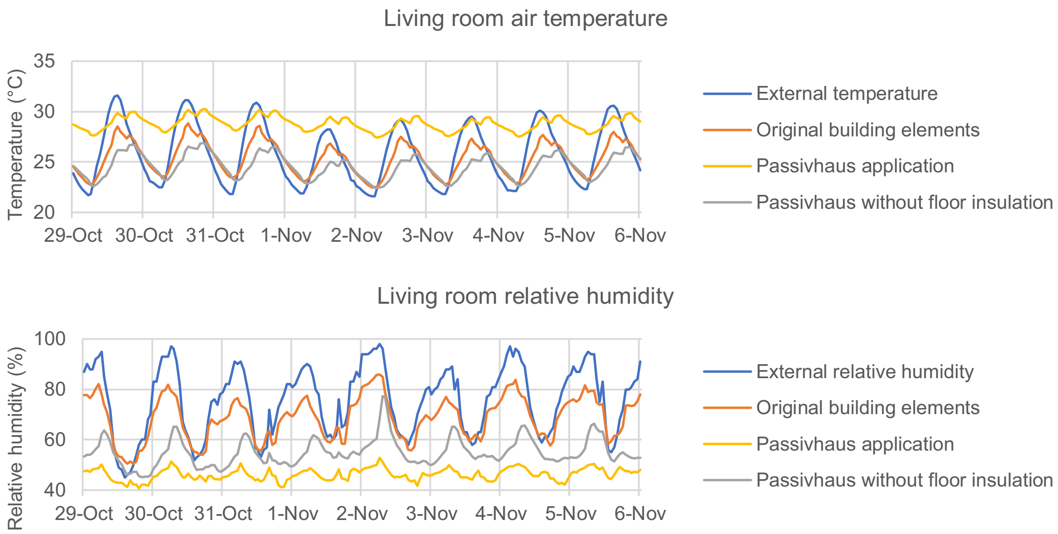


Figure 6. Hourly air temperatures comparison in living room for Passivhaus approaches and original building elements.

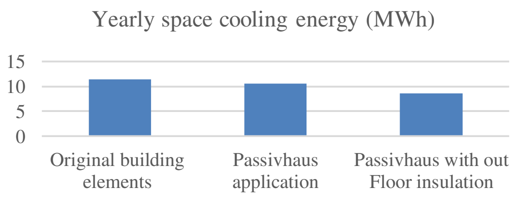


Figure 7. Yearly space cooling energy use for the original building elements, the Passivhaus and the Passivhaus without floor insulation.

7. Conclusions and discussion

This paper explored the effect of ground temperature on the performance of a Passivhaus-enhanced dwelling in a tropical climate. The original dwelling was monitored to gain air temperature, relative humidity and activity schedule data that were used to create a validated IES building model. The validation process identified ground temperature as an important variable in the model. The impact of coupling the building to the ground without using insulation was also examined and found to reduce cooling energy demand whilst maintaining good comfort levels. The application of the Passivhaus concept in tropical climates still needs further analysis. Besides the additional construction cost for the building, the skill of construction workers needs to be improved, especially residential construction workers, because the use of insulation, double glazing, and constructing air-tight building is not common practice in Indonesia.

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