EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(8), 219–233
https://doi.org/10.12912/27197050/207477
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.06.19
Accepted: 2025.07.17
Published: 2025.08.01

The impact of architectural preservation on thermal comfort and airflow in Gayo highlands' historical mosques

Laina Hilma Sari[1*], Elysa Wulandari[2], Yunita Idris[3,4], Brit Anak Kayan[5]

[1] Architecture Department, Engineering Faculty, Universitas Syiah Kuala, Banda Aceh, Indonesia
[2] Urban and Regional Planning, Engineering Faculty, Universitas Syiah Kuala, Banda Aceh, Indonesia
[3] Civil Engineering, Engineering Faculty, Universitas Syiah Kuala, Banda Aceh, Indonesia
[4] Tsunami and Disaster Mitigation Research Center (TDMRC), Universitas Syiah, Indonesia Kuala, Jl. Hamzah Fansuri No. 8, Darussalam, Banda Aceh 23111, Indonesia
[5] Building Surveying Department, Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia
* Corresponding author's e-mail: laina_hilma@usk.ac.id

ABSTRACT

Preserving historical mosques in their original designs enhances cultural heritage understanding and promotes the use of environmentally friendly local materials. This study investigates three historical mosques in the Gayo highlands of Indonesia, each with similar designs but different maintenance approaches. One mosque retains its original design, while the other two have undergone renovations. The study evaluates the performance of these mosques in terms of thermal comfort and airflow. Field measurements of the indoor thermal environment were conducted over three days for each mosque. Simulations using ANSYS Fluent were also performed to predict airflow performance. Thermal comfort is assessed based on air temperature, relative humidity, air velocity, predicted mean vote, predicted percentage of dissatisfied, and standard effective temperature values. The findings offer insights into how design and maintenance impact the environmental performance of historical mosques. This study indicates that the historical mosque maintained in its original design provides better thermal comfort than the renovated ones.

Keywords: architectural preservation; thermal comfort; airflow; historical Mosques; Gayo highlands.

INTRODUCTION

People work hard to maintain historical mosques to their original design to give people better knowledge of their history. The characteristics are similar to the traditional architecture which optimizes the use of the local material and thus is more friendly to the environment (Arda Akyıldız & Nur Olğun, 2020). Architecture in the past is regarded as environmentally friendly which is the best lesson to understand how the building design copes with the environment (Sari et al., 2024). Without seeing the standard, traditional architects were able to design the dwelling with sufficient comforts such as indoor thermal comfort, and airflow which are subjectively perceived as comfortable by the dwellers (Xu et al., 2018). In traditional worshipping areas such as mosques, we can find remarkable designs where we can presume the adaptivity of the worshippers to the sacred environment (Diler et al., 2021; Dwela & Kayili, 2023; Hoomanirad & Tahbaz, 2014). The different design in many architectures, including mosques, is mostly noticed on the roof (Azmi & Ibrahim, 2020). The earliest mosque was built by the prophet Muhammad in Arabian land in a square layout, and oriented to Mecca as the qibla for Muslims. Later, Middle Eastern styles that typically used domes on the roof grew rapidly (Jamaludin & Salura, 2018). In tropical areas, common roof designs include the four-sloped roof, a basic pyramid hip roof, or a more complex version featuring multiple stacked pyramid forms. (Budi, 2004; Jamaludin & Salura, 2018; Wibowo & Sasano, 2016).

Historically, technology was minimal, so mosques were designed in an open layout relying on sunlight to provide light and to give access to airflow (Wibowo & Sasano, 2016). Limited technological advancements aligned with the way people in the past adapted more easily to challenging environmental conditions. Compared to those living in modern homes, they had a lower thermal neutral sensation and were less sensitive to cold in winter but more sensitive to heat in summer. (Xu et al., 2018). In contrast, the current mosques are equipped with mechanical equipment to support light, thermal comfort, and room acoustics (Shohan & Gadi, 2020). Merely relying on mechanical equipment is unwise due to the excessive use of energy to run these comforts (Azmi et al., 2021; Dwela & Kayili, 2023; Yüksel et al., 2022a). Architectural science which includes thermal comfort, airflow, and daylight performance is also essential to promote environmentally friendly design which is in line with one of the SDGs goals, namely sustainable cities and communities (Montiel et al., 2020).

Based on this condition, This research explored how preserving traditional mosque architecture affects thermal comfort and airflow in three heritage mosques located in Indonesia's Gayo Highlands. The mosques studied – Asal Penampaan (M1), Tue Kebayakan (M2), and Al Jihad (M3) (Figure 1) – feature modest square-shaped designs with ventilation openings positioned at the roof level. Previously, the mosques had been investigated in terms of their design related to sustainability and local wisdom (Sari et al., 2024). In this study, further work was carried out to indicate their performance in thermal comfort and airflow.

Mosques and indoor thermal comforts toward sustainability

Mosques are places of worship for Muslims, designed to accommodate specific functional and operational needs due to their frequent use. Muslims pray five times daily – at Fajr (pre-dawn), Dhuhr (just after noon), Asr (late afternoon), Maghrib (just after sunset), and Isha (early night) – in addition to the weekly congregational Jumuah prayer held at midday every Friday. The solemnity is essential which is believed to be the way to get the worship accepted by God (Azmi & Ibrahim, 2020). However, the way to provide it is a challenge, where the inability to adapt to the local environment would use excessive energy and would harm the environment (Azmi & Ibrahim, 2020). Inadequate thermal performance in mosques significantly contributes to higher energy usage, leading to energy waste and reduced efficiency. Improving this issue by enhancing the thermal properties of the building envelope can greatly reduce the energy needed for heating and cooling systems (Azmi & Ibrahim, 2020).

An effective building envelope that enhances thermal performance must take into account the geographic setting and related factors like climate conditions, sun orientation, and both macro and microclimatic characteristics of the site. Additionally, a building's thermal efficiency relies on how well its envelope components – such as walls, roofs, windows, and openings – function collectively as an integrated system (Budaiwi et al., 2013). Naturally ventilated mosque buildings use less energy because they do not need mechanical thermal control systems (Sari & Ariatsyah, 2023). Environmentally sustainable mosque design relies on four key elements: the arrangement and size of spaces, the fixed direction of the prayer area, patterns of occupancy, and the users' activity levels and clothing. Considering these factors helps improve energy efficiency and minimize energy waste during regular use (Azmi & Ibrahim, 2020).

Natural ventilation created by open windows can also positively affect indoor air quality (Sari et al., 2023). The airflow can dilute indoor pollutants. During the pandemic, keeping the window open would decrease the CO_2 concentration (Sari et al., 2022; Yüksel et al., 2022b). The building envelope plays a crucial role in shaping indoor thermal comfort and influencing energy usage. Upgrading or enhancing the envelope can significantly boost indoor comfort while also lowering overall energy consumption (Dwela & Kayili, 2023). Some studies also revealed that the main factors behind the heat gain or loss in the mosque buildings were the low quality of the buildings' envelopes such as roofs, windows, doors, floors, and walls (Shohan & Gadi, 2020). Designing suitable Qiblah walls is also a way to reduce the mean radiant temperature by 4° to 6 °C. When paired with effective ventilation strategies, thermal comfort can be enhanced by a minimum of 40% during

(a) (b) (c)

Figure 1. The historical mosques in Gayo highland evaluated in this study: (a) M1 – Asal Penampaan mosque, (b) M2 – Tue Kebayakan mosque, (c) M3 – Al Jihad mosque

the hottest prayer times and up to 80% for prayers held at night (Azmi & Ibrahim, 2020).

Historic buildings serve as excellent references for understanding how local architectural styles effectively adapt to the surrounding climate and environmental conditions. (Aiyubi et al., 2024; Sari et al., 2020). One example of a heritage mosque is the Masjid Tanah in Malaysia (Yusoff & Ja'afar, 2019). This mosque has a passive design and responds well to the local tropical climate of Malaysia. The mosque's design creates a thermally comfortable indoor environment in the praying hall most of the time. The mosque features a straightforward floor plan without any interior partitions and includes numerous openings that promote effective cross ventilation. Additionally, the presence of a veranda helps block direct sunlight from penetrating into the area for prayer. (Yusoff & Ja'afar, 2019). In temperate humid climates, dividing the space into zones – such as adding a transitional area between the main prayer hall and the outdoors – can help maintain consistent indoor thermal comfort. This approach also reduces the impact of temperature differences between the interior and exterior on the prayer space (Atmaca & Gedik, 2019).

Thermal comfort and airflow

Recent research has extensively explored thermal comfort, highlighting its essential role in creating a quality indoor environment. Six main factors affect thermal comfort – four of them are environmental: air temperature (*Ta*), mean radiant temperature (*Tmrt*), relative humidity (*RH*), and air movement (*v*). The remaining two are personal: the body's metabolic activity (met) and the level of clothing insulation (*clo*) (Zhao et al., 2021).

Over the past few decades, thermal comfort models have evolved rapidly. The earliest and most well-known is the predicted mean vote (PMV) model, developed from Fanger's thermal balance equation. This model uses a seven-point scale to represent different thermal sensations experienced by occupants (Table 1). PMV estimates the average thermal sensation vote of a group of individuals based on this scale (refer to Table 3). It follows the ASHRAE 55 standard, incorporating various thermal parameters such as metabolic rate (*M*), mechanical work (*W*), clothing insulation (*fcl*), air temperature (*ta*), mean radiant temperature (*tc*), air velocity (*var*), water vapor pressure (*Pa*), convective heat transfer coefficient (hc), and the surface temperature of clothing (tcl). All these parameters are calculated using the formula (Eq. 1) recommended in ASHRAE (Gilani et al., 2015) which has been simplified through the engineering simulation tools namely RayMan.

$$\begin{gathered} PMV = (0.303exp - 0.0336M + 0.028) \times \\ \times \{(M - W) - 3.5 \times 10{-}3[5733 - 6.99\,(M - W) - pa] - \\ - 0.42(M - 58.5) - 1.7 \times 10{-}5 \times M(5867 - pa) - \\ - 0.0014M(34 - ta) - 3.96 \times 10 - 8fcl[(\mathrm{tcl} + 273)4 - \\ - (tr + 273)4] - fcl \times hc(tcl - ta)\} \end{gathered} \quad (1)$$

PMV ranges from -3 to +3 which is categorized and shown in Table 3. The model incorporates the human body's thermal regulation principles, describing how thermal comfort is achieved indoors under specific temperature and humidity levels, as represented in Equation 1. It is a widely adopted tool for assessing the thermal comfort of occupants in indoor environments (Gilani et al., 2015).

In estimating the percentage of people likely to feel thermally dissatisfied in a given environment, predicted percentage of dissatisfied (PPD)

Table 1. Categorization of PMV for different levels of thermal perception and physiological stress

PMV scale	Thermal perception	Grade of physiological stress
-3	Very cold	Extreme cold stress
-2.5	Cold	Strong cold stress
-1.5	Cool	Moderate cold stress
-0.5	Slightly cool	Slight cold stress
0	Comfortable	No thermal stress
+0.5	Slightly warm	Slight heat stress
+1.5	Warm	Moderate heat stress
+2.5	Hot	Strong heat stress
+3	Very hot	Extreme heat stress

Table 2. SET thermal perception (Błazejczyk et al., 2013)

Thermal perception	SET (°C)
Cool (moderate hazard)	<17
Comfortable (no danger)	17–30
Warm (caution)	30–34
Hot (extreme caution)	34–37
Very hot (danger)	>37

Table 3. Subjective reactions of different ranges of air velocities (Szokolay, 2012)

Air velocities (m/s)	Subjective reactions
< 0.25	Unnoticed
0.25–0.50	Pleasant
0.50–1.00	Awareness of air movement
1.00–1.50	Draughty
> 1.50	Annoyingly draughty

index is used (Eq. 2). It is based on the predicted mean vote index.

$$PPD = 100 - 95 \cdot e^{-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2} \quad (2)$$

Another model is standard effective temperature (SET) which is defined as effective temperature which is a rational index. It is calculated by taking skin temperature and skin wetness into account (Błazejczyk et al., 2013). The comfortable zone of SET thermal perception is within 17° to 30 °C (in Table 2).

Result from both natural forces and mechanical systems. Natural ventilation systems designed with specific openings generally fall into three types: wind-driven ventilation, stack (buoyancy) ventilation, and hybrid or mixed-mode ventilation. These openings may include elements such as windows, doors, chimneys, wind catchers, and roof vents. The flow of air significantly affects how occupants perceive thermal comfort (Han et al., 2024). Under typical conditions, people's responses to different air speeds vary accordingly.

These responses vary based on the air temperature. In warm environments, an airspeed of 1 m/s is generally comfortable, and speeds up to 1.5 m/s are still considered acceptable indoors. However, higher velocities can cause lightweight items to move and may lead to indirect discomfort. In contrast, during colder conditions in heated spaces, air movement should stay below 0.25 m/s to avoid discomfort. Nevertheless, if the air becomes too still – below 0.1 m/s – it is often perceived as stuffy, even in a warm room (Szokolay, 2012).

METHODOLOGY

Case study and location

Aceh is characterized by low and high lands with elevations from 0 to 2,000 meters above sea level (Figure 2). This study examines three historic mosques located in Gayo, a highland area in Aceh: Asal Penampaan mosque, Tue Kebayakan mosque, and Asir-Asir mosque. All three structures feature four-sided sloped roofs with tiered pyramid forms, resembling the traditional architectural style commonly found in Java. (Budi, 2004). This kind of style is also similar to the traditional mosque design in southeast-east Asia (Jamaludin & Salura, 2018), yet different from a number of roof layers and opening styles. As located in the highlands, the air temperature is lower than in the lowlands. This creates a smaller size of openings compared with those in the lowlands. As mentioned, the roofs of the two land mosques are designed in a pyramid-shaped stacked roof. However, the lowland has more roof layers providing more access to the air flow and well as the sunlight entering the mosque interior. In contrast, the Gayo highland mosques have only one layer of roof ventilation.

Among the three mosques investigated in this study, the oldest one is Asal Penampaan mosque (M1) (Figure 3a, Figure 4), which was built in 1412. It is located in Blangkejeren, at an altitude of 900 m above sea level. Even though it is the oldest, the mosque still stands well. The floor size is 11.5 by 11.5 m supported by a wooden structure. The traditional building enveloped still stands i.e. sago palm leaf roof, and stone and soil wall standing as a fence surrounding the floor plan. The openings are built running along the wall perimeter (Sari et al., 2024).

The second oldest mosque is Tue Kebayakan mosque (M2) (Figure 3b, Figure 5) which was built in 1920 by the community. The mosque is the first mosque built in Takengon, Aceh Tengah. It has an altitude of 1,270 m above sea level. The floor size is similar to M1 i.e. 11.5 by 11.5 m. From the old pictures and agreed upon by the elders, M2 was initially built from stone and soil walls, with a leaf roof and openings around the wall perimeter resembling the design of M1. Later, the mosque is renovated to be built from brick concrete wall and zinc roof. The opening was replaced with wooden jalousie windows.

The third mosque is Al Jihad (M3) (Figure3c, Figure 6), which was constructed from timber boards and built during the Dutch colonial period in 1929 (Bakri, 2017). It was

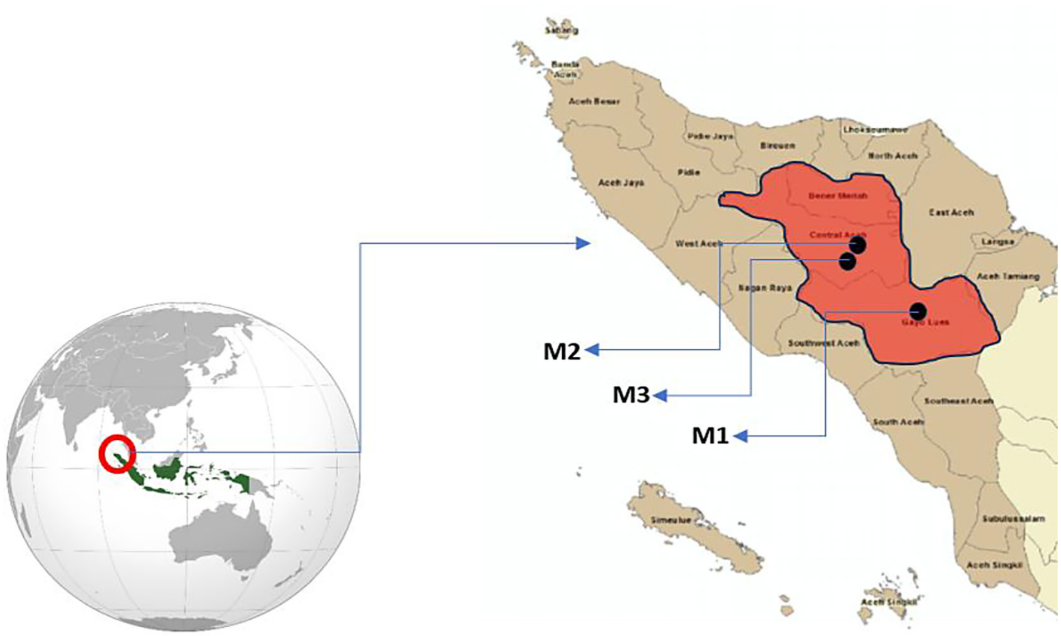


Figure 2. Location of the three mosques located in Gayo highland evaluated in this study M1 (3°59’39”N 97°20’36”E), M2 (4°38’15”N 96°51’11”E), and M3 (4°37’05”N 96°50’44”E)

Figure 3. The inner space of the examined mosque: (a) M1. Asal Penampaan mosque, (b) M2. Tue Kebayakan mosque, (c) M3. Al Jihad mosque

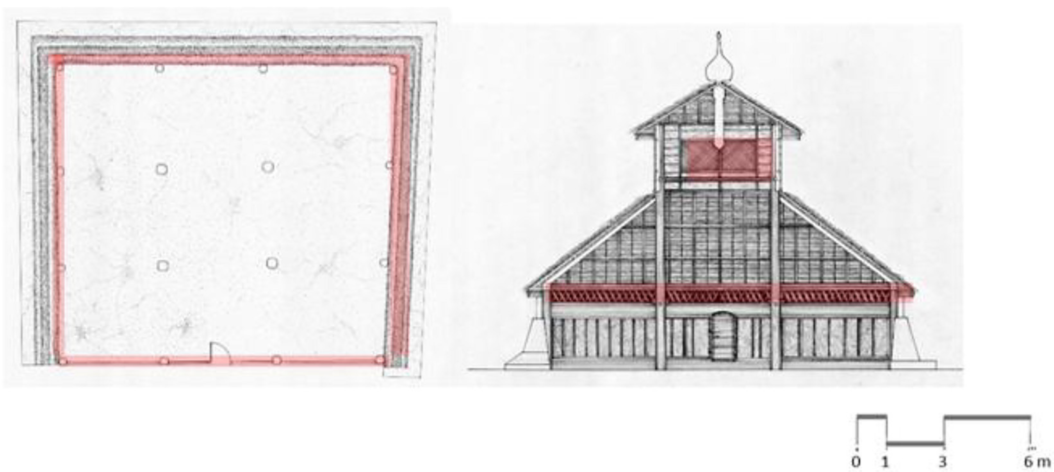


Figure 4. (M1) Asal Penampaan mosque (floor plan, vertical section, and ventilation shown in pink)

the first big mosque built in Takengon due to its large space for accommodating worshippers. The floor area is 25 by 24 m, which is over four times the area of the other mosques (144 m^2 compared to 600 m^2). It sits at an altitude of 1,200 m above sea level. The mosque was built semi-permanent with a concrete wall (1 m above the ground) and a timber plank wall at the top toward the ceiling. The roof is supported by a wooden structure. But all the interior surface was renovated to be enclosed with white gypsum ceiling and wall; and ceramic tile floor. The windows are jalousi types (Sari et al., 2024).

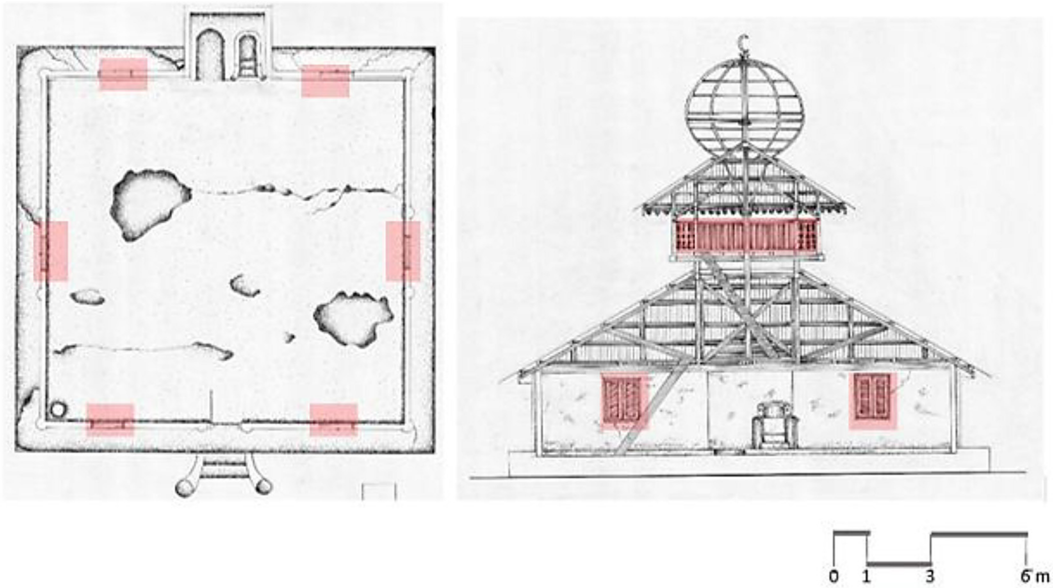


Figure 5. (M2) Tue Kebayakan mosque (floor plan, vertical section, and ventilation shown in pink)

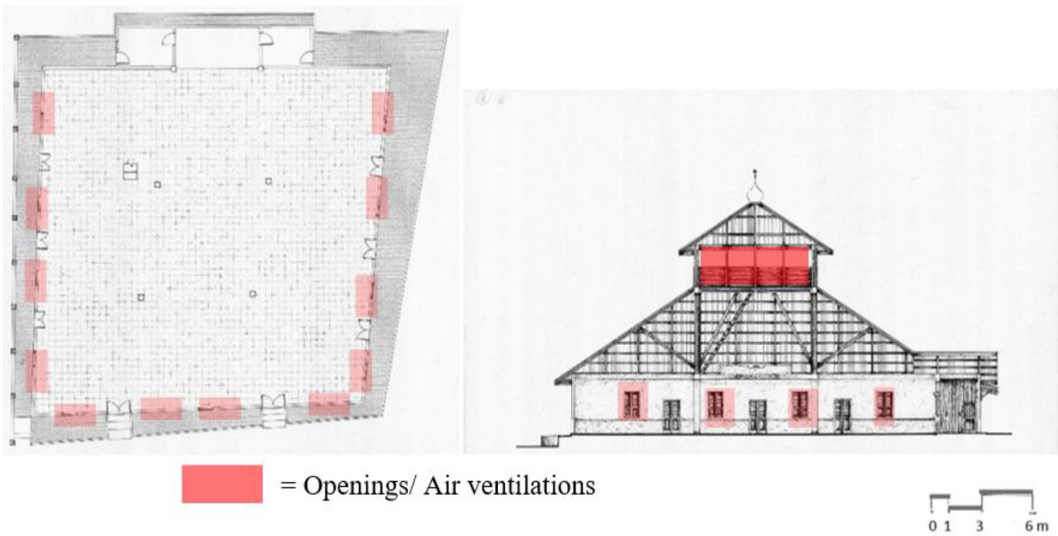


Figure 6. (M3) Al Jihad mosque (floor plan, vertical section, and ventilation shown in pink)

Field measurement

This study was conducted quantitatively through field measurements taken within 2 days, then followed by simulations. Thermal comfort measurements included the parameters air temperature (ta), air humidity (RH), wind speed (Av), and radiation temperature (MRT). The field measurements were carried out indoors and outdoors. During the measurement, the thermal instruments were placed in the middle of the mosque (Zone 5). (Figure 7).

Due to limited equipment availability, the measurements were carried out at different times. M1 was measured for 24 hours within two days i.e. from 7 to 9 July 2023. While M2 and M3, due to being located in the same district, were measured on the same date, namely 3 to 5 July 2023, for 24 hours on each day.

The outdoor measurements were carried out using Professional wifi weather (433 MHz) WH-5300-1. This tool measured air temperature (air temperature – °C), and relative humidity (relative humidity – %) both inside and outside the room. The wifi weather tool also measured the solar radiation in units of the amount of light (illuminance-lux), the amount of rainwater (rainfall – mm) and wind speed, but only outdoors. For

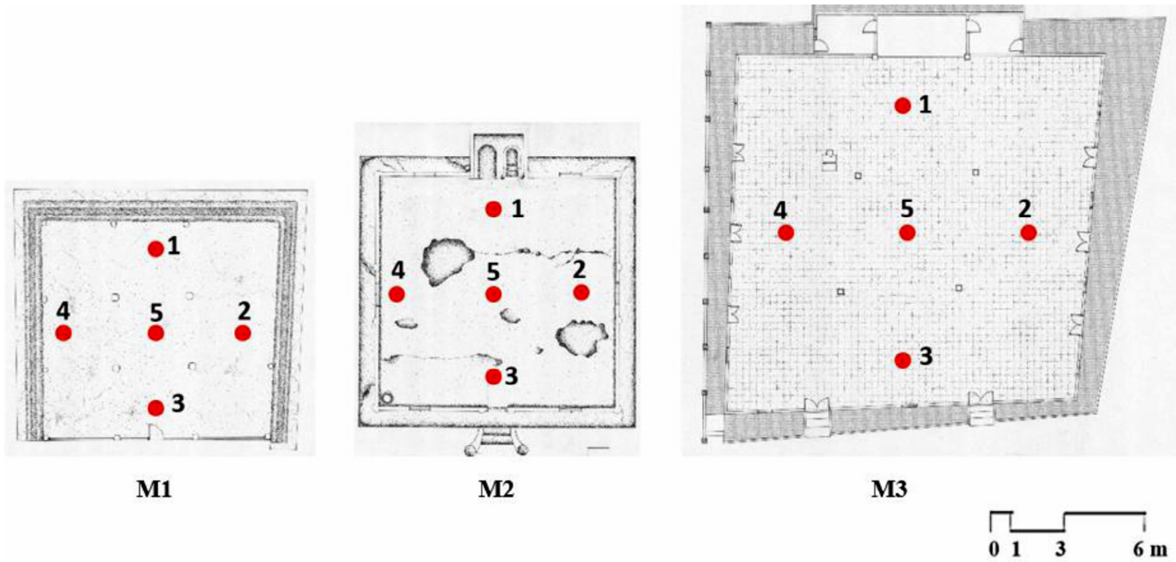


Figure 7. The locations of the measuring equipment

indoor wind speed, the measurements were carried out using a Testo 450i Thermal Anemometer.

Modeling simulation

Modelling simulations were conducted to analyze airflow. Ansys fluent, a computer-aided computational fluid dynamics (CFD) software used for modelling fluid flow and heat transfer in complex geometries, was utilized for predicting airflow. The system was configured to a wind tunnel model. The distance between the main building model and the wind tunnel wall was 30 meters on the west, north, and south sides, while the distance from the wind tunnel wall to the east side of the building was 90 meters (Figure 14). This setup ensures that the wind flow in the simulation is not disturbed by interactions with the wind tunnel walls.

RESULT AND DISCUSSION

Climatic data

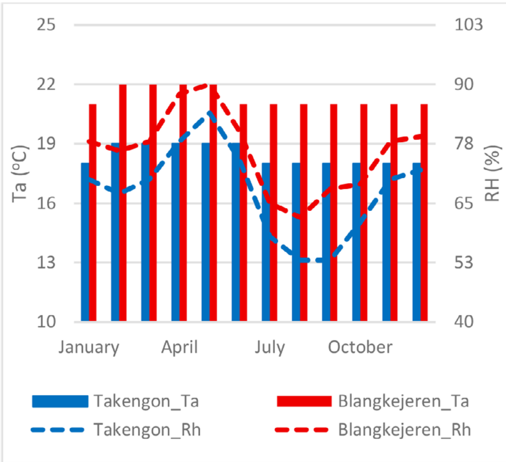
Takengon is situated at the heart of the Gayo highlands, whereas Blangkejeren is positioned slightly to the southeast, near Kutacane – the administrative center of the Aceh Tenggara district. Although both regions are part of the highland area, variations in altitude result in distinct microclimates. As illustrated in Figure 8, Takengon's higher elevation contributes to its cooler climate, with average air temperatures and relative humidity levels approximately 4 °C and 10% lower than those in Blangkejeren. In contrast, wind speed in Takengon tends to be stronger, exceeding that of Blangkejeren by roughly 0.4 m/s (Figure 8) (Weather Spark, 2016). The daytime climate is generally cool, but temperatures can drop significantly at night.

Thermal comfort

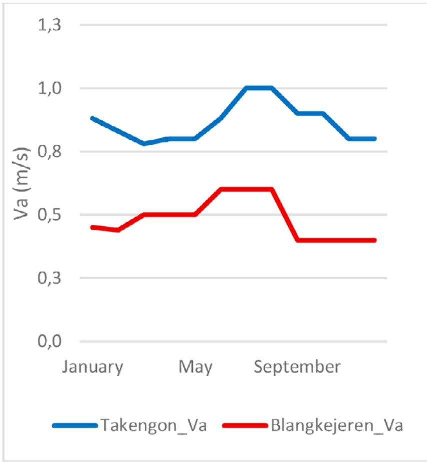
Air temperature, relative humidity and air velocity

An early performance of the indoor thermal environment (Ta, Rh, Av) in the three mosques is shown in Figure 9. As mentioned previously, M2 and M3 are located in the same place i.e. Takengon, so they have the same outdoor climatic data. From the figures, we indicate that from morning to afternoon (9 am to 5 pm), the air temperature (Ta) and the relative humidity (Rh) of the two mosques (M2 and M3) are just close to the outdoor data. However, at night and in the very early morning, the indoor air temperature of M2 and M3 was higher than the outdoor value, and vice versa the indoor relative humidity is lower than that of the outdoors. During that time, the value of the air temperature in M3 was higher than that in M2 which was 19 °C while M2 stood at 17 °C, the minimum value. Whereas M1 located in Blangkejeren has higher outdoor thermal performance compared to M2 and M3 in Takengon. But interestingly, Figure 9 shows that air temperature stayed almost constant at 25 °C.

Referring to the value of indoor air speed in Figure 10, the value of the air speed in the three

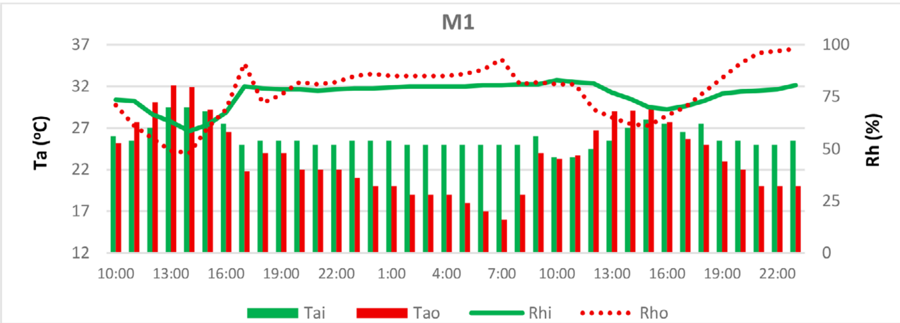


(a)

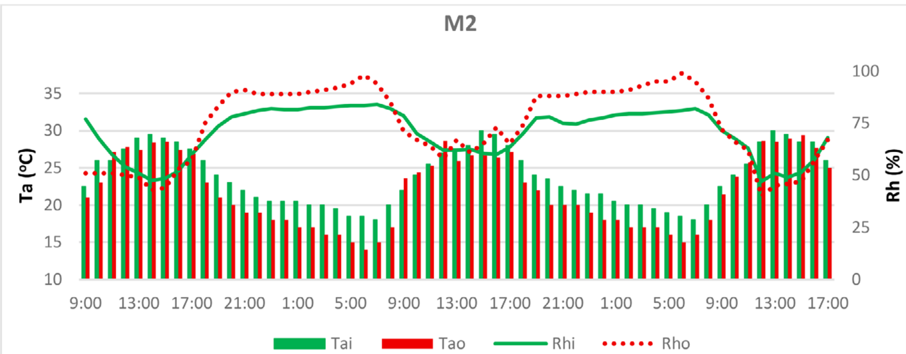


(b)

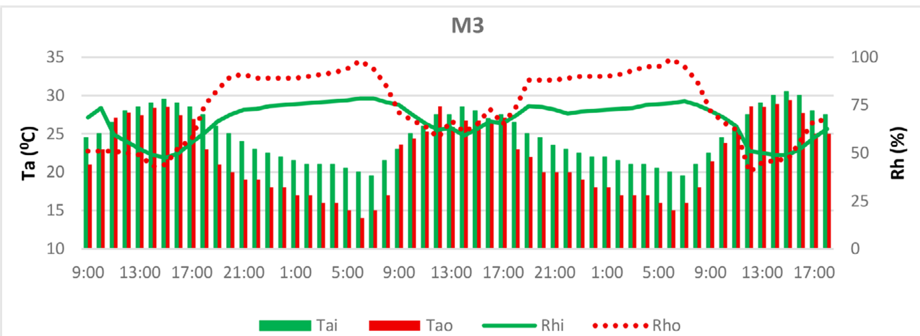
Figure 8. The average value of (a) air temperature, and relative humidity; and (b) air velocity in Takengon and Blangkejeren within a year (Weather Spark, 2016)



(a)



(b)



(c)

Figure 9. The performance of air temperature (Ta) and relative humidity (Rh) in (a) M1, (b) M2 and (c) M3

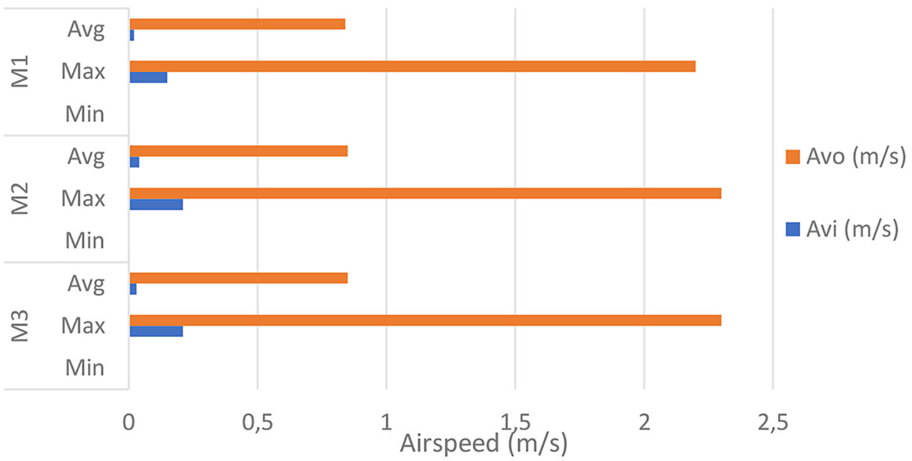


Figure 10. The air velocity of the three mosques surveyed in the study

mosques is quite low, compared to the outside data. This is probably caused by obstructions surrounding mosques like houses that reducing the air speed significantly. M1 is attached to the new mosque thus avoiding the wind entering the old mosque (M1). At the average of the outside air speed (Avo) which was 0.85 m/s, the indoor air speed (Avi) was just around 0.03 and 0.04 respectively in M3 and M2. While M1 had a lower average value of i.e. 0.02 m/s once the outside data was 0.84m/s. In regards to the subjective reactions, an airspeed lower than 0.25 m/s is reacted as 'unnoticed'(Szokolay, 2012).

The prediction of thermal perception is indicated through two indexes namely SET and PMV. Figure 11 shows the value of the average, maximum and minimum of the SET in the three mosques. During Fajr prayer, the SET value of M2 and M3 ran lower than that in M1. During Maghrib and Isha prayer, the value of SET in the three mosques was slightly closer to each other i.e. ranging from 23 to 25 °C. Apart from these, Figure 10 indicates that all the values run in the comfortable range (no danger) (Błazejczyk et al., 2013).

While the PMV index specifies more on the prediction of the thermal sensation. Figure 12 indicates that during fajr prayer, the prediction of thermal sensation in M2 is the lowest i.e -1.735 which means close to cold sensation. The grade of physiological stress is moderate cold stress. But in contrast during the day (Dhuhr prayer), the value of PMV in M2 is also the highest which is up to 1.31 (warm) with the grade of physiological stress being moderate heat stress. In general, M3 which is located in the same district as M2 has a slightly close value of PMV to M2. Figure 11 shows that M1 has a better value of PMV compared with the

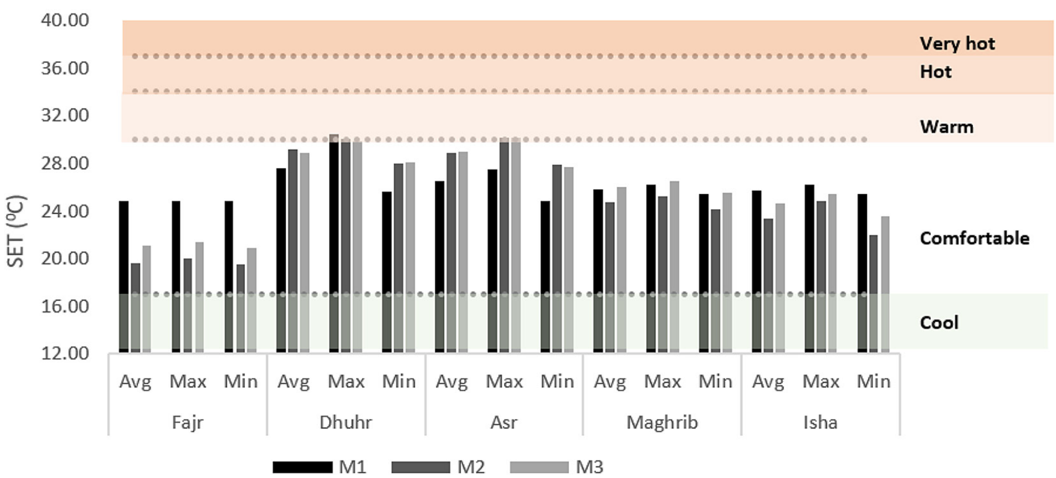


Figure 11. The value of SET of the three investigated mosque

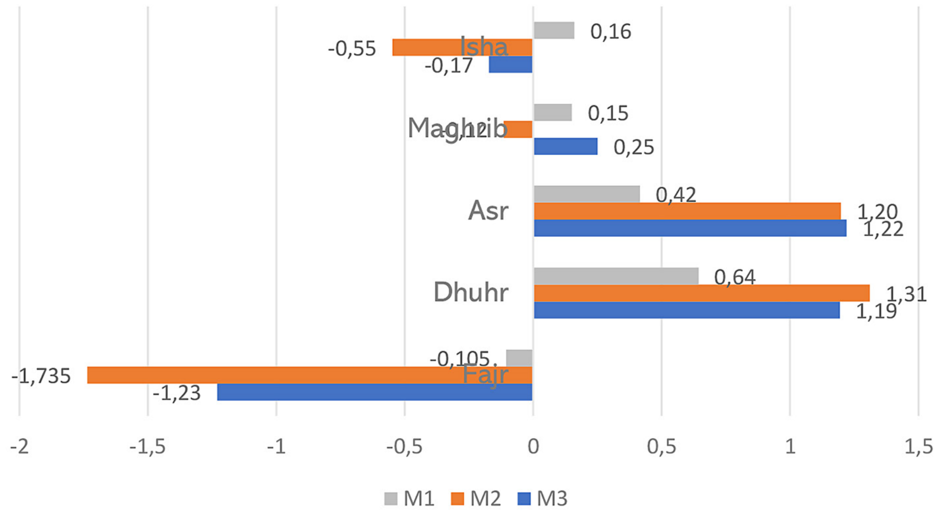


Figure 12. Predicted mean vote (PMV) in the three investigated mosques

three mosques which is close to 0 meaning comfortable sensation (no thermal stress).

Related to PMV, the value of the PPD figures show the percentage of dissatisfaction on the PMV. Figure 12 shows that fajr prayer is the time sensed as the most uncomfortable in M2 followed by M3, with values of 63.25% and 37% respectively. During the day, the value of PPD in M2 and M3 is also high but lower than in the early morning. This study shows that M1 has a small amount of dissatisfaction regarding the thermal environment (Figure 13).

In thermal comfort, airflow plays an important role in defining SET*, PMV and PPD. Figure 10 shows that the measured air velocity in the three mosques (M1, M2, M3) was very low. During the measurements, some openings were not open due to decay in the window structure. The roof openings in M3 were sealed with the gypsum ceiling. As previously mentioned the surrounding environment of the historical mosques is currently crowded by settlements, thus creating even more obstructions to airflow.

Design impact on thermal comfort

This study highlights the impact of mosque design on thermal comfort. The SET values in all three mosques fall within the comfortable range. M1, with a timber roof covered by sago palm leaves, maintains a stable indoor temperature of around 25 °C, despite outdoor

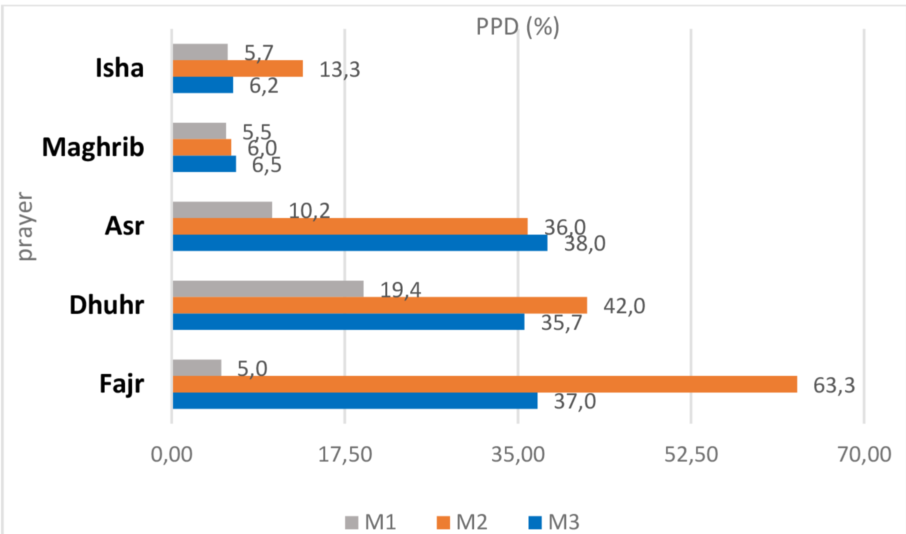


Figure 13. The predicted percentage of dissatisfied values

temperatures varying from 16 °C to 27 °C. In contrast, M2 and M3, which have concrete walls and metal roofs, experience more significant indoor temperature fluctuations. Metal roofs, particularly corrugated zinc, cause warmer indoor conditions during the day and colder conditions at night. M3 is 6K warmer indoors than outdoors, while M2 is 4-5K colder.

The sago palm leaf roof acts as effective insulation, similar to a thatch roof with a U-value of 0.23 W/m²K, reducing heat and cold effects and supporting sustainability (Latha et al., 2015; Masri et al., 2018). Roof material and ventilation also affect thermal sensation. M1, with its original openings, induces a slightly warmer sensation (PMV -0.05) in the early morning compared to M2 and M3, which are colder (PMV -1.735 and -1.23). During the day, M2 and M3 create a warmer sensation due to metal roofs, with higher PMV values (1.31 and 1.19). M1's roof ventilation helps release warm air, resulting in a cooler sensation (PMV 0.64). M3's roof ventilation is restricted by a gypsum surface, limiting airflow.

Airflow Simulation

This study investigates the existing mosque design with openings left open through the building envelopes, using airflow simulation with Ansys fluent fluid simulation software. Through the simulation, this study would like to asses how the elderly cope with the local climate and environment in order to optimize their comfort, especially during the day when the air temperature is higher. The simulation used Ansys 3D modelling to predict the airflow in the three mosques. The scenarios were set to have the windows/apertures and the roof openings open. The wind flow was set to be flowing from the major wind directions around the mosque namely 270° (M1 and M2) and 260° (M3) clockwise from the north. The outdoor wind speed was set based on the average value of the outdoor airspeed which was just close to each of the mosques i.e. 2.3 m/s.

Of the three mosques, we found that M1 and M2 had higher air velocity compared to M3 (Figures 14, 15, 16). M1 and M2 have access to the roof ventilation which creates the high air flow running throughout the mosque. M2 had an airspeed of up to 0.73 m/s in the centre of the mosque. The west aperture where the main air enters into the mosque registered the highest speed, nearly the same as the outside air velocity. There were just small parts of the mosque where there was zero airspeed. In M1, the airspeed at the door zone was the fastest and the same as the outdoor airspeed i.e. 2.3 m/s. The air speed near the upper ventilation running along the wall was just 0.73 m/s, which is still acceptable for pushing the air around the room.

M3 had the lowest air velocity compared to M1 and M2. Two scenarios were applied to the simulation i.e. with roof ventilation and without roof ventilation. These scenarios were set because in the old design of the mosque (M3) there was access to the roof ventilation. In its condition at the time of measurements, the access to the upper ventilation had been closed with a gypsum ceiling. M3 without access to the roof ventilation had less air flow at the roof which was about 0 to 0.13 m/s. There were also some zero airspeed zones in the roof area. The old design with free access to the roof ventilation gave faster air velocity running throughout the roof.

Design impact on airflow

In this study, we indicate that the mosque with roof ventilation and cross ventilation works best in inducing airflow. Even though the highland is characterized by lower air temperatures than the

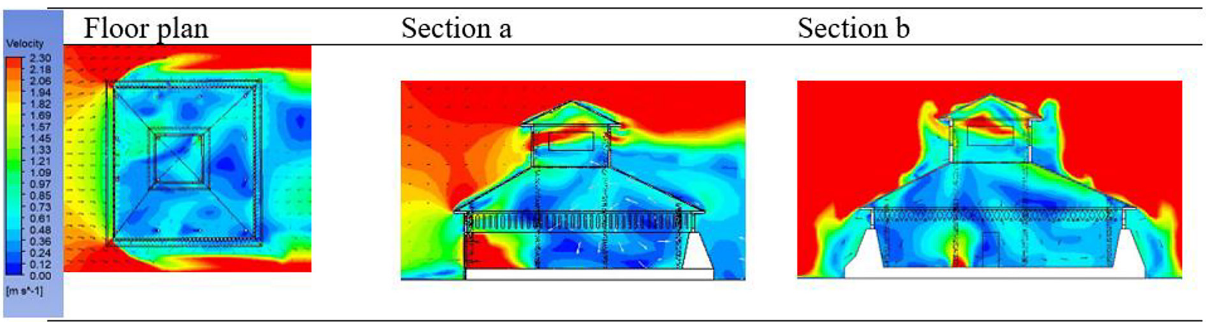


Figure 14. The airflow simulation in M1

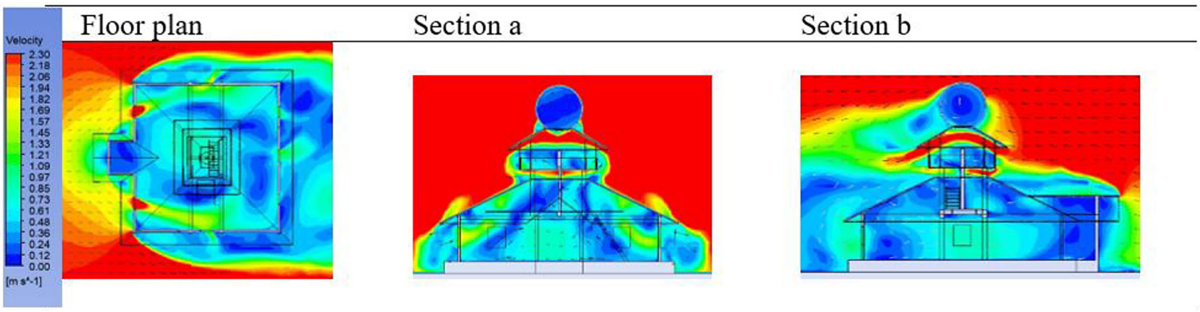


Figure 15. The airflow simulation in M2

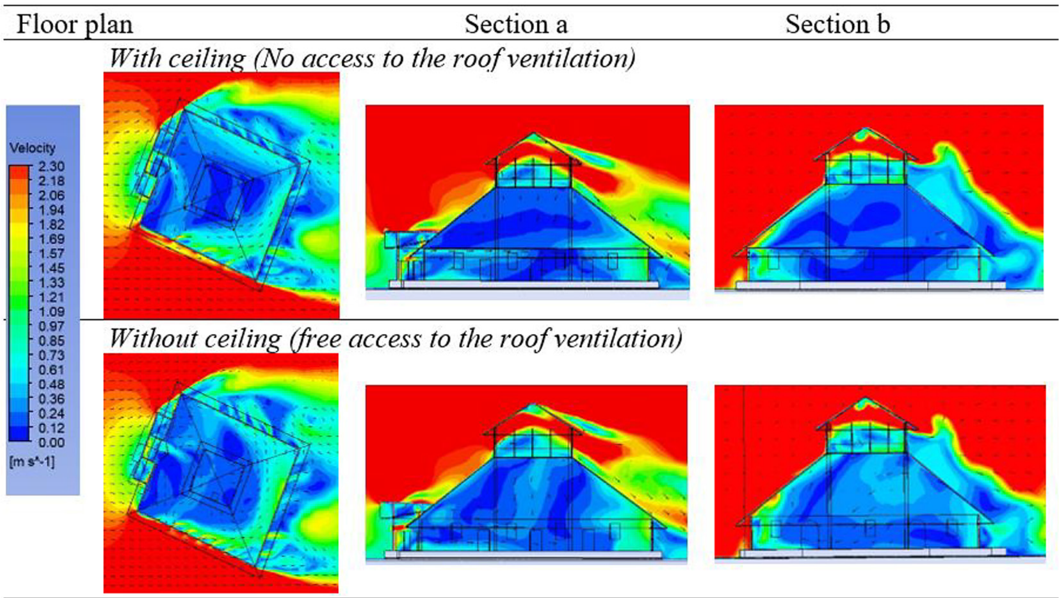


Figure 16. The simulation of airflow in M3

lowland, airflow is needed to circulate air and reduce excessive heat during the day. Top ventilation in buildings works best to enhance air movement and overall airflow dynamics (Zhang et al., 2024). This process exploits the natural tendency of hot air to rise due to its lower density compared to cooler air. The stack effect, driven by temperature differences between indoor and outdoor environments, causes warm air inside a building to rise and exit through higher openings like top ventilation, while cooler air is drawn in through lower openings (Dezfuli et al., 2023).

CONCLUSIONS

This study successfully demonstrated that preserving the original architectural features of historical mosques – especially in terms of materials and ventilation strategies – has a significant positive impact on thermal comfort and airflow. Among the three mosques examined, M1 (Asal Penampaan mosque), which retained its traditional design with sago palm roofing and original ventilation, showed the best thermal performance and airflow consistency. In contrast, the renovated mosques (M2 and M3), which used modern materials such as concrete and zinc, experienced greater temperature fluctuations and lower indoor air movement.

The findings confirm that traditional designs – optimized by local builders without formal thermal models – were more effective in creating comfortable indoor environments in the highland context. Scientifically, this study provides empirical evidence that vernacular building envelopes and ventilation strategies can outperform modern modifications in terms of passive thermal regulation, even under similar climatic conditions. This insight addresses a gap in the literature on the quantifiable benefits of architectural preservation in thermal performance, particularly in under-researched tropical highland contexts like Gayo.

The research opens up new prospects for integrating traditional passive design principles into sustainable architecture and retrofitting strategies for historical buildings. It encourages heritage preservation not only for cultural reasons but also for its environmental advantages, suggesting that historical design solutions can inform contemporary energy-efficient architecture, especially in resource-constrained or climatically sensitive regions.

Acknowledgement

The authors sincerely thank Universitas Syiah Kuala and the Ministry of Education, Culture, Research, and Technology (Kemendikbudristek) of the Republic of Indonesia, particularly the Directorate General of Higher Education, Research, and Technology, for providing financial support for this study through the PDKN research grant (Contract No. 2023 563/UN11.2.1/PT.01.03/DPRM/2023, dated May 3, 2023).

REFERENCES

1. Aiyubi, T.M.A., Sari, L.H., Safwan. (2024). The influence of air movement in providing thermal comfort in naturally ventilated old Mosque Gunong Kleng, West Aceh, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1356*(1), 012056. https://doi.org/10.1088/1755-1315/1356/1/012056
2. Arda Akyıldız, N., & Nur Olğun, T. (2020). Investigation for energy use and conservation of sustainable traditional architecture: case of Malatya/Turkey Bahri Mosque. https://doi.org/10.5923/j.arch.20201002.03
3. Atmaca, A.B., & Gedik, G.Z. (2019). Evaluation of mosques in terms of thermal comfort and energy consumption in a temperate-humid climate. *Energy and Buildings*, *195*, 195–204. https://doi.org/10.1016/j.enbuild.2019.04.044
4. Azmi, N.A., Arıcı, M., Baharun, A. (2021). A review on the factors influencing energy efficiency of mosque buildings. *Journal of Cleaner Production*, *292*, 126010. https://doi.org/https://doi.org/10.1016/j.jclepro.2021.126010
5. Azmi, N.A., Ibrahim, S.H. (2020). A comprehensive review on thermal performance and envelope thermal design of mosque buildings. *Building and Environment*, *185*, 107305. https://doi.org/https://doi.org/10.1016/j.buildenv.2020.107305
6. Bakri. (2017, October 6). *Al Jihad Asir-asir, Terbesar Masa Belanda*. Serambi News.Com.
7. Błazejczyk, K., Jendritzky, G., Bröde, P., Fiala, D., Havenith, G., Epstein, Y., Psikuta, A., Kampmann, B. (2013). An introduction to the universal thermal climate index (UTCI). *Geographia Polonica*, *86*(1), 5–10. https://doi.org/10.7163/GPol.2013.1
8. Budaiwi, I.M., Abdou, A.A., Al-Homoud, M.S. (2013). Envelope retrofit and air-conditioning operational strategies for reduced energy consumption in mosques in hot climates. *Building Simulation*, *6*(1), 33–50. https://doi.org/10.1007/s12273-012-0092-5
9. Budi, B.S. (2004). A study on the history and development of the Javanese Mosque. *Journal of Asian Architecture and Building Engineering*, *3*(1), 189–195. https://doi.org/10.3130/jaabe.3.189
10. Diler, Y., Turhan, C., Durmuş Arsan, Z., Gökçen Akkurt, G. (2021). Thermal comfort analysis of historical mosques. Case study: The Ulu mosque, Manisa, Turkey. *Energy and Buildings*, *252*. https://doi.org/10.1016/j.enbuild.2021.111441
11. Dwela, H., Kayili, M.T. (2023). The Determination of the retrofitting strategies on thermal comfort and energy efficiency of Mosques: the case of Yasamkent Mosque. *Computational Research Progress In Applied Science & Engineering*, *9*(1), 1–10. https://doi.org/10.52547/crpase.9.1.2841
12. Gilani, S.I.U.H., Khan, M.H., Pao, W. (2015). Thermal comfort analysis of PMV model prediction in air conditioned and naturally ventilated buildings. *Energy Procedia*, *75*, 1373–1379. https://doi.org/10.1016/j.egypro.2015.07.218
13. Han, M., Jin, Z., Zhao, Y., Zhang, Y., Han, W., Zhang, M. (2024). Indoor thermal environment evaluation for emergency medical tents in heating season: on-site testing and case study in China. *Atmosphere*, *15*(3). https://doi.org/10.3390/atmos15030388
14. Hoomanirad, M., Tahbaz, M. (2014). Assessment of daylight role in creating spiritual mood in contemporary Mosques. *Armanshahr Architecture & Urban Development*, *7*(1), 11–23. https://www.armanshahrjournal.com/article_39216.html
15. Jamaludin, J., Salura, P. (2018). Understanding the meaning of triangular shape in mosque architecture in Indonesia. *International Journal of Engineering & Technology*, *7*(4.7), 458. https://doi.org/10.14419/ijet.v7i4.7.27359
16. Latha, P.K., Darshana, Y., Venugopal, V. (2015). Role of building material in thermal comfort in tropical climates – A review. *Journal of Building Engineering*, *3*, 104–113. https://doi.org/https://doi.org/10.1016/j.jobe.2015.06.003
17. Masri, T., Ounis, H., Sedira, L., Kaci, A., Benchabane, A. (2018). Characterization of new composite

material based on date palm leaflets and expanded polystyrene wastes. *Construction and Building Materials*, *164*, 410–418. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2017.12.197

18. Montiel, I., Mayoral, A.M., Pedreño, J.N., Maiques, S., Santos, G.M. Dos. (2020). Linking sustainable development goals with thermal comfort and lighting conditions in educational environments. *Education Sciences*, *10*(3). https://doi.org/10.3390/educsci10030065
19. Dezfuli, R.R., Bazazzadeh, H., Taban, M., Mahdavinejad, M. (2023). Optimizing stack ventilation in low and medium-rise residential buildings in hot and semi-humid climate. *Case Studies in Thermal Engineering*, *52*, 103555. https://doi.org/https://doi.org/10.1016/j.csite.2023.103555
20. Sari, L. H., Ariatsyah, A. (2023). An appraisal of indoor thermal comfort in a naturally-ventilated modified old mosque in Banda Aceh, Indonesia. *JIA 364 | Journal of Islamic Architecture*, *7*(3). http://ejournal.uin-malang.ac.id/index.php/
21. Sari, L.H., Ghassan, M.L., Munir, A. (2023). Air movement to remove barriers and provide thermal comfort in the global south: a case study of a classroom in the warm humid tropics, Banda Aceh, Indonesia. In L. Marín-Restrepo, A. Pérez-Fargallo, M.B. Piderit-Moreno, M. Trebilcock-Kelly, P. Wegertseder-Martínez (Eds.), *Removing Barriers to Environmental Comfort in the Global South* (pp. 59–71). Springer International Publishing. https://doi.org/10.1007/978-3-031-24208-3_5
22. Sari, L.H., Izziah, Meutia, E. (2020). Adaptation of local wisdom in contemporary mosque design for achieving good building physics and earthquake resistance. *IOP Conference Series: Materials Science and Engineering*, *737*(1). https://doi.org/10.1088/1757-899X/737/1/012021
23. Sari, L.H., Kayan, B.A., Zahriah, Z. (2022). An assessment of indoor environmental quality in COVID-19 affected houses: a case study in Banda Aceh, Indonesia. *International Journal of Building Pathology and Adaptation*. https://doi.org/10.1108/IJBPA-02-2022-0033
24. Sari, L. H., Wulandari, E., Idris, Y. (2024). An investigation of the sustainability of old traditional mosque architecture: case study of three mosques in Gayo Highland, Aceh, Indonesia. *Journal of Asian Architecture and Building Engineering*, *23*(2), 528–541. https://doi.org/10.1080/13467581.2023.2245006
25. Shohan, A.A.A., Gadi, M.B. (2020). Evaluation of thermal and energy performance in Mosque buildings for current situation (simulation study) in mountainous climate of Abha city. *Sustainability (Switzerland)*, *12*(10). https://doi.org/10.3390/SU12104014
26. Szokolay, S. (2012). *Introduction to Architectural Science*. Routledge.
27. Weather Spark. (2016). *Climate and Average Weather Year Round in Lampuuk Indonesia*. Https://Weatherspark.Com/y/112350/Average-Weather-in-Lampuuk-Indonesia-Year-Round.
28. Wibowo, A.S., Sasano, S. (2016). Historical assessment of the Saka Tunggal Mosque in Banyumas: Study on the single column mosque on Java Island, Indonesia. *Journal of Asian Architecture and Building Engineering*, *15*(3), 373–380. https://doi.org/10.3130/jaabe.15.373
29. Xu, C., Li, S., Zhang, X., Shao, S. (2018). Thermal comfort and thermal adaptive behaviours in traditional dwellings: A case study in Nanjing, China. *Building and Environment*, *142*, 153–170. https://doi.org/10.1016/j.buildenv.2018.06.006
30. Yüksel, A., Arıcı, M., Krajčík, M., Civan, M., Karabay, H. (2022a). Energy consumption, thermal comfort, and indoor air quality in mosques: Impact of Covid-19 measures. *Journal of Cleaner Production*, *354*, 131726. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.131726
31. Yüksel, A., Arıcı, M., Krajčík, M., Civan, M., Karabay, H. (2022b). Energy consumption, thermal comfort, and indoor air quality in mosques: Impact of Covid-19 measures. *Journal of Cleaner Production*, *354*, 131726. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.131726
32. Yusoff, W.F.M., Ja'afar, N.H. (2019). Preliminary evaluation of indoor thermal comfort in Malaysia heritage mosque. *MATEC Web of Conferences*, *277*, 02016. https://doi.org/10.1051/matecconf/201927702016
33. Zhang, R., Xu, X., Liu, K., Kong, L., Wang, W., Wortmann, T. (2024). Airflow modelling for building design: A designers' review. *Renewable and Sustainable Energy Reviews*, *197*, 114380. https://doi.org/https://doi.org/10.1016/j.rser.2024.114380
34. Zhao, Q., Lian, Z., Lai, D. (2021). Thermal comfort models and their developments: A review. In *Energy and Built Environment.* KeAi Communications Co, *2*(1), 21–33). https://doi.org/10.1016/j.enbenv.2020.05.007