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IMPROVEMENT OF THERMAL COMFORT INSIDE A MOSQUE BUILDING

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Graphical abstract

Abstract

A combined natural ventilation and mechanical fans are commonly used to cool the interior space inside the mosques in Malaysia. This article presents a study on thermal comfort in the Al-Jawahir Mosque, located in Johor Bahru, Malaysia. The objective is to assess the thermal comfort inside the mosque under the present ventilation system by determining the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). These values were then compared to the limits stated in the ASHRAE Standard-55. It was found that the PMV varies from 1.68 to 2.26 while the PPD varies from 61% to 87%. These show that the condition inside the mosque is quite warm. Computational fluid dynamics (CFD) method was used to carry out flow simulations, to identify a suitable strategy to improve the thermal comfort inside the mosque. Results of CFD simulations show that installing four exhaust fans above the windows on the west-side wall of the mosque is the most effective strategy to improve the thermal comfort inside the mosque. Both the PMV and PPD values can potentially be reduced by more than 60%.

Keywords: Mosque building; mechanical fan; space cooling; thermal comfort; hot and humid environment

Abstrak

Kombinasi di antara pengudaraan nutral dan kipas mekanikal lazimnya digunakan untuk menyejukkan ruang dalaman bagi masjid di Malaysia. Artikel ini mengemukakan satu kajian ke atas keselesaan terma dalam Masjid Al-Jawahir yang terletak di Johor Bahru, Malaysia. Objektif kajian adalah untuk menilai keselesaan terma di dalam masjid tersebut di bawah sistem pengudaraan sedia ada dengan menentukan indeks Predicted Mean Vote (PMV) dan Predicted Percentage Dissatisfied (PPD). Nilai-nilai ini dibandingkan dengan limit yang dinyatakan di dalam ASHRAE Standard-55. Didapati bahawa nilai PMV berada dalam julat 1.68 hingga 2.26 manakala nilai PPD adalah dalam julat 61% hingga 87%. Ini menunjukkan bahawa keadaan di dalam masjid tersebut adalah agak panas. Kaedah Computational Fluid Dynamics (CFD) telah digunakan untuk melakukan simulasi aliran, untuk mengenal pasti strategi yang sesuai untuk meningkatkan keselesaan terma di dalam masjid tersebut. Keputusan simulasi CFD menunjukkan bahawa memasang empat kipas ekzos pada bahagian atas tingkap di atas dinding sebelah barat bagi masjid adalah strategi paling berkesan untuk meningkatkan keselesaan terma di dalam masjid tersebut. Nilai bagi kedua-dua PMV dan PPD berpotensi untuk dikurangkan sebanyak lebih dari 60%.

Kata kunci: Bangunan masjid; kipas mekanikal; penyejukan ruang; keselesaan terma; sekitaran lembab dan panas

1.0 INTRODUCTION

The high span spaces were constructed in many places for various purposes. These spaces are also known as enclosed ventilated air spaces and they usually contain various air contaminants [1]. Large space constructions such as mosques, sports halls and open stadiums are distinguished from other high span space constructions in terms of energy consumption. These spaces possess issues that are related to indoor air quality and thermal comfort [1-5]. A mosque is considered as a special type of large space construction, used by Muslims to perform their congregational prayers and other communal religious activities. Thermal comfort inside the mosque is, therefore, an important requirement to ensure adequate comfort to the occupants when performing their activities. Unfortunately, this issue together with aspect of indoor air quality inside mosque buildings have not been comprehensively studied [2, 6-8].

In general, thermal comfort can affect productivity, health and thermal satisfaction of the occupants. According to the ASHRAE Standard-55 [9] and Fanger [10], thermal comfort can be defined as "that condition of mind which expresses satisfaction with the thermal environment". Based on Fanger [10] thermal comfort is determined by evaluating six governing parameters. Four of these parameters are related to the environment while the other two are related to the human occupants. The environmental parameters are relative humidity (RH), air temperature, (T_a), air flow velocity (V_a) and mean radiant temperature (T_{mrt}). The human parameters are their clothing and activity levels.

Various indices have been developed to evaluate the thermal comfort inside occupied spaces in buildings. These are the Effective Temperature Index, Equatorial Comfort index, Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD), and Corrected Effective Temperature (CET) index [11]. However, most of these indices have limitations in their applications under different climatic conditions. The only exception is the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD). They are widely used to represent the thermal comfort in many types of occupied spaces [2, 3, 12, 13]. The PMV is defined as "an index that predicts the mean value of the votes of a large group of a persons on the seven-point thermal sensation scale" [14, 15].

Several thermal comfort studies carried out in Malaysia, Singapore, Pakistan and Thailand showed that to achieve good thermal comfort, the air temperature has to be from 23.8°C to 28.6°C, the airflow velocity from 0.3 m/s to 1.0 m/s and relative humidity from 30% to 70%. Ibrahim [8] found that the most suitable airflow velocity is in the range of 0.5 to 1.0 m/s, the relative humidity from 35% to 70% and air temperature from 25°C to 28°C.

Previous thermal comfort studies in different types of building at several places in Malaysia showed that the use of new insulation materials that has very low thermal conductivity for the roof construction can significantly improve the thermal comfort inside the mosque buildings [8]. Installing a solar chimney in the terrace residential houses would also help improve the thermal comfort [18]. Also, a good thermal comfort in residential houses can be achieved with the air temperature ranging from 25.5°C and 28.5°C [19].

This article presents findings of thermal comfort study conducted on the Al-Jawahir mosque in Johor Bahru, Malaysia. The goal is to evaluate the PMV and PPD values under the presently used ventilation system. Air temperature, airflow velocity, mean radiant temperature, and air relative humidity were measured in the months of October 2014 (warmest month) and March 2015 (coldest month), from 11 AM to 3 PM. Computational fluid dynamics (CFD) method was then employed to predict the distributions of airflow velocity and air temperature inside the mosque. A parametric study was carried out to identify the most effective modification to the ventilation system that would improve the thermal comfort inside the mosque.

2.0 METHODOLOGY

2.1 Description of the Mosque Building

The Al-Jawahir mosque is shown in Figure 1(a). It has a rectangular shape with the length, width and height measuring 35m, 30m and 12m, respectively, as depicted in Figure 1(b). The total built-up area of the main prayer hall (MPH) is 915 m^2 and the wall is of 12 m height. The hall can be occupied by about 1270 people. The roof was constructed together with a dome, which is located at the middle and above the main prayer hall. The side walls of the prayer hall are facing the North and South directions. There are 12 doors and 12 windows on each side wall. The rear wall has 10 doors and 10 windows, as shown in Figure 1(c). The dimension of each door is 1.4 m x 2.2 m. The doors and windows provide natural ventilation to the main prayer hall. In addition, the prayer hall is furnished with 28 units of wall fans and 20 units of stand fans, as shown in Figure 1(d).

2.2 Field Measurement and Instrumentation

The following parameters were measured inside the main prayer hall: air temperature, airflow velocity, relative humidity and mean radiant temperature. Measurements were made at 5 locations inside the hall as indicated in Figure 2(a). The measuring instruments were placed at a height of 1.1m from the floor [12, 21], as shown in Figure 2(b). The data were conducted from 11 AM to 3 PM with a 10-minutes interval. The measuring instruments are shown in Figure 3 and their specifications are given in Table 1. They were calibrated before being used in the field measurement.

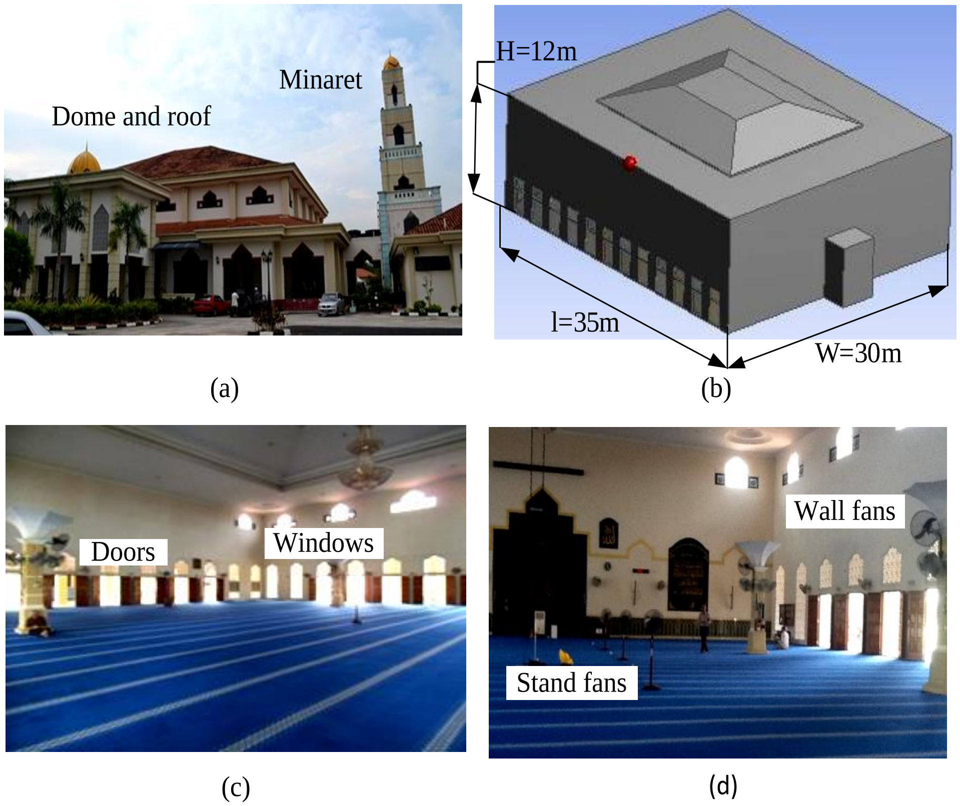


Figure 1 (a) The Al-Jawahir mosque, (b) Simplified model of the prayer hall of the mosque, (c) Internal view of the main prayer hall, and (d) Mechanical wall- and stand-fans.

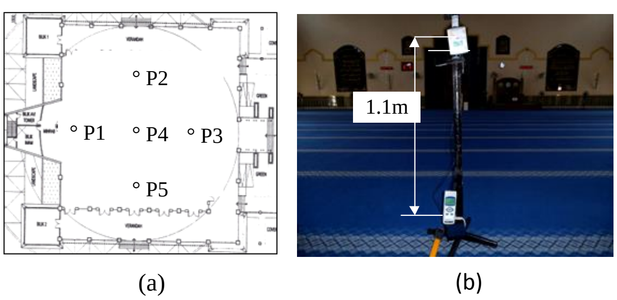


Figure 2 (a) Locations of data collection points, and (b) setup of the measuring instrument.

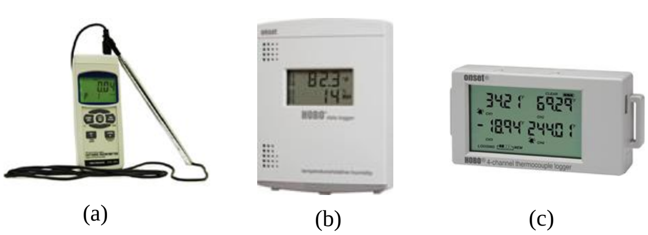


Figure 3 (a) Hot Wire Anemometer with Data Logger; (b) HOBO Temperature/Relative Humidity Data Logger; and (c) HOBO UX120 Series Data Loggers.

Table 1 Specifications of the measuring instruments.

Variables	Specifications
Air temperature	Hot Wire Anemometer with real time Data Logger.
Air flow velocity	Model HHF-SD1 Flow Velocity: Accuracy ± 15%. Temperature: Accuracy ± (0.4% + 0.5°C).
Relative humidity	HOBO Temperature & Relative Humidity Data Logger - H14-001. Accuracy ± 3.5% RH from 25% to 95% over range of 5° to 55°C.
Mean radiant temperature	HOBO UX120 Series Data Loggers. Measuring temp range -20 to 70°C, Accuracy ±0.21°C from 0° to 50°C.

2.3 Evaluation of Thermal Comfort Parameters

The predicted mean vote (PMV) is derived based on Fanger's model and it includes six primary parameters namely air temperature, airflow velocity, relative humidity, mean radiant temperature, metabolic rate (activity levels) and clothing [16]. The Predicted Percentage Dissatisfied (PPD) index refers to the percentage of occupants who complained about the environment. The PMV and PPD are determined using the following relations [15]:

$$PMV = [0.303\exp(-0.036M) + 0.028]L \qquad (1)$$

where M is the metabolic rate (W/m^2) and L is the thermal load on the body expressed as
L= internal heat production – heat loss to the actual environment

$$L = M - W - \{3.96 \times 10^{-8} f_{cl}[(T_{cl} + 273) \times 4] + f_{cl}h_c(T_{cl} - T) + [5733 - 6.99(M - W) - P_V] + 0.42(M - W - 58.15) + 1.7 \times 10^{-5} M(5867 - P_V) + 0.0014M(34 - T)\} \quad (2)$$

where W stands for active work (W/m^2) and f_{cl} is the garment insulation factor ($1\,c_{lo}$= $0.155\,W/m^2$) expressed as

$$f_{cl} = \begin{cases} 1.05 + 0.645 I_{cl} \text{ for } I_{cl} > 0.078 \text{ and} \\ 1 + 1.291 I_{cl} < 0.078 \end{cases} \quad (3)$$

where I_{cl} clothing insulation (m^2K/w). The T_{cl} (°C) refers to the cloth temperature given by

$$T_{cl} = 35.7 - 0.028(M - W) - I_{cl} \quad (4)$$

In Eqs. (2) and (4), T_r(°C) is the mean radiant temperature, T(°C) is the local air temperature and h_c is the heat transfer coefficient between the clothing and the surrounding air (W/m^2K). The heat-transfer coefficient given by

$$h_c = 12.1u0.5 \text{ for } 2.38(T_{cl} - T)0.25 < 12.1 \quad (5)$$

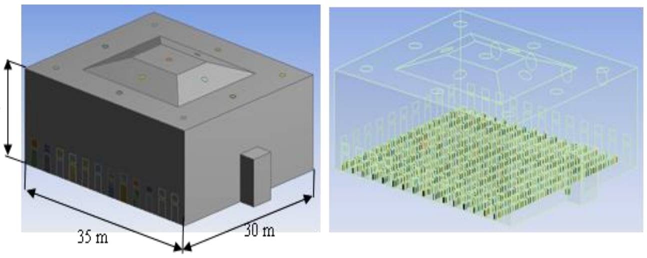
where u is the local air flow velocity (m/s).

The predicted percentage of dissatisfied index (PPD) represents the percentage of the people who felt more than slightly warm or slightly cold [17]. It is used to assess the thermal comfort satisfaction of the occupants. The value of PPD should be less than 10% [9]. It is calculated using Eqn. (6) as follows [15]

$$PPD = 100 - \exp[-0.03353PMV^4 + 0.271PMV^2] \quad (6)$$

2.4 Computational Fluid Dynamic Simulation

A computational fluid dynamic (CFD) method was employed to carry out flow simulations to predict the airflow velocity and air temperature distribution inside the main prayer hall of the mosque. The method was also used to carry out a parametric study to identify a suitable strategy for improving the thermal comfort inside the main prayer hall. FLUENT software was used to develop a simplified three-dimensional model of the mosque, as shown in Figure 4.



(a) (b)

Figure 4 (a) A simplified model of the main prayer hall, and (b) Models of the occupants.

The CFD model was meshed using tetrahedral volume elements. A grid independent test (GIT) was performed to determine the suitable number of elements to use. The airflow velocity at location P4 (Figure 2a) was chosen as the reference parameter in performing the GIT. The number of elements used were increased until the airflow velocity becomes unchanged. The results of the GIT is shown in Figure 5. The meshing of the CFD model is shown in Figure 6. The skewness, orthogonal quality and element quality of the meshing are 0.12, 0.97 and 0.98, respectively.

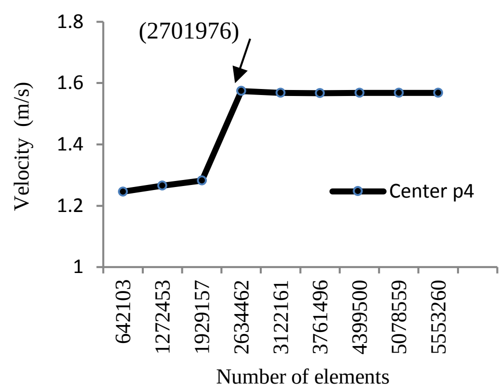


Figure 5 The grid independent test (GIT).

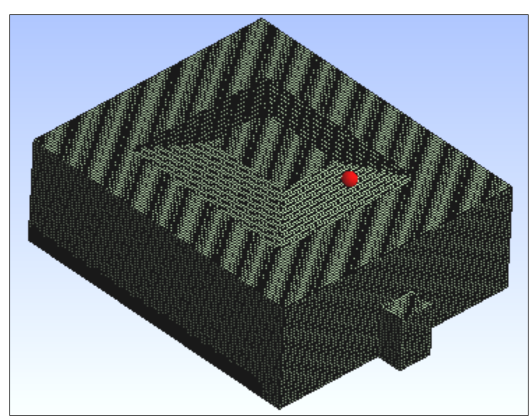
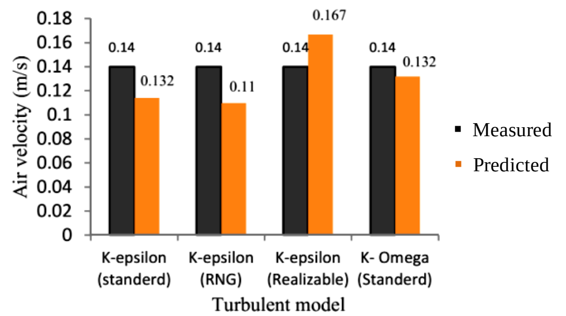
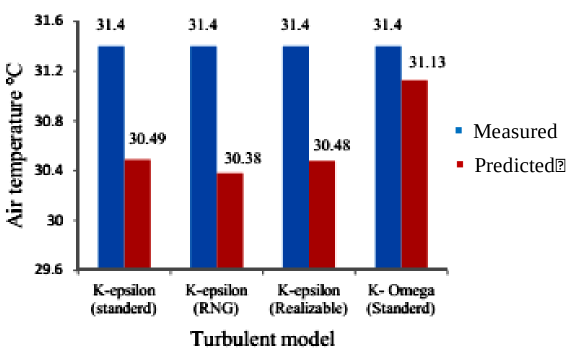


Figure 6 The meshing of the CFD model of the mosque.

A flow model test was carried out to identify the suitable turbulent flow model. Both the k-ε and k-ω family models were tested. The airflow velocity and air temperature at point P4 (Figure 2a) were chosen as the reference parameters. The results of the flow simulations using the Standard *k-ε*, RNG *k-ε*, Realizable *k-ε* and Standard *k-ω* are compared with the measured parameters at the same point. The comparison is shown in Figure 7. It was found that the standard *k-ω* flow model produces the smallest differences in both the airflow velocity and air temperature. Hence this model was chosen for the proceeding flow simulations.



(a)



(b)

Figure 7 Comparison of (a) Airflow velocity, and (b) air temperature for various turbulent flow models with the corresponding measured values.

The properties of the air and solid boundaries for the CFD model are given in Table 2. The air was assumed to behave as an ideal gas and its properties remain unchanged with temperature.

Table 2 Properties of the medium for CFD analysis.

Properties	Air	Concrete	Human body
Density, (m^3/kg)	1.16	2400	985
Specific heat (J/kg K)	1007.30	0.75	3500
Thermal conductivity (W/m K)	0.0265	0.9	0.8
Viscosity (kg/m s)	1.88×10^{-5}	-	-

Boundary conditions were prescribed on the CFD model for the airflow simulations. Inlet airflow velocity and temperature were prescribed at the doors at the back and right side of the prayer hall. Mean radiant temperatures were specified at all the walls of the hall. Body temperature, metabolic rate and heat flux were specified on the models of the human body. Finally, airflow velocity was prescribed at all the exhaust fans. Details of the boundary conditions are given in Table 3. The magnitudes of the airflow velocity, air temperature, and mean radiant temperatures of the walls were obtained from the field measurement. The values of parameters for the human body were based on the ASHRAE Standard-55 [14, 21]. The relative humidity of the air was taken as constant at 75%.

Table 3 Boundary conditions for the CFD simulations.

Section		Boundary condition	Parameters
Right door		Inlet airflow velocity & temperature	V_a = 0.5 m/s, T_a = 31.2°C
Back door			V_a = 0.3 m/s, T_a = 31.2°C
Walls	Dome	Temperature	T_d = 34.4°C
	Ceiling		T_c = 31.8°C
	Front		$T_{w, front}$ = 28.8°C
	Rear		$T_{w, rear}$ = 29.5°C
	Right		$T_{w,R}$ = 29°C
	Left		$T_{w,L}$ = 29.2°C
	Mehrab		$T_{w,M}$ = 29.4°C
	Floor		T_F = 28°C
Human body		Temperature	T_{body} = 31.2°C
		Metabolic rate	M = 150 W
		Heat flux	60 W/m^2
Exhaust fan		Airflow velocity	V_{fan} = 28 m/s

Flow simulations were performed in steady-state condition using a pressure-based segregated solver, a semi-implicit method, and with a second order upwind discretization scheme. The convergence criterion used for all equations was 10^{-4} except for the energy equation, in which the convergence criterion was taken as 10^{-6}, based on Hussin [12].

The validation of the CFD model was carried out by comparing the values of air temperature and airflow velocity obtained from the field measurement at all the measuring points (Figure 2a), with the respective values obtained from the flow simulation. The comparison is shown in Table 4 and Table 5, respectively. It was found that percentage differences of predicted data of airflow velocity are below 20% while those for the air temperature are below 5%. Based on the ASHRAE Standard-55 [14, 21], a 20% difference between predicted and measured data is considered acceptable for flow analysis involving a complex geometry.

Table 4 Comparison of predicted and measured airflow velocity

Location	Predicted	Measured	% Difference
P1	0.69	0.84	17
P3	0.83	0.71	16
P4	0.14	0.13	6
P5	1.49	1.37	8

Table 5 Comparison of predicted and measured air temperature

Location	Predicted	Measured	% Difference
P1	31.1	31.0	3
P3	30.9	31.0	1
P4	31.3	31.4	3
P5	31.2	31.2	0

Thermal comfort inside a confined space can be improved by improving the ventilation system [24]. An effective ventilation system is one which produces an even distribution and suitable airflow velocity magnitude inside the space. This will in turn lower the air temperature and improves its distribution inside the space. One method to improve the ventilation system is by installing ventilation fans on the walls. This approach was chosen in this study as it is easy to implement and does not consume high electrical energy. Three cases of exhaust fans installation were considered. These are illustrated in Figure 8.

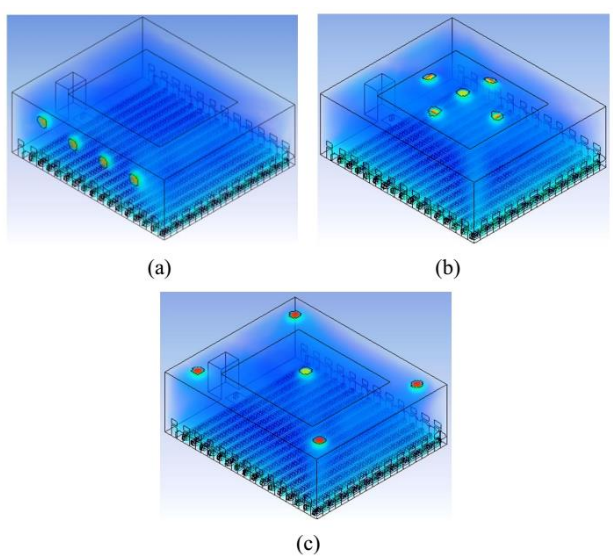


Figure 8 Cases of exhaust fans installation for improving thermal comfort: (a) four exhaust fans installed on the west-side wall, (b) five exhaust fans installed at the roof, and (c) five exhaust fans installed at the ceiling.

The airflow velocity at the exhaust fans was determined based on the air change per hour (ACH) for the main prayer hall. This represents the number of times the air inside the prayer hall is to be replaced with the fresh outside air, in one-hour. The volume of the main prayer hall is 12600 m^3. For a space of this size, the ASHRAE Standard-55 [14, 21] specifies an ACH value in the range of 8-12 per hour. To be conservative, the ACH value of 8 was chosen in this study. Based on this value, the volume flow rate of the air (m^3/s) to be exhausted from the main prayer hall can be obtained using Eqn. (7) as follows:

$$V = \frac{\text{ACH}}{3600} \times V = \frac{8}{3600} \times 12600 = 28\frac{\text{m}^3}{\text{s}} \qquad (7)$$

The exhaust fans available in the market have many sizes (diameters). In this study, the exhaust fans with a diameter, *D* of 56 cm was chosen because these fans will fit well into the wall and roof sections of the prayer hall envelope, as shown in Figure 8. The cross-sectional area for each fan is described in Eqn. (8):

$$\text{A}_{\text{c,fan}} = \frac{\pi}{4} \times \text{D}^2 = \frac{\pi}{4} \times 0.56^2 = 0.25\text{m}^2 \qquad (8)$$

For case 1, with four exhaust fans, the total area for the airflow path is 1.0 m^2 while for cases 2 and 3, the total is 1.25 m^2. The airflow velocity at each exhaust fan for case 1 would then be as in Eqn. (9)

$$\text{V}_{\text{airflow}} = \frac{\text{V}}{\text{A}_{\text{c,fan}}} = \frac{28}{1}\frac{\text{m}}{\text{s}} \qquad (9)$$

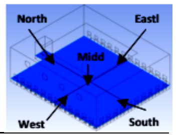
When five fans are used, the corresponding value of the airflow velocity is 22.4 m/s.

Flow simulations were carried out on the CFD models for the three cases of ventilation modification shown in Figure 8. The goal was to obtain the distributions of airflow velocity and air temperature inside the main prayer hall, for all the cases, and compare them with the corresponding distributions for the base case. The average values of airflow velocities and air temperatures obtained from the flow simulations were used to compute the new values of PMV and PPD. These values were then compared to the corresponding values for the base case, to evaluate the effectiveness of the proposed ventilation modifications.

3.0 RESULTS AND DISCUSSION

The PMV values corresponding to the present ventilation system (base case) were determined based on the average values of the air temperature, airflow velocity, mean radiant temperature, relative humidity, metabolic rate of the occupants and clothing thermal resistance, using Eqs. (1) - (4). Values of the metabolic rate and clothing thermal resistance were taken from the ASHRAE Standard-55 [14, 21] as 1.2 W/m^2 0.55 m^2K/W, respectively. The values of PMV and PPD in the middle-, west-, east-, north- and south-region of the main prayer hall under the present ventilation system (i.e. the base case) are tabulated in Table 6.

Table 6 The values of PMV and PPD in regions of the main prayer hall under the present ventilation (base case).



Indices	Regions of the prayer hall				
	Middle	West	East	North	South
PMV	2.26	1.68	2.04	2.16	1.95
PPD (%)	87	61	79	83	75

It can be seen from the table that the PMV values in the middle-, east- and north-region of the main prayer hall are higher than 2.0, while for the west- and south-region, the PMV values are 1.68 and 1.95, respectively. These are well above the comfort range specified by the ASHRAE Standard-55 [14, 21], which is between +1 (warm) and -1 (cool). These finding indicates that the thermal comfort inside the main prayer hall is very warm and uncomfortable for the occupants.

Figure 9 shows the comparative plots of average airflow velocity in the east-, middle- and west-zone on a vertical symmetrical plane that runs (east-to-west) across the main prayer hall, obtained from the flow simulations. The average airflow velocities for all the proposed ventilation modifications are compared with the corresponding values for the base case. It can be seen that the highest increments in the average airflow velocity in all the three zones are obtained when four exhaust fans are installed on the west-side wall of the main prayer hall. The average airflow velocity increases by about 0.78 m/s, 0.54 m/s and 1.03 m/s in the east-, middle- and west-zone respectively, compared to the corresponding values for the base case.

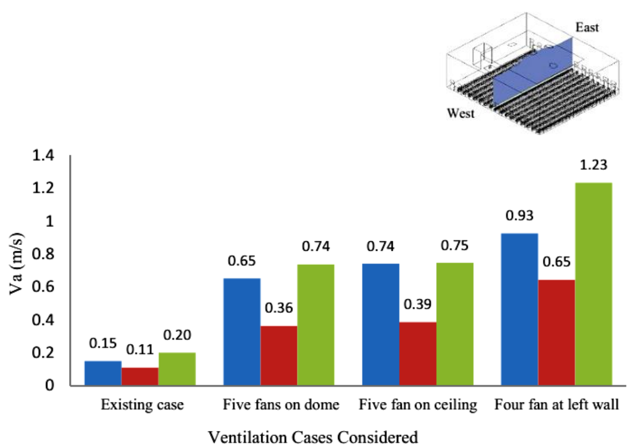


Figure 9 Plots of average airflow velocity in the east-, middle- and west-zone on a vertical (east-to-west) symmetrical plane.

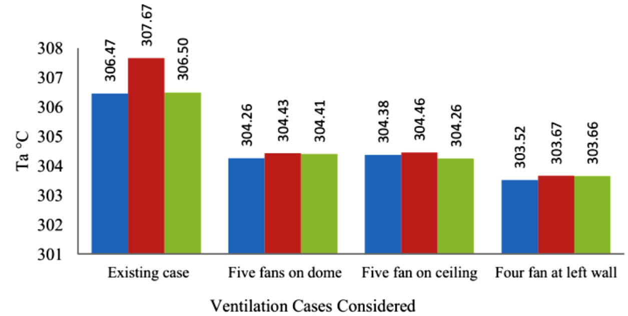


Figure 10 Plots of average air temperature in the east-, middle- and west-zone on a vertical (east-to-west) symmetrical plane.

The comparative plots for the average air temperature in the three zones on the same plane are illustrated in Figure 10. It can be observed from this figure that the average air temperature in the east-, middle- and west-zone of the plane drops by about 3°C, 4°C and 3°C, respectively when compared to the corresponding values for the base case. These findings can be considered as significant as reduction in both the airflow velocity and the air temperature would lead to the improvement in thermal comfort inside the main prayer hall.

Figure 11 shows the comparative plots of average airflow velocity in the north-, middle- and south-zone on a vertical symmetrical plane that runs (north-to-south) across the main prayer hall, obtained from the flow simulations. The average airflow velocities for all the proposed ventilation modifications are compared with the corresponding values for the base case.

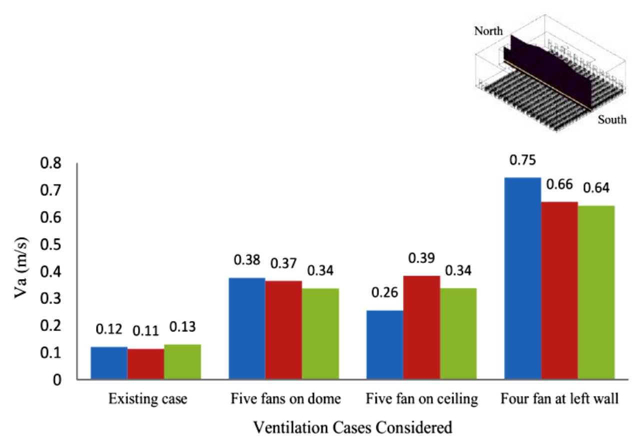


Figure 11 Plots of average airflow velocity in the north-, middle- and south-zone on a vertical (north-to-south) symmetrical plane.

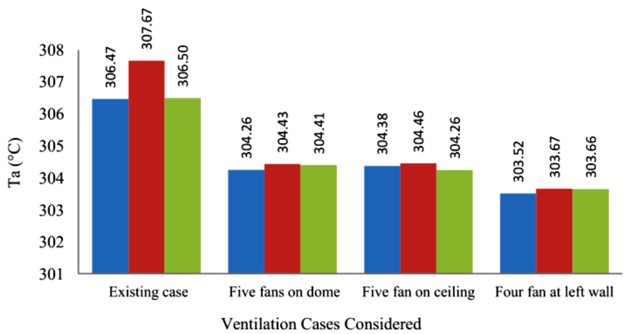


Figure 12 Plots of average air temperature in the north-, middle- and south-zone on a vertical (north-to-south) symmetrical plane.

It can be observed Figure 11 that the highest increments in the average airflow velocity in the three zones occur with the proposed ventilation modification of case 1, i.e. when four exhaust fans are installed on the west-side wall of the prayer hall. The average airflow velocity increases by about 0.63 m/s, 0.55 m/s and 0.51 m/s in the north-, middle- and south-zone, respectively, compared to the corresponding values for the base case. The comparative plots for the average air temperature in the three zones on the same plane are illustrated in Figure 12. It can be seen that the average air temperature in the north-, middle- and south-zone drops by about 3°C, 4°C and 3°C, respectively when compared to the corresponding values for the base case.

A comparison of the PMV values in the middle-, west-, east-, north- and south-region of the main prayer hall of the mosque, between the base case and all cases of the proposed ventilation modification is given in Table 7. It can clearly be seen from the table that the proposed modification of case 1, i.e. installing four exhaust fans on the west-side wall of the prayer hall, results in the greatest reductions in the PMV values in all the regions, compared with the other two proposed modification cases. It is observed that the PMV values are reduced by 67.7%, 63.7%, 69.1%, 67.6% and 59.5% in the middle-, west-, east-, north- and south-region of the prayer hall, respectively. The corresponding comparative plots of the PMV values are shown in Figure 13.

Table 7 Comparison of PMV values for all cases of ventilation modification with the base case values.

Case*	PMV				
	Middle	West	East	North	South
Base	2.26	1.68	2.04	2.16	1.95
Case 1	0.73	0.61	0.63	0.70	0.79
Case 2	1.27	0.92	0.77	1.27	1.29
Case 3	1.24	0.90	0.91	1.43	1.31

*Case 1: Four exhaust fans installed on the west-side wall; Case 2: Five exhaust fans on the dome; Case 3: Five exhaust fans at the ceiling.

Table 8 Comparison of PPD values for all cases of ventilation modification with the base case values.

Case*	PPD (%)				
	Middle	West	East	North	South
Base	87	61	79	83	75
Case 1	16	13	13	15	14
Case 2	39	23	17	39	40
Case 3	37	22	22	47	41

*Case 1: Four exhaust fans installed on the west-side wall; Case 2: Five exhaust fans on the dome; Case 3: Five exhaust fans at the ceiling.

A comparison of the PPD values in the middle-, west-, east-, north- and south-region of the main prayer hall of the mosque, between the base case and all cases of the proposed ventilation modification is given in Table 8. The PPD values for the middle-, west-, east-, north-, and south-region of the hall are 87%, 61%, 79%, 83% and 75%, respectively. With the proposed ventilation modification of case 1, the PPD values are reduced by 71%, 48%, 66%, 68% and 61% in the middle-, west-, east-, north- and south-region of the hall, respectively. The PPD is related to the PMV as given in Eq. (5). The ASHRAE Standard-55 [14, 21] specifies that for a good thermal comfort, the PPD value should be less than 20%. With proposed modification case 1, the PPD value in all the regions are reduced to well below the 20%. Therefore, the above finding is considered as a very significant improvement in the thermal comfort inside the main prayer hall. The corresponding comparative plots of the PPD values are shown in Figure 14.

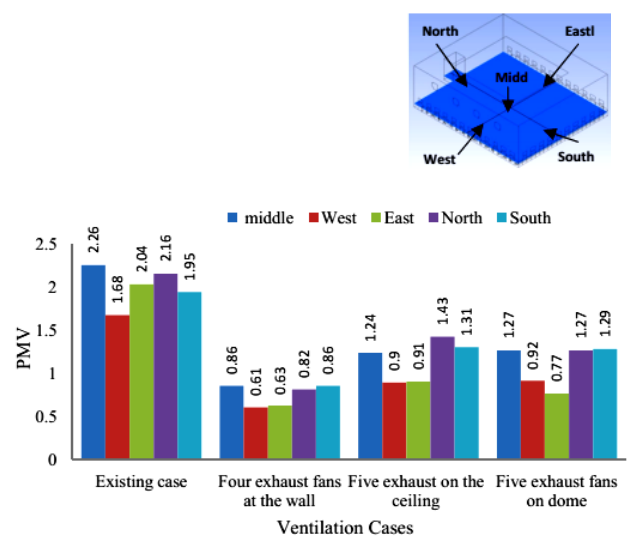


Figure 13 Comparative plots of PMV values in the middle-, west-, east-, north- and south-region of the main prayer hall.

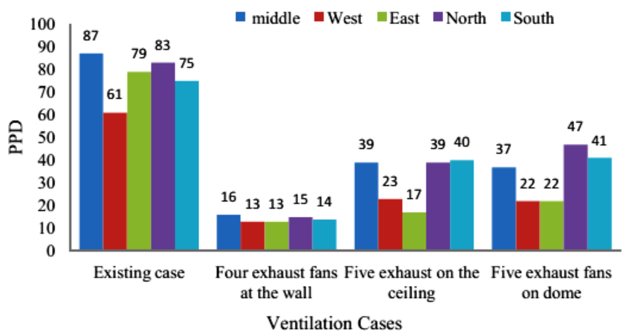


Figure 14 Comparative plots of PPD values in the middle-, west-, east-, north- and south-region of the main prayer hall.

4.0 CONCLUSIONS

This study evaluates the thermal comfort in Al-Jawahir Mosque located in Johor Bahru, Malaysia. Field measurements were conducted to obtain the parameters required for determining the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) which are indices for thermal comfort. A computational fluid dynamics (CFD) method was employed to carry out flow simulations to evaluate the effects of several ventilation modifications on the PMV and PPD indices. It was found that the PMV values inside the main prayer hall are well outside the comfort limit specified in the ASHRAE Standard-55. The values of PPD in inside the hall are also well above the 20% limit stated in the ASHRAE Standard-55. Results of CFD flow simulations show that installing four 56-cm diameter exhaust fans on the west-side wall of the prayer hall could significantly improve the thermal comfort inside the main prayer hall. With this modification, the PMV and the PPD values can be reduced by more than 60%.

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