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EFFECTIVENESS OF VENTILATION STRATEGIES IN REDUCING THE TEMPERATURE IN THE MAIN PRAYER HALLS OF MOSQUES IN MALAYSIA

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Abstract

Mosques may have an impressive architecture, but the lack of ventilation strategies compromises the ventilation inside mosques which leads to the high use of electrical equipment and energy (i.e., the air conditioning system) to maintain desired indoor conditions. Despite the attractive designs of mosques, their central prayer halls have uncomfortable indoor temperatures. What is the role of architectural form that contributed to the high indoor temperature within the "as-built" mosques in the tropical country of Malaysia? Hence, this study aims to evaluate the effectiveness of "as-built" ventilation strategies by assessing the effects of roof types, availability of air conditioning split units (ACSUs), window-to-wall ratio (WWR) and the percentage of opaque walls within the main prayer halls of Malaysian mosques. Data collection was conducted through monitoring 21 mosques, with different roof designs, in Penang and Malacca, Malaysia. The indoor air temperature was measured according to 1) roof design (Ottoman, pyramidal and Iran and Middle East styles), 2) mechanical ventilation (ACSUs and fans), 3) WWR and 4) the percentage of opaque walls. Results show that a) the type of mechanical ventilation system, the portion of opaque walls and WWR influence high indoor air temperatures, b) the roof design types have a less significant effect on the reduction of indoor air temperature, and c) more openings on walls and facades improve air circulation and hence significantly lower the indoor air temperature.

Keywords: Mechanical ventilation, Opaque wall, Roof design, Temperature, Window-to-wall ratio.

1. Introduction

Malaysia is a tropical country near the equator and experiences moderately warm ambient temperature throughout the year. The buildings' envelope may receive significant heat, increasing their thermal loads and solar radiation that may cause low thermal comfort for the occupants [1]. Non-industrial buildings, like mosques which serve as a multi-functional space (i.e., for the worship, preaching and other religious activities of Muslims), are a vital building typology because they involve occupancy [2]. Good thermal comfort in mosques is required because of high attendance, particularly during prayer times [3]. Worshipers or congregators must feel comfortable, calm, and peaceful during their prayers (solah) or while performing other religious activities within the main prayer halls of mosques.

However, many of these modern architecture buildings are poorly designed for the prevailing climate, leading to the excessive use of electrical equipment and energy to maintain the desired indoor conditions. When the temperature is too high, these modern buildings consume a large amount of energy to provide thermal comfort because of the inefficient air conditioning, the lack of insulation, the lack of shade, over-glazed and tight skinned [4]. This situation challenges engineers to ensure efficient architectural designs to provide healthy low-energy consumption [5, 6]. Despite the attractive designs of mosques, their central prayer halls have unfavourable indoor temperatures [1, 7]. What are the effects of the ventilation strategies on the architectural components that contributed to the high indoor temperature within the "as-built" mosques in the tropical country in Malaysia? Thus, alternatives to air conditioning split units (ACSUs) are of great importance. These alternatives include installing double-shelled domes [7], applying light surface colours and varying the density thermal mass [8]. Furthermore, building facades are essential in mitigating the heat effects of the tropical climate [9].

Moreover, low thermal comfort or thermal discomfort has an adverse impact on the occupants' health over prolonged periods [10]. The adverse effects include respiratory and cardiopulmonary illnesses [11]. Thermal discomfort issues in non-industrial premises, like mosques, are common in Malaysia. However, study data and local regulations are limited, making thermal comfort an urgent matter [12]. Some aspects of building conditions may cause thermal discomfort, such as the façade's design parameters (i.e., dimensions of the building, ventilation, size and type of doors and windows) and religious activities (i.e., praying) in mosque buildings [11]. Therefore, indoor thermal comfort in mosques must be maintained to the recommended level for occupants' comfort and health.

To maintain acceptable thermal comfort in buildings, a good ventilation system is needed. Ventilation is a process of supplying air to or discharging air from indoor spaces to control the air contaminant levels, humidity or temperature [13]. Two types of ventilation process exist, namely natural and mechanical ventilation. Natural ventilation is produced by thermal, wind or diffusion effect through doors, windows, or the other intentional openings of buildings. Meanwhile, mechanical ventilation respectively supplies and exhausts air into and from the room through mechanically powered equipment (i.e., fans and air-conditioning system) [13]. Figure 1 illustrates the natural and mechanical ventilation processes in a space [14].

Natural ventilation is preferable because it can reduce the operating cost compared to mechanical ventilation and protect the environment. In addition, natural ventilation can help supply oxygen which assists in mitigating excessive heat or moisture and indoor air contaminants as it promotes and directs air movement in buildings [15]. Furthermore, a study by Noman et al. [16] proved that natural ventilation might help improve thermal comfort inside mosque buildings as the air movement in and out of these buildings could decrease the temperature within the space.

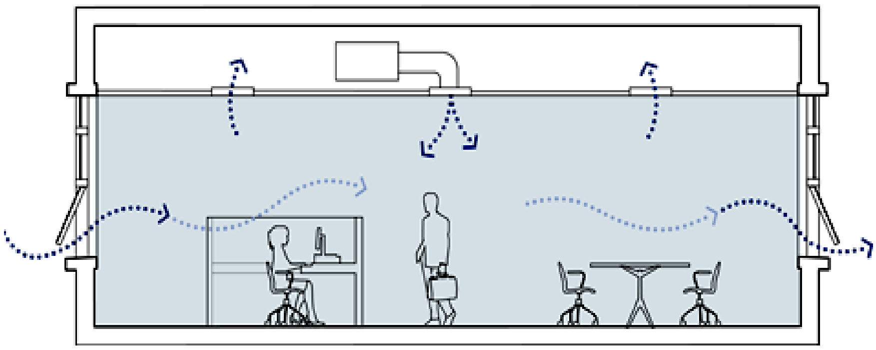


Fig. 1. Air movement within the indoor environment from natural and mechanical ventilation [14].

2. Literature Review

In this study, the authors chose to conduct parametric research under a hot and humid climate to provide a design aid for architects and designers. The following parameters were studied:

- Roof height, which is influenced by the roof design.
- The types of mechanical ventilation.
- The percentage of window-to-wall ratio (WWR).
- The percentage of opaque walls.

The architectural design characteristics of mosques in Malaysia are influenced by many factors, such as ethnicity, culture, climatic conditions, colonialism, technology utilisation and political environment [17]. Based on MS2577:2014, the seven design types of mosques around the world represent the heritage and local cultures of their locations [18]. Mosques in Malaysia generally have pyramidal roofs, an Ottoman-style and an Iran and Middle East architecture. Figure 2 shows the design types (characteristic) of mosques according to their respective regions, and the designs are the distinctive characteristics of mosques according to MS 2577: 2014 [18]. The inclined roof design has better solar collection efficiency than the perpendicular roof design, and the formation of the building (i.e., height, length, and width) significantly affects the energy usage [19]. The space design of mosques is termed as a single volume (approximately 10 ft or slightly more than 10 ft of floor-to-ceiling height) or the combination of single and double volumes (more than 10 ft of floor-to-ceiling elevation at the area next to the mihrab) [20]. Chua and Chou [21], found that increasing the building height could improve outdoor ventilation. However, the effect of the stack height from the roof slope is still a challenge, and studies have yet to be conducted on this issue [22].

Fig. 2. Designs of mosques around Malaysia: (a) Mosques in South East Asia (pyramidal-shaped roof), (b) Mosques in Turkey (Ottoman style) and (c) Mosques in Iran and the Middle East ("Iwan" (vaulted space)) [18].

Most mosques in Malaysia have air conditioning systems to cool down the indoor air temperature for worshippers. ACSUs are preferred because they are inexpensive and easy to install and maintain. Nevertheless, air conditioning systems consume a considerable amount of electricity and increase carbon emission [1]. Furthermore, the indoor air quality is also reportedly worse in mosques with ASCUs than in mosques without ASCUs. Rasli et al. [20] reported that the concentrations of three chemical air contaminants (i.e., TVOC, O_3 and CH_2O) in air-conditioned mosques are higher than those in non-air-conditioned mosques which is possibly caused by the lack of ventilation system. Meanwhile, the widespread uses of ACSUs tend to lead to dampness problems that can produce moisture that favours bacterial and fungal growth [23]. Rasli et al. [24] also revealed that the total bacterial counts (range: 166 cfu/m3 to 660 cfu/m^3) and total fungal counts (118 cfu/m^3 to 660 cfu/m^3) in mosques with ACSUs were higher than those in mosques without ACSUs.

Nik [25] suggested that in a hot and humid climate, like that of Malaysia, WWR is an essential determining factor for obtaining an optimum design that can provide thermal comfort and improve energy performance. WWR can be defined as the net glazing area to the gross exterior wall area [26]. WWR is the determined amount of incident solar radiation that enters a building [27] and increases the daylight factors in tropical countries for indoor visibility and lighting purposes [28]. However, increasing the WWR will increase solar heat gains. Accordingly, the heat exchange will also increase as the heat transfer coefficient of a window is generally higher than that of a wall [29, 30]. The optimum suggested WWR of thermal comfort in residential buildings is approximate 24%-25% [26, 31]. Massive, glazed roofs or walls would contribute to low thermal comfort, which caused internal heat to gain due to solar radiation, especially in air-conditioned buildings because of the increase in cooling load [32].

Opaque surfaces can be defined as building structures with walls, doors, roofs, and ceilings [33]. Increasing the openings on façade walls through passive design enables sufficient air circulation in indoor spaces [1]. In naturally ventilated buildings with opaque walls, the coupling of natural wind and mechanical ventilation could promote free-flowing airflow, thus promoting proper ventilation [26]. Furthermore, the air movement in warm and humid environments provides adequate ventilation to accommodate heat loss from the human body in building envelopes [34]. Finally, although temperature and humidity are difficult to control, promoting adequate indoor air circulation creates direct physiological cooling [35] through better airflow and natural ventilation [36].

In summary, these factors (i.e., (1) the roof height of the roof design; (2) the types of mechanical ventilation; (3) the WWR and (4) the percentage of opaque walls) mentioned above were very vital to explore in reducing the indoor temperature within the mosque building for energy and cost-saving and also for worshippers' comfort in the mosque buildings. To set the target for a comfortable indoor environment, Malaysia's Industrial Code of Practice (ICOP) [37] suggested guideline limits for indoor air temperature ranging from 23 °C to 26 °C. This temperature range is not achievable even though it is lower than the ambient temperature for a tropical setting due to these factors. Therefore, this paper aims to evaluate the ventilation strategies by assessing the effects of:.

- The roof types (i.e., Ottoman, pyramidal and Iran and Middle East styles).
- The availability of ACSUs (ACSUs and fans).
- The WWR.
- The percentage of opaque walls on the temperatures within the main prayer halls of mosques.

3. Methodology

3.1. Monitoring locations

Monitoring was conducted at 16 mosques in Penang and five mosques in Malacca. Table 1 shows the locations and coordinates of the selected mosques.

Table 1. Location and monitoring details.

Mosque	Coordinate
MQS01	N5.162445, E100.515366
MQS02	N5.132205, E100.479464
MQS03	N5.468727, E100.278318
MQS04	N5.225988, E100.495166
MQS05	N5.127116, E100.443831
MQS06	N5.144331, E100.465058
MQS07	N5.146839, E100.450196
MQS08	N5.152006, E100.465278
MQS09	N5.197372, E100.468805
MQS10	N5.276925, E100.517778
MQS11	N5.274137, E100.444558
MQS12	N5.275097, E100.427235
MQS13	N5.284583, E100.509856
MQS14	N5.148894, E100.487500
MQS15	N5.167577, E100.493589
MQS16	N5.148779, E100.420434
MQM17	N2.221526, E102.162424
MQM18	N2.196674, E102.247285
MQM19	N2.204063, E102.232085
MQM20	N2.179007, E102.248871
MQM21	N2.199205, E102.247514

MQS - Penang; MQM - Malacca

3.2. Monitoring method

The indoor air temperatures were measured and evaluated according to four categories:

1) Roof design styles (i.e., Ottoman style, pyramidal shape and Iran and Middle East architecture)
2) Mechanical ventilation (ACSUs and fans)
3) WWR
4) The percentage of opaque walls.

The monitoring schedules covered Zuhr-'Asr prayers for 5 h to 5.5 h (based on the local prayer time) from 12:00 to 17:00 or 17:30s because Zuhr and 'Asr prayers are performed during the hottest times of the day, i.e., between afternoon and evening. An indoor air quality probe (IQ-610), Graywolf Plc Inc., whose detection range and accuracy are from 10 °C to 71 °C and ±0.3 °C, respectively, was used for temperature measurement. The probe was placed on a tripod, and monitoring was carried out at approximately 1.3 m above the floor at 1-min data logging intervals. The instrument was placed at the centre of the main prayer area, below the dome of each mosque. Only one sampling point is needed as the mosques have the same ventilation system within the main prayer hall and the total floor area in the main prayer halls of the selected mosques are lower than 3,000 m^2. This is the minimum recommended number of sampling points recommended by ICOP [37] to assess thermal comfort.

3.3. Determination of facade of the mosque

The main prayer halls in mosques are divided into four facades. Facade 1 represents the front side of the main prayer hall and is known as the qiblah. Facades 2, 3 and 4 represent the left, rear, and right sides, respectively, of the main prayer hall of the mosque. The facades of the mosques are determined, as shown in Fig. 3. Meanwhile, examples of the inner and outer views of the facades from the main prayer hall are illustrated in Figs. 4 and 5, respectively.

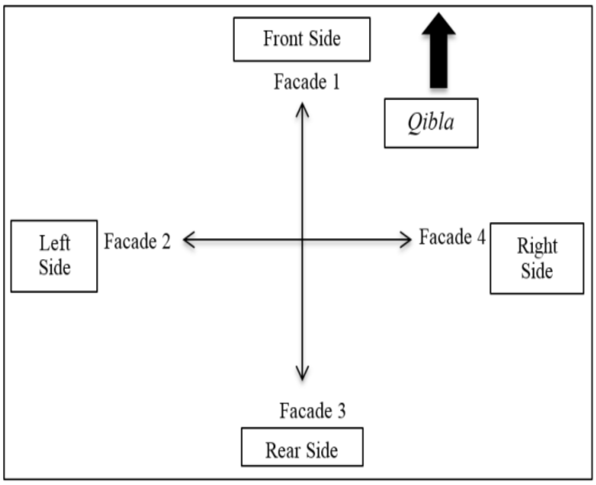


Fig. 3. Determination of facades of the mosques.

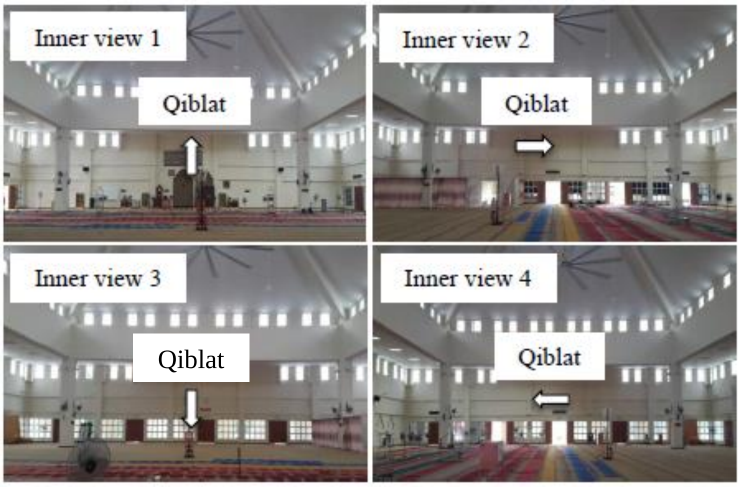


Fig. 4. Inner views of the mosque's facades from the main prayer hall (MQS14).

Fig. 5. Views of the mosque's facades (MQS14).

3.4. Determination of window to wall ratio

WWR is the sum of all the glazing areas of the upper opening, the windows, and the doors over the facade areas. Examples of glazing areas (i.e., upper opening, windows, and doors) are shown in Fig. 6. The glazing area of the facade and the average WWR are calculated according to Eqs. 1 and 2, respectively.

$$\text{Glazing Area of façade} = \frac{\text{Opening (glazing area)} + \text{Window (glazing area)} + \text{Door (glazing area)}}{\text{Facade Area}} \tag{1}$$

$$\text{Avg. Window to Wall Ratio} = \frac{\text{Glazing Area (F1)} + \text{GlazingArea (F2)} + \text{Glazing Area (F3)} + \text{Glazing Area (F4)}}{4} \tag{2}$$

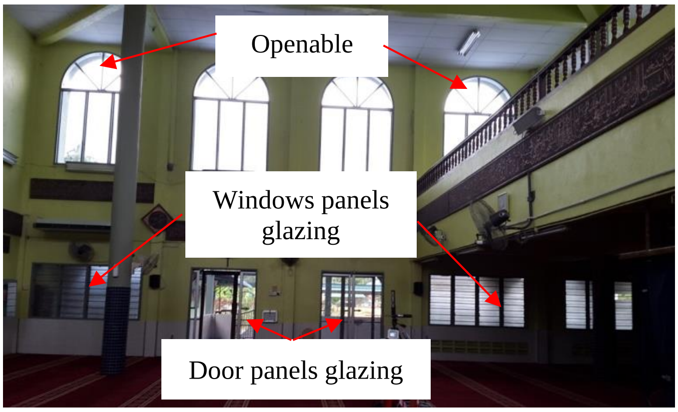


Fig. 6. Example of a glazing area (i.e., opening, windows and doors) (MQS06).

3.5. Determination of opaque wall

A facade may consist of openings, windows, and doors. Each facade is divided into six categories: (a) Opening areas (open), (b) Opening areas (close), (c) Windows (open), (d) Windows (close), (e)Doors (open), and (f) Doors (close)

As shown in Table 2. An opaque wall usually has no penetrable parts, i.e., windows or doors. Most of the facades were classified as opaque walls as openings, windows and doors within the main prayer halls are closed for security and protection from rainwater. An opaque wall is defined as a wall without opening, including bricks, concrete, glass, and wood. Figure 7 shows an example of an opaque wall (i.e., opening areas and doors are closed).

Table 2. Categories of facades.

Panels	Open (active)	Close (passive)
Opening area	Yes	No
Windows	Yes	No
Doors	Yes	No

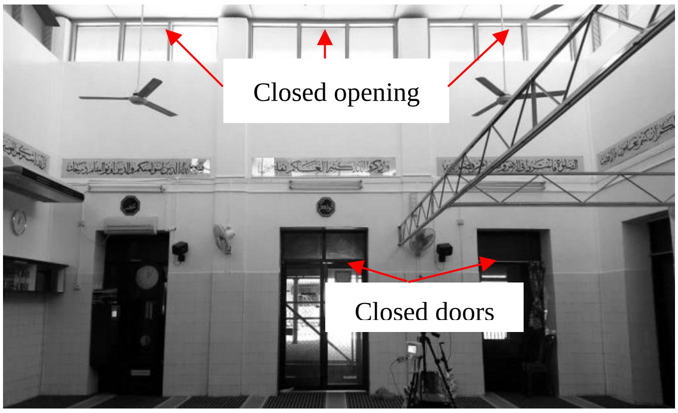


Fig. 7. Example of an opaque wall, where openings and doors were closed (MQS09).

The opaque wall area is calculated by subtracting all the active panels (open) of a wall area from the total area for each facade, as shown in Eq. 3. The average percentage of opaque walls is calculated according to Eq. 4.

$$\text{Opaque Wall} = \frac{\text{Wall Area} - \text{Opening Area (open)} - \text{Window (open)} - \text{Door (open)}}{\text{Facade Area}} \quad (3)$$

$$\text{Avg. Dead Wall} = \frac{\text{Dead Wall (F1)} + \text{Dead Wall (F2)} + \text{Dead Wall (F3)} + \text{Dead Wall (F4)}}{4} \text{ x } 100 \quad (4)$$

3.6. One-way ANOVA

One-way ANOVA was conducted to test the hypothesis that given populations means are equal, where the population groups are more than two. One-way ANOVA compares the mean of the samples or groups to make inferences on the population means [38].

3.7. Cluster analysis

Cluster analysis is a group of multivariate statistical techniques for classifying parameters. The parameters are classified based on proximity. Cluster analysis aims to identify groups within data, analyse groups of similar observations instead of individually and simplify the data structure. For this study, cluster analysis was performed on airconditioned and non-airconditioned mosques to differentiate their indoor temperatures. The dendrogram or the tree graph is shown to indicate the hierarchical procedure. The data set of mosques with and without ACSUs was divided into several groups of observations, depending on their characteristics. The numbers of significant clusters were determined based on the biggest drop in the Ward linkage coefficients [39]. Parameters with similar features were placed in the same cluster [40].

4. Results and Discussion

Table 3 shows the physical parameters of mosques with and without ACSUs. The average indoor temperature recorded for all mosques ranged from 28.80 °C to 35.63 °C, which is higher than the permissible limit set by ICOP (i.e., 23-26 °C). Therefore, the indoor air temperature in the 21 studied mosques did not comply with the allowable limit set by ICOP. Meanwhile, the average outdoor temperature recorded for all mosques ranged from 29.88 °C to 35.01 °C. The average indoor temperature of mosques with ACSUs was high than the average outdoor temperature in MQS05, MQS10, MQS12, and MQS11 with the percentage different of 3.86 %, 7.85%, 9.37 %, and 1.74 %, respectively. The percentage different of mosques without ACSUs in MQS13, MQS21, MQS15, MQS17, MQS14, and MQS03 were 3.93 %, 0.66 %, 2.32 %, 1.91 %, 1.91 %, and 2.84 %, respectively. The results recorded show the average indoor temperature in 10 out of 21 mosques were higher than average outdoor temperature with the higher percentage different range of mosques with ACSUs (1.74-9.37 %) compared to without ACSUs (0.66 - 3.93 %). The average WWR and the average percentage of opaque walls or facades ranged from 0 to 0.53 and 72.75% to 100.00%, respectively.

Meanwhile, Table 4 shows the average indoor and outdoor temperature related to roof designs, mechanical ventilation, the WWR average, and the average percentage of opaque walls in all mosques.

Table 3. Physical parameters of mosques with and without ACSUs.

No.	Mosques	The ceiling height (m)	Floor area (m^2)	Volume (m^3)	No. of worshiper	Average Occupant Density (per m^2)
			Mechanical Ventilation: ACSU			
1.	MQS06	7.12	225.93	1608.17	44	0.19
2.	MQS01	2.82	693.75	1954.99	22	0.03
3.	MQS04	2.8	452.76	1266.82	20	0.04
4.	MQS07	2.65	137.31	364.42	28	0.2
5.	MQS02	7.38	364.01	2686.39	47	0.13
6.	MQS05	2.58	606.82	1565.6	31	0.05
7.	MQS08	3.03	145.62	441.37	20	0.14
8.	MQS09	6.02	81.5	490.63	15	0.18
9.	MQS10	3.02	204.1	615.57	17	0.08
10.	MQS12	3.19	183.67	586.64	15	0.08
11.	MQS11	2.86	119.08	340.69	10	0.08
			Mechanical Ventilation: Non-ACSU			
12.	MQM19	4.32	162.94	703.41	54	0.33
13.	MQM20	7.46	635.37	4739.22	109	0.17
14.	MQM18	4.27	157.88	673.67	15	0.10
15.	MQS13	3.71	366.95	1361.75	27	0.07
16.	MQS16	8.27	382.31	3160.94	58	0.15
17.	MQM21	4.08	151.39	618.28	73	0.48
18.	MQS15	6.83	915.36	6250.08	50	0.05
19.	MQM17	2.21	153.26	338.70	31	0.20
20.	MQS14	6.94	1616.63	11214.56	18	0.01
21.	MQS03	6.73	497.95	3352.70	38	0.08

Table 4. Average ascending temperature based on four criteria: roof design, mechanical ventilation, the average WWR (all facades) and the opaque walls (all facades) of mosques with and without ACSUs.

No.	Mosque	Indoor Avg. T ±SD (ºC)	Outdoor Avg. T ±SD (ºC)	Avg. RH ±SD (%)	Avg. AM ±SD (m/s)	Avg. WWR	Avg. opaque wall (%)	Roof designs style
				Mechanical Ventilation: ACSU				
1.	MQS06	28.80 ±2.96	30.51 ±2.62	62.48 ±1.60	0.22 ±0.59	0.13	99.28	I
2.	MQS01	29.03 ±1.14	32.85 ±0.51	59.65 ±1.78	0.10 ±0.49	0.33	99.05	P
3.	MQS04	29.53 ±1.65	33.44 ±0.73	66.90 ±2.26	0.32 ±0.99	0.48	100.00	I
4.	MQS07	29.59 ±1.39	32.28 ±0.91	52.98 ±3.14	0.19 ±0.68	0.30	94.50	O
5.	MQS02	29.73 ±1.37	32.26 ±0.71	64.96 ±1.03	0.18 ±0.60	0.21	93.12	O
6.	MQS05	31.64 ±1.74	30.42 ±2.38	63.57 ±1.89	0.17 ±0.68	0.38	100.00	I
7.	MQS08	31.74 ±1.40	32.46 ±0.72	53.83 ±1.84	0.06 ±0.41	0.39	100.00	P
8.	MQS09	31.86 ±1.52	33.14 ±0.74	58.28 ±2.57	0.10 ±0.36	0.28	100.00	P
9.	MQS10	32.86 ±0.56	30.28 ±2.68	61.82 ±1.98	0.32 ±0.75	0.47	80.95	I
10.	MQS12	32.97 ±1.04	29.88 ±2.16	60.54±5 .07	0.38 ±1.47	0.30	84.64	P
11.	MQS11	35.63 ±0.89	35.01 ±1.00	51.74 ±1.36	2.32 ±0.09	0.53	92.53	P
				Mechanical Ventilation: Non-ACSU				
12.	MQM19	29.95 ±0.49	31.63 ±0.38	70.53 ±1.16	0.31 ±0.09	0.17	76.69	P
13.	MQM20	30.85 ±0.38	31.69 ±0.89	65.14 ±4.30	1.10 ±0.52	0.06	88.29	O
14.	MQM18	31.21 ±0.18	33.69 ±0.71	64.49 ±1.49	0.31 ±0.65	0.01	72.75	P

15.	MQS13	31.28 ±0.88	30.05 ±1.22	63.40 ±2.80	0.06 ±0.07	0.42	84.01	P
16.	MQS16	31.68 ±0.66	30.67 ±1.05	65.95 ±4.35	0.42 ±1.04	0.32	84.23	O
17.	MQM21	31.80 ±0.91	31.59 ±0.63	59.91 ±3.53	0.29 ±0.56	-	82.59	P
18.	MQS15	32.80 ±0.54	32.04 ±0.76	57.38 ±1.79	0.36 ±0.78	0.19	98.98	O
19.	MQM17	32.90 ±0.60	32.27 ±0.67	61.79 ±1.64	0.16 ±0.49	0.15	90.32	P
20.	MQS14	33.49 ±0.62	32.85 ±0.75	53.83 ±2.82	0.36 ±0.27	0.14	98.49	O
21.	MQS03	33.50 ±0.99	32.55 ±0.80	50.54 ±2.67	0.54 ±0.98	0.08	92.49	O

SD: Standard deviation; I: Iran and the Middle East; P: Pyramidal; O: Ottoman

For thermal insulation, generally, the thermal insulation materials used by those mosques are mainly of brick, tiles, aluminium frames, aluminium dooms, and glass ether tinted or not. Typical of material is as shown in Table 5.

Table 5. Typical materials used [41].

Construction	Description	Material	Width
1	External wall	Plaster, brick, plaster	0.016, 0.105, 0.016
2	Single glazing	Window glass	0.006
3	Solid ground floor	Carpet, concrete, earth	0.015, 0.100, 1.600
4	Internal ceiling	Insulation quilt, plasterboard	0.10, 0.01
5	Roof	Tiles	0.01
6	Internal partition	Plaster brick (inner), plaster	0.016, 0.105, 0.016
7	Timber griller wall/ partition	Timber (oak)	0.19
8	Concrete roofing	Concrete (light mix)	0.450
9	Roof 1	Roof tiles, Styrofoam, plasterboard	0.013, 0.085, 0.013
10	Solid ground floor with tiles	Tiles, concrete, earth	0.30, 0.1, 1.6
11	Opening	Void	0.015
12	Dome roofing	Polycarbonate	0.012

In summary, these factors (i.e., (1) the roof height of the roof design; (2) the types of mechanicals in the study on the influence of domed and pitched roof types, [41] revealed that in the naturally ventilated situation, both designs have the same effect on the air temperature within the prayer hall as the indoor air temperature is heavily dependent on the outdoor temperature. However, the domed roof was found to have the ability to stratify the air according to the temperature layering the coolest air at the lowest level and the hottest air at the highest level, creating a stagnant air situation inside the space, whereas the pitched roof can mix the cool and hot air to achieve the state of equilibrium, creating an active air movement inside the space naturally.

The roof contributes more heat gain into the mosque space as compared to the wall and floor elements [41]. Generally, modern mosques in Malaysia have shaded corridors, especially alongside the façade 2, 3 and 4 (Fig. 3). As for façade 1, some mosques would have another layer of covered space for administrative use. That would leave the roof to be the main element exposed to sunlight and contribute the most heat gain to the space compared to the other building elements. Thus, the use of insulation material in the roof construction is more in prevalent the Malaysian context. According to MS 2680:2017, the typical thermal transmittance (U-value) for the common cement sand brick wall, lightweight roof with roof tile (50 mm) and heavyweight roof (100 mm) is 3.1, 0.35 and 0.34 W/m^2K respectively [42].

Depending on the directions of the sun, heat built up could occur at a different time of the day as many have poor thermal insulation properties in the built-up areas.

4.1. Roof designs (Ottoman, pyramidal and Iran and Middle East styles)

Figure 8 shows the influence of the three types of roof designs (Ottoman, pyramidal, and Iran and Middle East styles) on temperature. The distribution of the average temperature for each roof design indicates that the type of roof design has no significant influence on indoor air temperature. Observations indicate slight differences in temperature between the Ottoman, pyramidal, and Iran and Middle East roof styles with ranges from 28.23 °C to 33.51 °C, 29.95 °C to 35.56 °C and 28.81 °C to 33.44 °C, respectively. Table 6 shows the temperature of the roof design style mosque buildings based on one-way ANOVA. The result above is proven by one-way ANOVA. The average T (°C) has no significant difference, with a p-value > 0.05 between roof design styles (i.e., Iran and the Middle East, pyramidal and Ottoman styles).

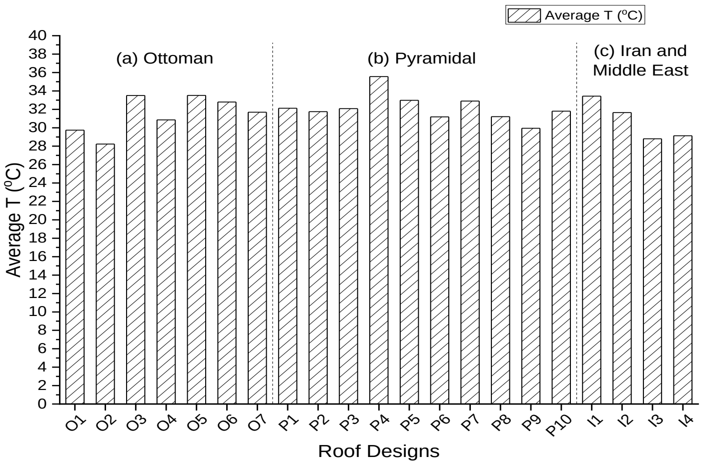


Fig. 8. Roof designs: (a) Ottoman, (b) Pyramidal and (c) Iran and the Middle East styles vs average temperature within main prayer halls.

Table 6. The temperature of the roof design style of mosque buildings based on one-way ANOVA.

		Sum of squares	df	Mean square	F	Sig. (p-value)
Avg. T (°C)	Between Groups	3.748	2	1.874	0.600	0.559
	Within Groups	56.183	18	3.121		
	Total	59.931	20			

4.2. Mechanical ventilation (air conditioning split units (ACSUs) and fans)

Figure 9 shows the effects of mechanical ventilation systems, that is, ACSUs and fans on indoor temperature. The average temperature between ACSUs and fans ranged from 28.8 °C to 35.56 °C and 29.95 °C to 33.51 °C, respectively. The minimum temperatures recorded during the actual praying time for ACSUs and fans were due to the settings for the operation of the mechanical ventilation systems. During outside prayer times, before Zuhr and between Zuhr and ‘Asr, high average maximum temperatures were recorded because ACSUs and fans were not in operation. The results reveal that the mechanical ventilation systems installed in prayer halls reduce the indoor air temperature only when in operation.

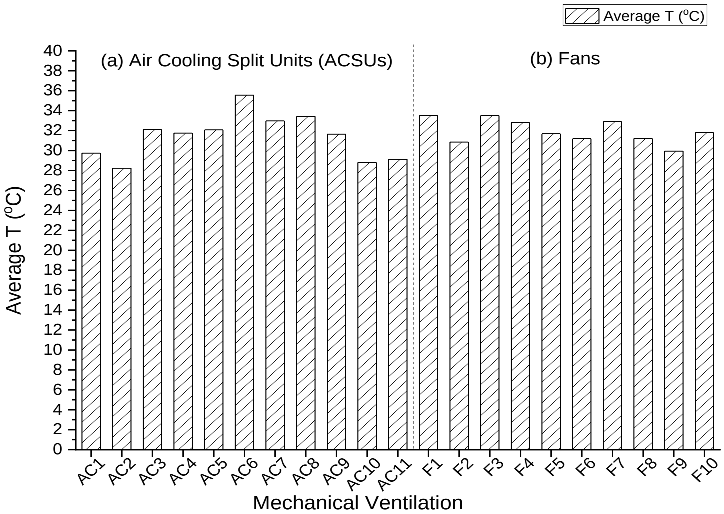
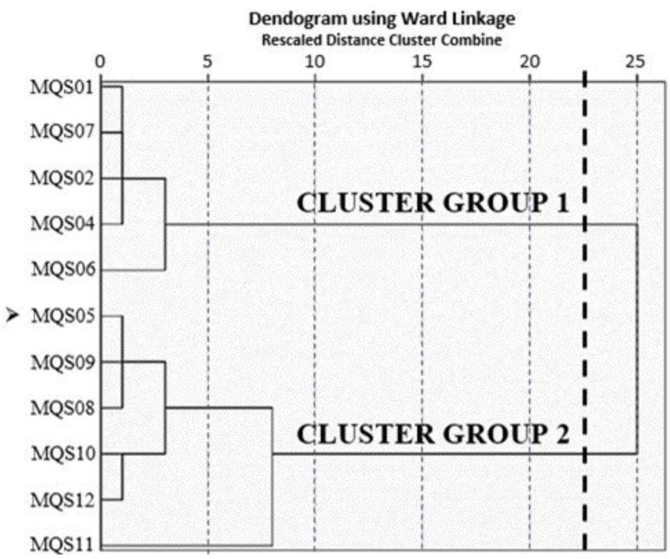
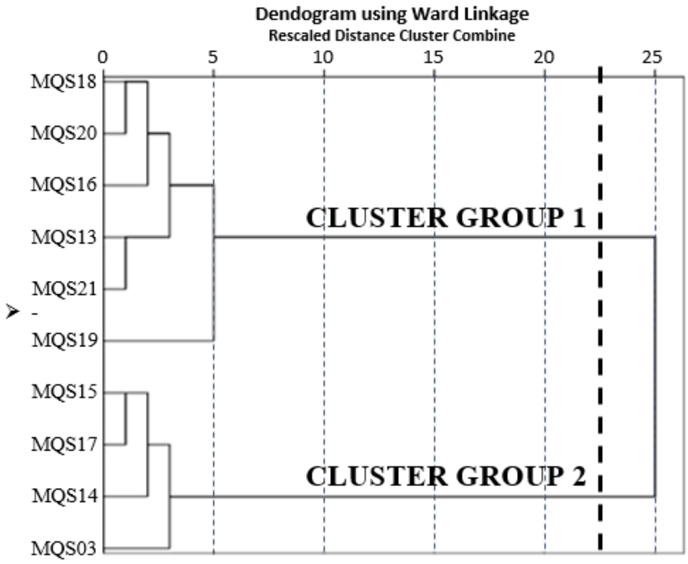


Fig. 9. Mechanical ventilation: (a) ACSUs and (b) Fans vs. average temperature within the main prayer halls.

Figure 10 shows the dendrogram for mosques (a) with ACSUs and (b) without ACSUs based on temperature, while Table 7 shows the cluster analysis based on temperature for mosques with and without ACSUs. The dendrogram in Fig. 10 illustrates the classification of 11 mosques with ACSUs and 10 mosques without ACSUs on temperature. The summary of 15 min temperature for each cluster group is shown in Table 7.



(a)



(b)

Fig. 10. Dendrogram of cluster analysis of mosques
(a) With ACSUs and (b) Without ACSUs based on temperature.

Table 7. Cluster analysis based on the temperature of mosques with and without ACSUs.

ACSU Mosques			
Cluster Group 1 (N=5)		Cluster Group 2 (N=6)	
Mosques	15-minutes T °C	Mosques	15-minutes T °C
MQS01	29.0	MQS05	31.6
MQS02	29.7	MQS08	31.7
MQS04	29.5	MQS09	31.9
MQS06	28.8	MQS10	32.9
MQS07	29.6	MQS11	35.6
		MQS12	33.0
Mean = 29.3		Mean = 32.8	
non-ACSU Mosques			
Cluster Group 1 (N=6)		Cluster Group 2 (N=4)	
Mosques	15-minutes T °C	Mosques	15-minutes T °C
MQS13	31.3	MQS03	33.5
MQS16	31.7	MQS14	33.5
MQM18	31.2	MQS15	32.8
MQM19	29.9	MQS17	32.9
MQM20	30.9		
MQM21	31.8		
Mean = 31.1		Mean = 33.2	

The cluster analysis results of mosques with and without ACSUs show that the mosques were divided into two cluster groups. The numbers of significant clusters were determined based on the biggest drop in the Ward linkage coefficients [39]. For mosques with ACSUs, cluster group 1 consisted of 5 mosques with nearly similar concentrations, and the other six mosques formed cluster group 2. The mean temperature of 15-min average for cluster group 1 was 29.3 °C, while that for cluster group 2 was 32.8 °C. Meanwhile, for non-airconditioned mosques, cluster group 1 consisted of six mosques, and the other four mosques formed cluster group 2. The mean temperatures for cluster groups 1 and 2 were nearly similar, with cluster group 2 exhibiting a slightly higher temperature with a 15-min average of 33.3 °C than that of cluster group 1's 31.1 °C. This analysis indicates that the mean temperature of cluster group 2 (32.8 °C) from airconditioned mosques was between the mean temperature of cluster groups 1 (31.1 °C) and 2 (33.3 °C) from the non-airconditioned mosques. Thus, some of the airconditioned mosques have a nearly similar temperature as the non-airconditioned mosques.

4.3. Window-to-wall ratio (WWR)

Figure 11 shows the average indoor temperature versus the average WWR. The results show that the highest of WWR (0.53) influenced the highest indoor air temperature (35.63 °C). A high WWR indicates that many of the wall areas were built with glass panels. Glass has a low thermal mass, resulting in high indoor temperature because of the penetrating sunlight [8].

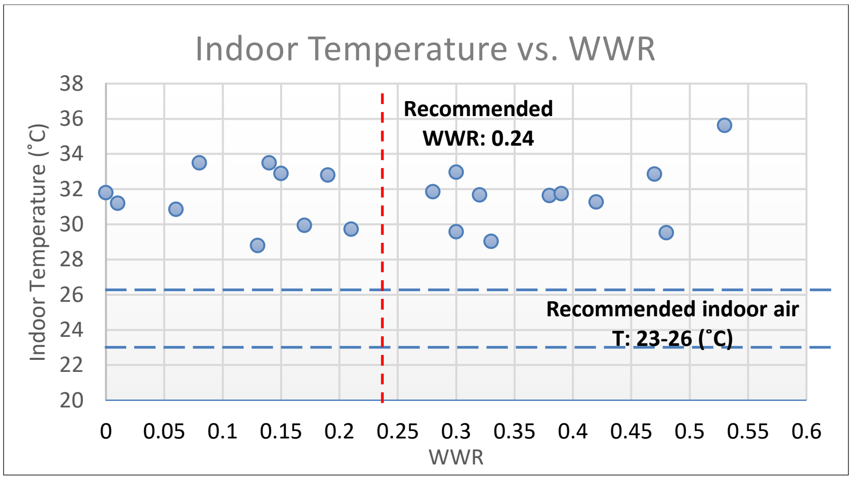


Fig. 11. Average indoor temperature vs average WWR.

For the hot and humid climate of Malaysia, WWR is an essential determining factor for obtaining an optimum design that can provide thermal comfort and improved energy performance [25]. The WWR increases linearly with the solar heat gains, and this increase results in high heat exchange and heat transfer coefficient [29, 41]. Additionally, window position primarily affects the heat load when the glazing-to-wall ratio is greater than 20% [43] and impacts the energy loss [44]. Wall types should also be considered in addition to the glazing features [45].

4.4. Percentage of opaque walls

Figure 12 shows the average indoor temperature vs average opaque wall. The results showed that the average indoor temperature (28.8-35.63˚C) exceeded the recommended indoor air temperature (23-26˚C) by ICOP [37] with the percentage of the opaque wall of 72.75-100%. Opaque walls frequently reduce the stack effect of hot air circulation within prayer halls. In this study, the opaque wall of the facade considerably influenced the indoor air temperature. The high percentage opaque wall of the facade showed small percentages of openings from the roof to the wall at the main prayer halls. The results suggested that free-flowing air was minimal from the indoor to the outdoor areas; thus, hot air was vented from the main prayer halls. ICOP has recommended that the acceptable limit for indoor air movement is between 0.15 and 0.5 ms^{-1} [37].

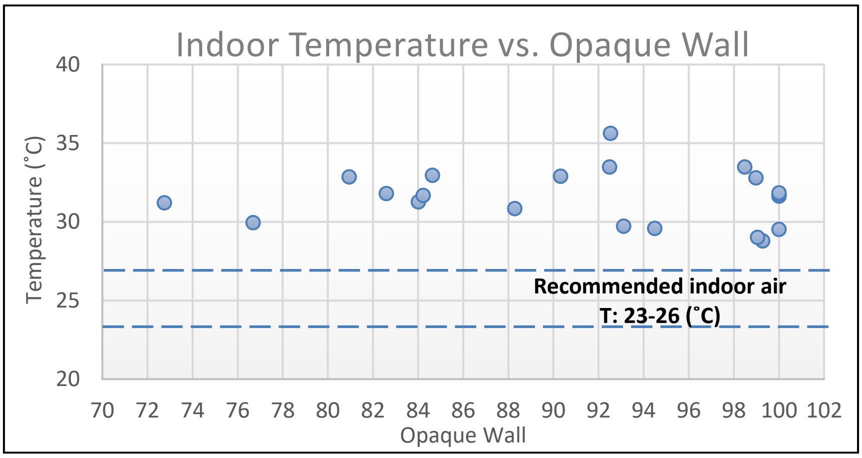


Fig. 12. Average indoor temperature vs average opaque wall.

Increasing the openings on facade walls through passive design enables sufficient air circulation into indoor spaces. The high indoor air temperatures recorded inside the prayer halls can be due to the lack of cross and stack ventilation. According to MS 1525:2007, stack ventilation enhances the airflow across space because of the air density differences within the main prayer hall [46]. Warm indoor air at the upper levels is discharged through openings near ceilings or roofs. Simultaneously, fresh air from outside enters the buildings through the lower openings. In mosques, the openings near the ceilings are often shut, thereby retaining the warm indoor air at the upper levels.

5. Conclusions

Many as-built modern architecture mosque buildings are poorly designed for the prevailing climate, leading to the high use of electrical equipment and energy (i.e., air conditioning systems) to maintain the desired indoor conditions.

Despite the attractive designs of mosques, their central prayer halls have uncomfortable indoor temperatures. What is the role of architectural form that contributed to the high indoor temperature within the "as-built" mosques in the tropical country of Malaysia?

Hence, this study evaluated the effectiveness of "as-built" ventilation strategies in decreasing the temperature in main prayer halls based on four criteria: 1) roof design (i.e., Ottoman, pyramidal and Iran and Middle East styles), 2) mechanical ventilation (ACSUs and fans), 3) WWR and 4) the percentage of opaque walls.

This study was conducted on 21 mosque buildings in Penang and Malacca, Malaysia from 12:00 to 17:00 or 17:30 (i.e., from Zuhr-'Asr prayer times) with different roof designs. The results show that the type of mechanical ventilation system, percentage of opaque walls and the WWR is the most significant factors that influence high indoor air temperatures in the mosque buildings.

Meanwhile, the roof design (i.e., Ottoman, pyramidal or Iran and Middle East styles) has a less significant effect on the reduction of indoor air temperature as no vast differences in temperature ranges were found. The ranges of indoor air temperatures in mosques with Ottoman, pyramidal, and Iran and Middle East styles were from 28.23 °C-33.51 °C, 29.95 °C-35.56 °C and 28.81 °C-33.44 °C.

Meanwhile, the ranges of indoor air temperature in mosques with ACSUs (28.23 °C-35.56 °C) was higher than with fans (29.95 °C-33.51 °C). The highest of WWR (0.53) influenced the highest indoor air temperature (35.63 °C).

Meanwhile, the average indoor temperature (28.8-35.63 °C) exceeded the recommended indoor air temperature (23-26 °C) by ICOP with the percentage of the opaque wall of 72.75-100%.

Therefore, this study is significant for the future design of modern mosques, by considering the application of non-air-conditioned in mosques, the maximum WWR requirement of 24% and the lower percentage of opaque walls which at least below than 72.75 % (i.e., wide openings of windows and upper openings) as ventilation strategies to improve air circulation to lower the indoor air temperature within the main prayer halls.

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