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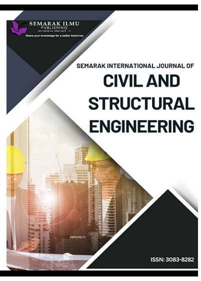

Computational Fluid Dynamics Analysis to Evaluate Effect of Furniture on Thermal Comfort in Residential House in Tropical Area

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ABSTRACT

The energy consumption in a residential house is typically influenced by factors such as the household size, as indicated by the number of family members, and the financial resources available to the household, as indicated by the household income. In Malaysia, the domestic sector accounts for 82% of the total electricity customers, 10.08 million people. This study presented a computational fluid dynamic (CFD) of three different scenarios involving the positioning of wooden furniture indoors to examine their impact on wind circulation and thermal comfort. The temperature and wind velocity data were obtained from the average historical meteorological data for the Putrajaya region. The CFD analysis was performed under varying environmental conditions, including wind velocities and ambient temperatures, during daytime and nighttime. The study concluded that the impact of the furnishings during daylight hours was negligible. The room was bare of furniture during the nighttime period, and the room with fewer furnishings in Scenario 1 and Scenario 2 exhibited a more rapid decline in temperature than the room with densely arranged furniture. There is an observed increase in the predicted mean vote (PMV) ranging from +1.0 to +1.2 during nighttime compared to PMV values recorded during daytime. Wooden furniture can play a role in moderating indoor temperatures and offering a degree of insulation against outdoor temperature variations.

1. Introduction

Energy efficiency and greenhouse gas emissions have become an issue in various industries. Residential energy consumption is the underpinning for 16% to 50% of all energy sectors and accounts for around 30% of the world's energy consumption [1]. Domestic electricity customers account for 81.93% of Malaysia's 9.9 million total consumers, as stated in the report [2,3]. In nearly every region, the housing industry is a significant energy user. Due to the complexity and interdependence of the residential house's energy consumption characteristics, this sector must utilize energy efficiently [4]. Due to centralized ownership, vested interests, expertise in enhancing

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energy efficiency, and numerous rules and restrictions, energy consumption in other critical sectors, such as commercial, industrial, agricultural, and transportation, is realized better than in the housing sector.

An increase in gross domestic product (GDP) will automatically increase the electricity demand but in varying proportions. Malaysia has the highest energy consumption, with the same percentage as other high-energy consumption countries, such as Italy, Sweden, Norway, and Finland [5]. Extreme energy consumption has risen in Malaysia in recent years due to the country's rapid economic growth, particularly in the country's commercial and residential buildings. Nearly half of all power produced is used in buildings for living and business. Electricity consumption in Malaysia rises by 1.5% for every 1% growth in GDP, according to the country's GDP elasticity of roughly 1.5 [2,6].

Various factors on individuals' social and economic status can significantly impact residents' perspectives and behaviors concerning energy consumption. Multiple factors have been identified to substantially affect overall energy consumption, including climate conditions, building design characteristics, tenant behavior patterns, as well as social and economic influences. The energy requirements of a building are subject to the effect of the behavioral patterns and practices exhibited by the individuals operating within and utilizing premises [7]. The factors are interrelated when analyzing energy consumption in the housing sector. Economic growth for locals will be affected by their energy usage. The 3-star concept is illustrated graphically in the interrelation representing the environment, population action, and technology issues. Axis A is the neighborhood in which the house is built. Axis B is the occupant's interaction with the house. Axis C is a technical feature, for example, the properties of materials and installed equipment [8]. These three factors play their respective roles but are interrelated to obtain the perfect energy consumption pattern.

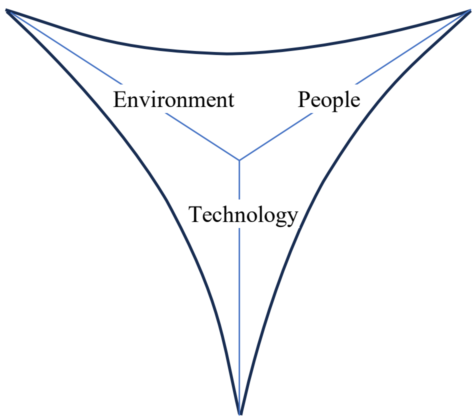


Fig. 1. The 3-star concept [8]

Earlier research has relied on total power load or peak use. However, analysis of lower power consumption limitations offers valuable information about the structure's physical features or design [9]. For instance, a building with leaks may have an enormous idle load since the heating or cooling system must work continually [10]. Physical components of a structure include things like windows. One of the essential tools for controlling the internal climate and circulation is the use of windows. In order to achieve the minimum air quality or ventilation that ensures thermal comfort in the home, a window is adjusted to generate a specified air flow rate or air exchange rate that is more linked to the interior of the space. This method assumes that the inhabitants use window apertures to get the intended ventilation level [11]. Another illustration of a physical characteristic is furniture.

Furthermore, by lowering heat loss via the building envelope, double-pane windows and thermally insulated buildings (exterior walls, roofs, and floors) can reduce yearly energy usage for space heating. Buildings that are separated from the outside environment may use between 20% and

40% less energy overall [12]. Thermal insulation will improve the management of overheating and interior temperature. Tents or other forms of external shade can block solar radiation from entering a structure and lessen the cooling demand. The cooling demand of the area can be lowered by up to 30% by adequately putting up the shade [13]. Moreover, by extending the thermal area by 2 to 3 degrees Celsius, the ceiling fan in the apartment's main room can lower the yearly cooling load while improving the space's thermal comfort. Ceiling fans provide a 70% reduction in the cooling burden of the room [14]. A lightweight roof and outside walls also minimize the heat absorbed by the building envelope, lowering the yearly cooling demand. Previous studies used computational fluid dynamics (CFD) to examine the heat loads and furniture on the thermal comfort of an isolated family house in Kurdistan [15], and another study took place in Mumbai on single furniture in different positions [16]. Both studies concluded that the minimum effect of furniture on thermal comfort is limited to specific opening and spatial parameters. This study aimed to examine the impact of three scenarios involving the positioning of furniture indoors on wind circulation and thermal comfort in a residential house in a tropical area. Wooden furniture and its arrangement will be examined as a physical feature in this study.

2. Method and Materials

2.1 Study Area

The research location in this paper is Precinct 14, located on the edge of the Putrajaya Federal Territory in a twelve-story apartment. Computational fluid dynamics (CFD) simulation will be carried out on the one-unit model of the apartment building. Figure 2 shows the location of the building. The temperature and average rainfall per month throughout the year for the Putrajaya area are shown in Figure 3. The maximum rainfall can reach 400 mm in November, and the lowest rainfall is less than 100 mm in February. Figure 4 shows the wind speed and its direction. The highest average wind speed occurred in December and January at 2.1 m/s, with a maximum wind speed of more than 3.5 m/s. In January, the wind direction is more dominant towards the east, and in July, it is dominant towards the south. The CFD simulation will use the highest monthly average wind speed of 2.1 m/s. The presence of furniture in a building unit will be considered, and temperature emissions from electrical devices throughout the study will be ignored. Then, a discussion of the results of the CFD analysis will be carried out.

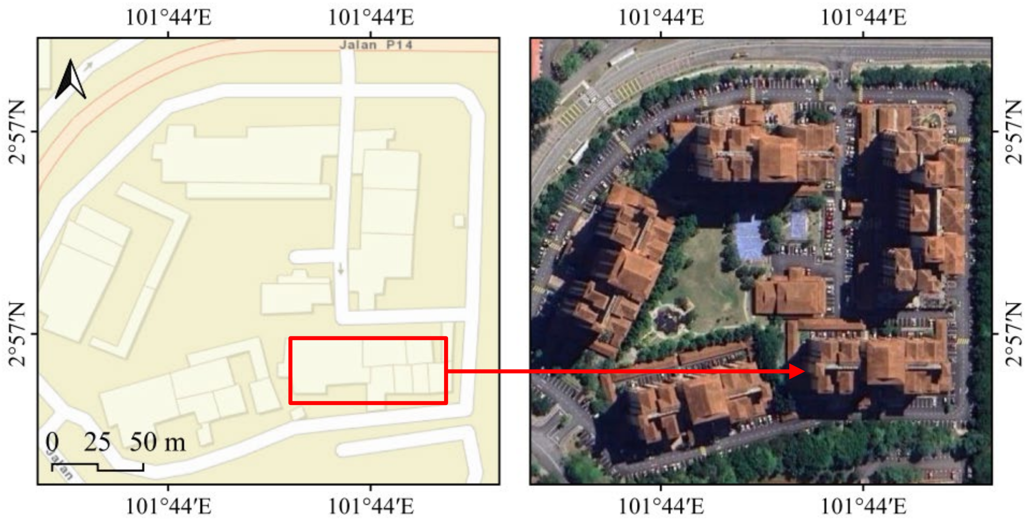


Fig. 2. The study area at Precinct 14, Putrajaya, Malaysia

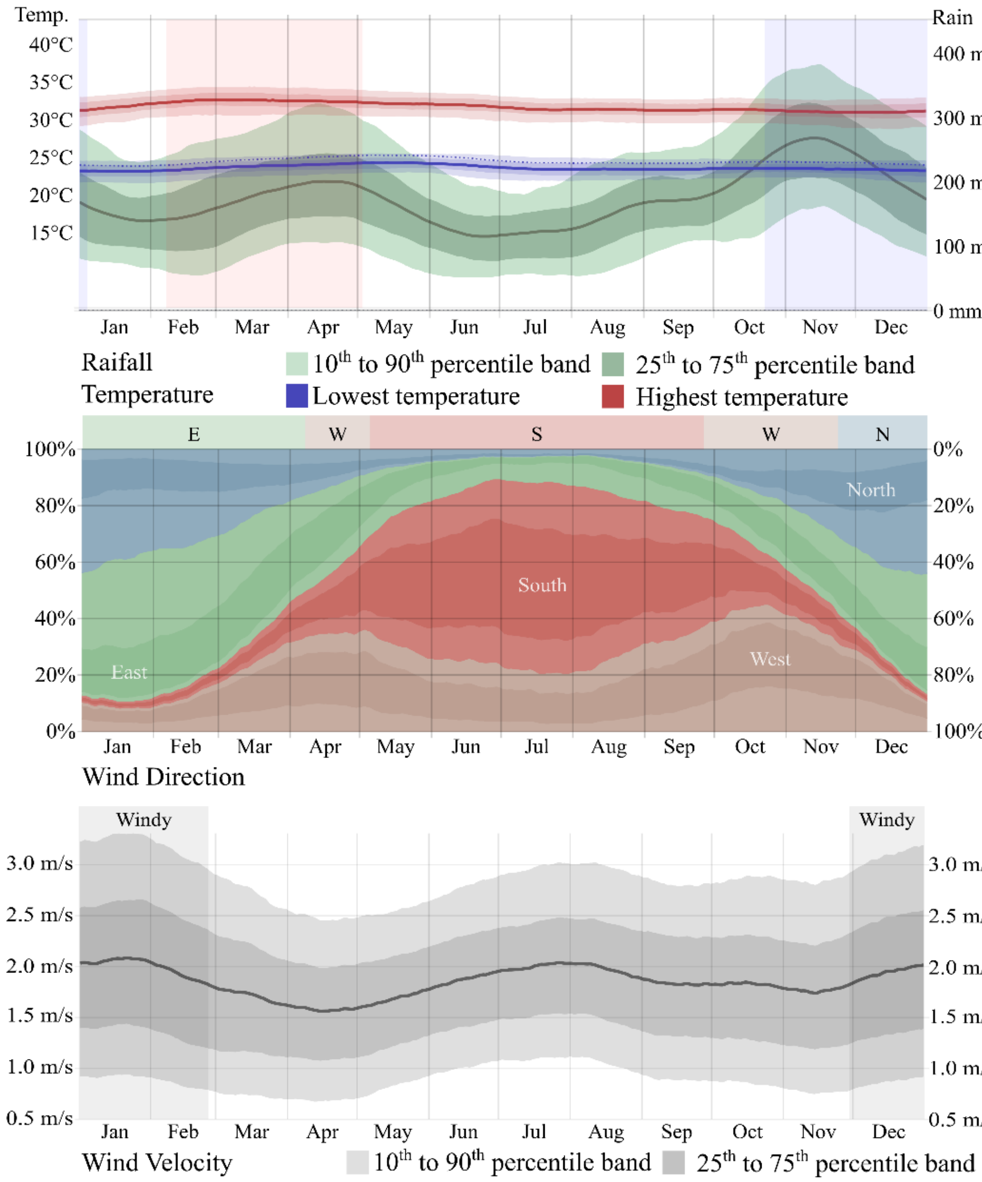


Fig. 3. The monthly temperature, wind, and received rainfall

2.2 CFD Models and Analysis

The CFD model can simulate complex phenomena, such as buoyancy-driven flow, vortex discharge, and multi-scale eddy motion [12]. Several steps need to be taken before completing the simulation. First, define the materials. All materials were set for particular objects, including air volume. The simulations were performed with the commercial CFD analysis software Autodesk CFD 2023. The materials were selected from the material database. Then, the next step is to define the boundary conditions. Boundary conditions were assigned to the simulation model, such as wind speed, flow rate, and how fluids enter or leave the model [17]. The Navier-Stokes equations for incompressible flow are commonly employed as the governing equations for fluid flow, as they provide a comprehensive description of the conservation principles of momentum and mass for a fluid [18]. The equation comprises three primary constituents: the continuity equation in Eq. (1) and the momentum equation in Eq. (2). For this study, the boundary condition is summarized in Table 1. Figure 4 shows three furniture placement scenarios in the house. The boundary condition for the wall is a no-slip wall with heat transfer that solves conduction and convection. The heat transfer coefficient, U (W/(m^{2}K)), for a wall surface consisting of several layers of different materials is presented in Eq. (3). Where h_{ci} and h_{co} (W/(m^{2}K)) are convection heat transfer coefficients, k_n (W/(mK)) is the thermal conductivity of the material for each layer, and s_n (m) is the thickness of each layer. Table 2 lists the variables used in CFD analysis.

Table 1
Boundary Condition

Boundary	Type	Detail	
Surface facing SE	Wall	Film Coefficient	4.61 W/(m^{2}K)
		Temperature	41^o Celsius
Surface facing SW and NW	Wall	Film Coefficient	4.61 W/(m^{2}K)
		Temperature	28^o Celsius
Floor surface	Floor	Film Coefficient	3.43 W/(m^{2}K)
		Temperature	25^o Celsius
Glass surface	Glass	Film Coefficient	12.1 W/(m^{2}K)
		Temperature	26^o Celsius
Surface facing NW	Outlet	Pressure	0 Pa Gage
Surface facing SE	Inlet	Velocity Normal	2.1 m/s
		Temperature	32^o Celsius
Volume	Human body	Total Heat Generation	60 W

$$\nabla \cdot \mathrm{u} = 0 \tag{1}$$

$$\frac{\partial \mathrm{u}}{\partial t} + (\mathrm{u} \cdot \nabla)\, \mathrm{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathrm{u} \tag{2}$$

where, u is velocity vector, ρ is density, p is pressure, and ν is kinematic viscosity.

$$\frac{1}{U} = \frac{1}{h_{ci}} + \sum \frac{s_n}{k_n} + \frac{1}{h_{co}} \tag{3}$$

Table 2
Thermal conductivity of the materials

Material	s_n	k_n	$h_{ci,o}$ air
Plaster	0.02	1.73	25
Bricks	0.11	0.8	
Reinforced Concrete	0.15	0.7	
Glass	0.006	1.05	

The applied boundary conditions are based on the wall and floor U-values on the wall surface, as in Eq. (1). The value of U used in this study for masonry walls with a thickness of 110 mm and 20 mm thick plaster on both sides is 4.61 W/(m^{2}K). The standard k-epsilon model is used for its consistency and stable to predict airflow. The three scenarios of furniture arrangement in this study are as follows. Scenario 1: Figure 5 (a) the house is empty. Scenario 2: Figure 5 (b) the furniture is arranged partially full in the house. Scenario 3: the house is fully furnished.

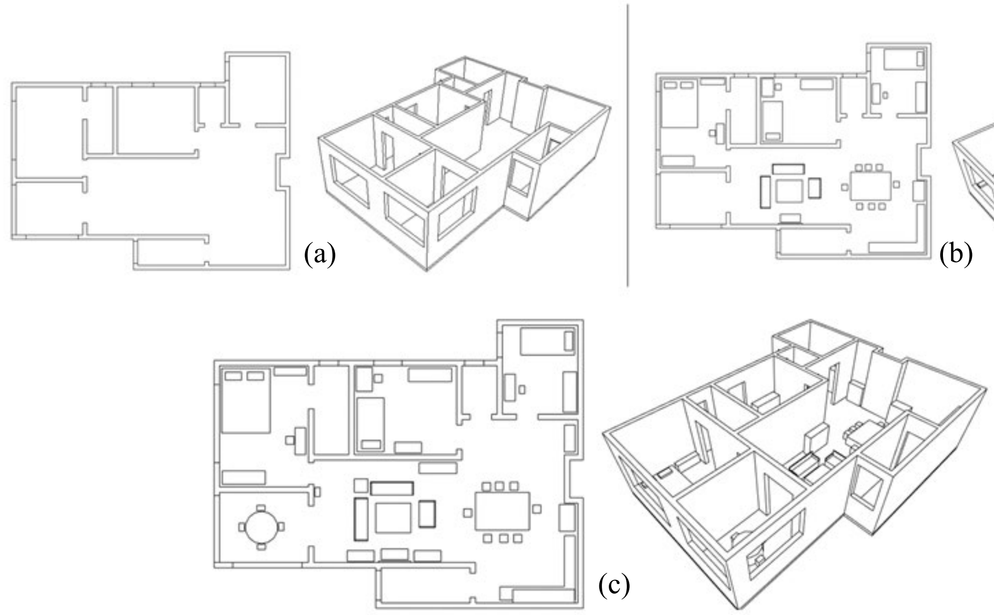


Fig. 5. The three scenarios of furniture placement

A 150 mm thick reinforced concrete floor with tiles has a *U* value of 3.43 W/m^{2}K. The highest surface temperature of 41^{o}C was applied to the side of the wall facing the sun based on a study in [13]. Furthermore, the wall side with indirect sunlight has a temperature of 35.9^{o}C. The surface temperature at night was 25.9^{o}C, and the floor temperature was set at 30^{o}C. Table 3 lists the U-value for all parts of the building. The thermal comfort of the house occupants was evaluated by placing three human models in several locations, as shown in Figure 6. The PMV is a function in which the tenants' clothing and metabolic activity are included. For this study, the metabolic activity was assumed to be seated or writing that emits a temperature of 60 W all the time and wearing trousers and a short-sleeve shirt with a *clo*-value of 0.57. The CFD analysis was set to iterate up to 700 iterations, and for most of the model, the convergence was achieved before the end of the last iteration. Figure 7 shows the convergence plot, whereby the simulation was converged in step 578. Most of the parameters converged early in the simulation except the two turbulence models of turbulent kinetic energy (TKE) and turbulent energy dissipation (TED). Two turbulence equations are commonly employed in scenarios involving expansive stationary areas or situations characterized by numerous obstacles slowing the flow and reducing local flow velocities.

Table 3
The *U*-value for different materials

Material	*U-value*
Plastered brick wall (150 mm)	4.61
RC slab floor (150 mm)	3.43
Glazed window (6 mm)	12.1

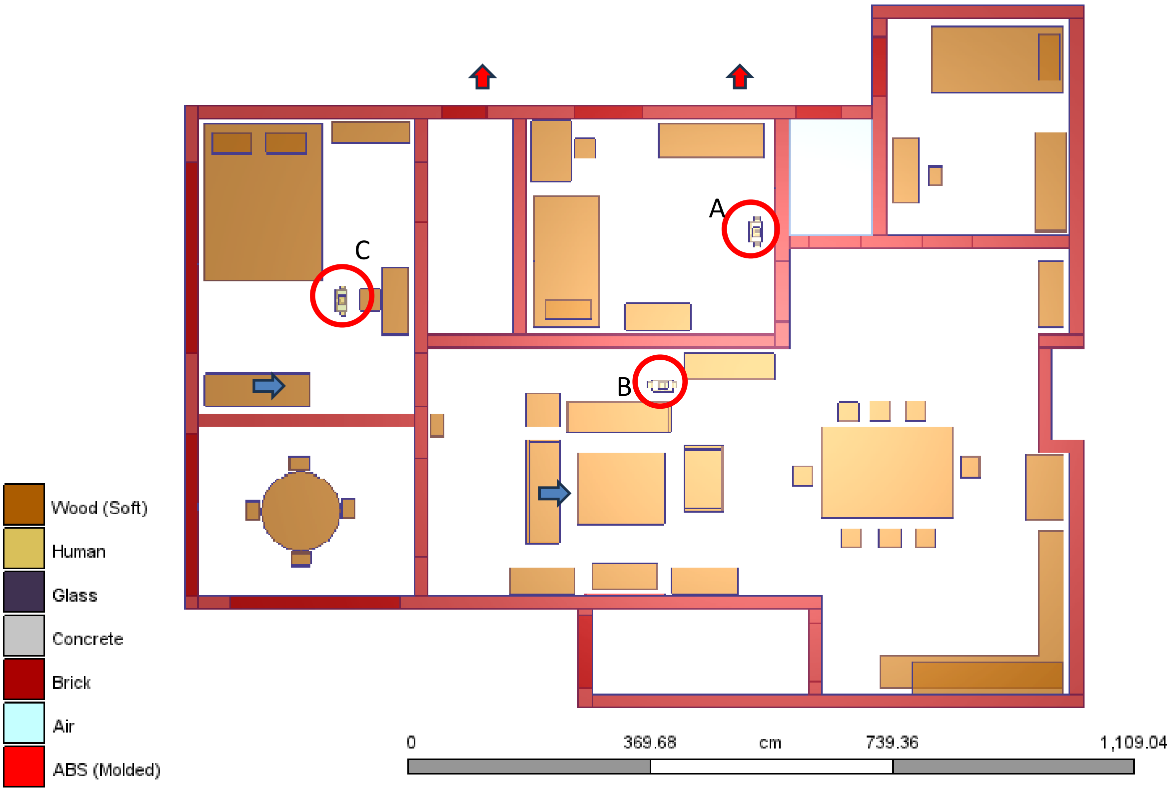


Fig. 6. The inlet (blue arrow) and outlet (red arrow) scenario and position of the human models (red circle)

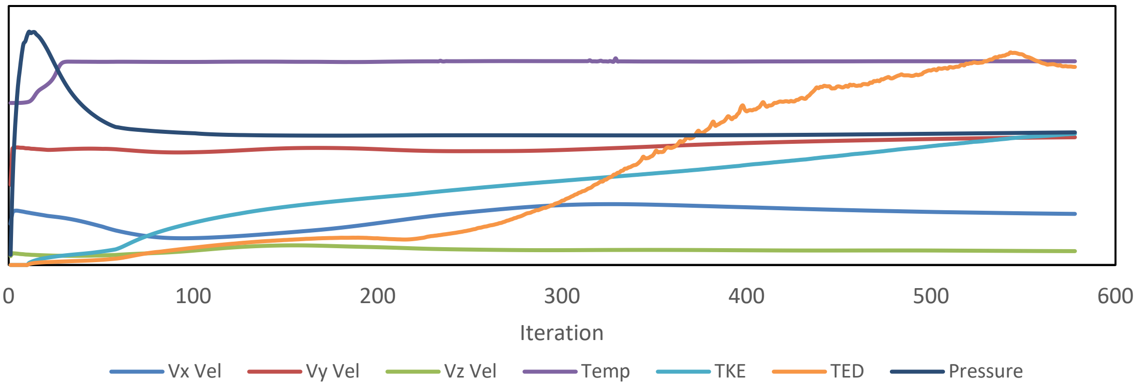
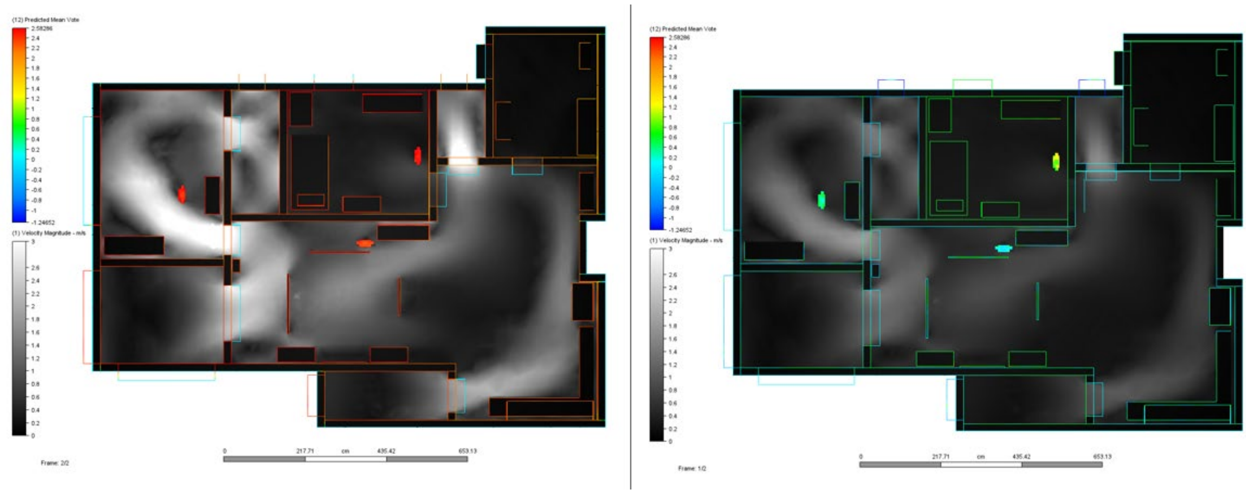


Fig. 7. The iteration plot of the simulation for the third scenario

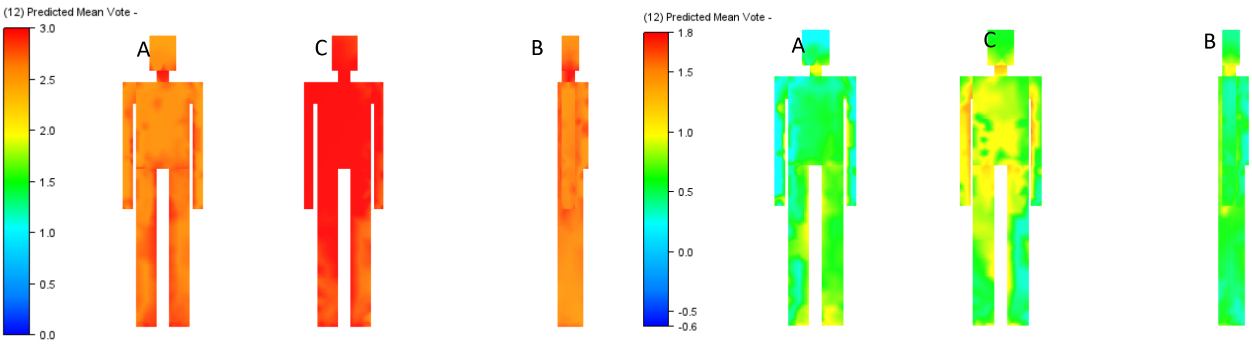
3. Results

CFD analysis was conducted to determine the furniture's effect on wind velocity. Its effect on the thermal comfort of the occupants was also examined. The predicted mean vote (PMV) is employed as an index of thermal comfort according to ASHRAE 55:2017. According to MS 2680:2017, the PMV value for naturally ventilated areas in warm conditions is found to overstate the comfort experience by roughly 2°C [19]. The simulation of CFD on the conditions listed in Table 4 revealed the PMV value for solid human models. The MS 2608: 2017 indicated that the operational temperature range might be selected based on adaptive thermal comfort. For an outside air temperature of 31.5°C, the operational temperature should be between 24 and 31 degrees Celsius. The PMV for the human model in Scenario 1 was between 1.87 and 1.92. Figure 9 depicts the PMV on the human body's solid tissues. Scenario 3 gave the PMV value on a human body model ranging from +2.0 to +3.0 in the daytime and from +0.5 to +1.80 during nighttime. Table 4 lists the temperature of the human models during the daytime and nighttime.



(a) (b)

Fig. 8. The simulated airflow and the PMV of the occupant for Scenario 3 in (a) daytime and (b) nighttime



(a) (b)

Fig. 9. (a) The PMV in the daytime and (b) The PMV in the nighttime for Scenario 3 on the human models as in Figure 6

Table 4
The temperature on the human body model at different locations

Location	Temp. (°C)	Day			Night		
		Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
A	Min.	33.5	32.6	33.7	28.7	27.4	28.4
	Ave.	32.4	30.8	32.8	27.1	25.5	27.3
	Max.	34.2	33.4	34.0	29.7	28.2	28.7
B	Min.	33.2	32.9	33.5	28.3	27.4	28.4
	Ave.	32.2	31.0	32.6	26.5	25.5	27.3
	Max.	33.8	33.7	33.9	29.1	28.3	28.7
C	Min.	34.8	33.9	34.8	28.7	27.5	29.1
	Ave.	32.5	32.0	33.3	27.1	25.6	27.7
	Max.	36.0	34.7	35.4	29.7	28.3	29.7

4. Discussion

This study aimed to examine the impact of three scenarios involving the positioning of wooden furniture indoors on wind circulation and thermal comfort in a residential house in a tropical area. It was observed that for the furniture material, which was assigned as wood, apparently the hygrothermal properties of the material can improve the indoor air humidity, as stated in the previous study [20]. The CFD analysis observed that in Scenario 1, where the room has no furniture, the indoor temperature was only affected by the wall and floor's thermal conductivity. The temperature of the human models in Scenario 1 during the daytime was 21.4% higher than during nighttime as compared to Scenario 3, and the temperature difference was 19.18%. The presence of furniture within the residential house seemed to have a noticeable cooling impact throughout the day and night in all three designated areas (A, B, and C). In the context of furniture occupancy, it was seen that Scenario 2, which was partially furnished, tended to exhibit marginally lower temperatures compared to Scenario 3, which was fully furnished. In Scenario 1, it was observed that the absence of furniture led to higher temperatures throughout both the daytime and nighttime. This finding suggested that furniture can play a role in moderating indoor temperatures and offering a degree of insulation against outdoor temperature variations. It showed that the wooden furniture released the temperature gradually, thus affecting the overall indoor temperature.

5. Conclusion

The CFD study yielded satisfactory results in modeling the influence of the furniture and interior temperature on a human model. This study was limited to using wood as furniture without indoor mechanical ventilation. Regardless of the orientation of the house and the direction of the wind, it was determined that the effect of the furniture during the day was insignificant. However, during nighttime, the room without furniture and with less furniture in Scenario 1 and Scenario 2 had a faster temperature drop than the room with packed furniture. There was a +1.0 to +1.2 improvement in PMV during nighttime compared to PMV during the day. A study in [21] found that the direction of the wind and opening on the wall improved the ventilation rate values. From this study, the number of furniture in the house should be considered to improve human comfort and indirectly reduce the dependency on mechanical ventilation, especially in the tropical area of Malaysia with an average size of a residential house of 118 m^2 and a minimum size of 63 m^2 with three bedrooms.

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