

Original Research Paper

# Space Quality of Two Indonesian Mosques: Architectural Style, Development Process and Environmental Condition

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**Abstract:** Mosque buildings in Indonesia show the influence of architectural styles from the Middle East and other parts of the world. Today, information technology and the development of architectural schools play important roles in mosque styles in Indonesia. This study compared two Indonesian mosques (the Cabean and Eco Pesantren mosques in Central and West Java, respectively) in different architectural styles and considered construction processes, development actions and environmental conditions (highlands and lowlands close to the coast). Architectural quality was measured in terms of thermal comfort in the mosques. Field surveys and environmental quality measurements were undertaken at both mosques, consisting of  $T_{DB}^{\circ C}$ ,  $T_{WB}^{\circ C}$ ,  $T_{BG}^{\circ C}$  and  $v$  m/s. The results showed differences in mosque quality in the following aspects affecting thermal comfort: (1) the size and location of ventilation openings, (2) building aspect ratio and distance to other buildings, (3) thermal mass and (4) outdoor design quality. Horizontal and vertical openings play a significant role in thermal comfort in terms of airflow, which is affected by the distance between buildings. Building materials also play an important role in thermal comfort with regard to the penetration of direct solar radiation through the roof.

**Keywords:** Space Quality, Mosque Architectural Style, Development Process, Adaptation to the Environment, Mosque Design Thermal Comfort, Ventilation and Lighting Openings, Building Materials

## Introduction

Thermal comfort in a mosque is important considering that mosques are generally wide and high with many openings, making the use of artificial air conditioning wasteful. Mosques in various regions tend to be built with the same typology. Differences in topography and sea level, however, can greatly affect environmental conditions such that mosques in highlands and lowlands require different designs. Thus, mosque designs cannot be considered the same for all regions. As such, mosque designs may require various adjustments according to the area to obtain the best performance.

Mosques located in highlands and lowlands receive different solar and environmental radiation. The higher the geographic and solar altitude, the higher the radiation

value (Oki and Shiina, 2003). Houbolt's theory (Mangunwijaya, 1994) regarding the correlation between air temperature and altitude indicates that in areas below a latitude of  $60^{\circ}$ , every 100 m increase will decrease the temperature by  $0.57^{\circ C}$ . Thus, mosques in highland areas tend to experience cold temperatures while those in lowlands experience high temperatures.

Differences in environmental conditions have different effects on thermal comfort levels (Humphreys and Nicol, 2000; Brager and de Dear, 2001). Lippsmeier (1994) noted that the comfortable boundary on the equator is in the range of  $22.5^{\circ C}$ – $29.5^{\circ C}$  with a relative humidity of about 40%–60% RH. Thermal comfort in a building in a tropical climate is comfortably cool in the range of  $20.8^{\circ C}$ – $22.8^{\circ C}$ , optimally comfortable between  $22.8^{\circ C}$  and  $25.8^{\circ C}$  and

comfortably warm between 25.8°C and 27.1°C (Latifah, 2015). Henderson and Harper (2003) noted that areas at lower altitudes require higher wind speeds.

Since the Middle East is the centre of Islamic civilization, mosques are often oriented toward the architectural typology of that region (Humariah and Mastutie, 2013; Wiryoprawiro, 1984). However, mosques that adopt architectural styles from other regions must adjust to the conditions of their surroundings. Architectural factors that may play a significant role include space function, geometric aspects (including the form and order of space) and culture-related styles of the region (Sulistijowati, 1991).

The arrangement of openings in a mosque is related to achieving desired thermal comfort conditions. In naturally ventilated buildings, thermal comfort depends on the size and orientation of window openings (Prakash and Ravikumar, 2015). Thermal comfort is achieved when humidity is reduced by facilitating air movement through openings in the south and north ends of a mosque (Kusyanto *et al.*, 2017). Hassana *et al.* (2007) investigated the effect of different combinations of window openings on thermal comfort in buildings. One-sided ventilation with two openings slightly apart has been found to provide better ventilation than adjacent openings (Munir and Wonorahardjo, 2004).

Airflow through a mosque space is necessary, especially during Friday prayers, given the accumulation of heat and humidity, which causes the space to become uncomfortable. Natural ventilation via large openings is therefore needed to facilitate smooth airflow and reduce discomfort (Indrayadi, 2011). As sources of natural ventilation, window openings allow air to flow into buildings (Amin *et al.*, 2010). In dense settlements, however, natural ventilation is often ignored because of the difficulty of putting windows in the walls (Prawira, 2011). To facilitate comfort, ventilation openings in buildings should be larger in hotter areas than in colder areas (Samodra, 2009). Moreover, different types and positions of openings cause different types of air movement in different rooms. In fact, the performance of one-sided ventilation is influenced by the type and position of the window (Munir and Wonorahardjo, 2004).

A mosque's thermal quality is influenced by the locations of openings as well as the mosque's location in relation to surrounding buildings (Kusyanto *et al.*, 2017). The distance between buildings determines the movement of air in the gaps between the buildings. Areas with high building density generally have higher environmental temperatures than low-density areas; yet, the density of vegetation, altitude and orientation to the sun must be considered as well (Santosa, 2001). Vegetation in particular plays a role in shading the environment, moistening the air (Akbari *et al.*, 2001), reducing the wind rate (Novak *et al.*, 2000; Novak and Crane, 2002), reducing the penetration and reflection of sunlight (Walker, 1991; Heisler and Grant, 2000).

Material properties can also influence thermal conditions in mosques. Specifically, the selection of building materials affects a building's thermal properties (Wonorahardjo, 2012). Thus, the type and thickness of building materials are included in climate-related architectural design factors (Latifah, 2015). A lightweight building system can determine the thermal performance of inner and outer spaces (Goulart, 2004). Considering material properties such as thermal mass (density) and thickness is therefore very important. The greater the density of the building material, the easier it is to store heat; with thicker material, more heat can be stored and the heat-transfer process is longer (Latifah, 2015). Meanwhile, using lightweight materials in hot areas allows heat to rapidly flow into buildings during the day, but that heat is also quickly released into the environment. In cold regions, however, heavy materials are needed to withstand incoming heat during the day and provide passive warming at night (Samodra, 2009). In short, when heat is stored in a heavy, thick material, it takes a long time to release it back into the air (Balaras, 1996).

The present study aimed to determine the role of design factors-such as wall design, the width and position of openings, the distance between buildings and building material types-in the thermal quality of mosques. To this end, two mosques built in different areas and in different ways were compared. One is the Baitul Muttaqin mosque in the Cabean subdistrict of Demak in Central Java, Indonesia. It is built in a lowlands on the North Coast of Java. The other is the Eco Pesantren Daarut Tauhid mosque in Bandung, West Java, Indonesia. It is built in a highlands. Figure 1 shows a comparison of the microclimates of Demak and Bandung according to daily sunshine duration. Daily sunshine lasts longer in Demak than in Bandung and Bandung's skyline is cloudier than Demak's. The locations of the two mosques are shown in Fig. 2.

## Method

To achieve the study's objectives, the two mosques were investigated by examining the distance between buildings, opening configurations, airflow and the configuration of vegetation and topography.

### Data Collection

Data collection was conducted through observation and field measurement in both mosques. The collected data included the following: (1) building physical data, including the extent and location of ventilation openings, distance to other buildings and the types of materials and (2) thermal environmental data, including dry bulb temperature ( $T_{DB}$ °C), wet bulb temperature ( $T_{WB}$ °C), globe temperature ( $T_{GT}$ °C) and air velocity ( $v$  m/s).

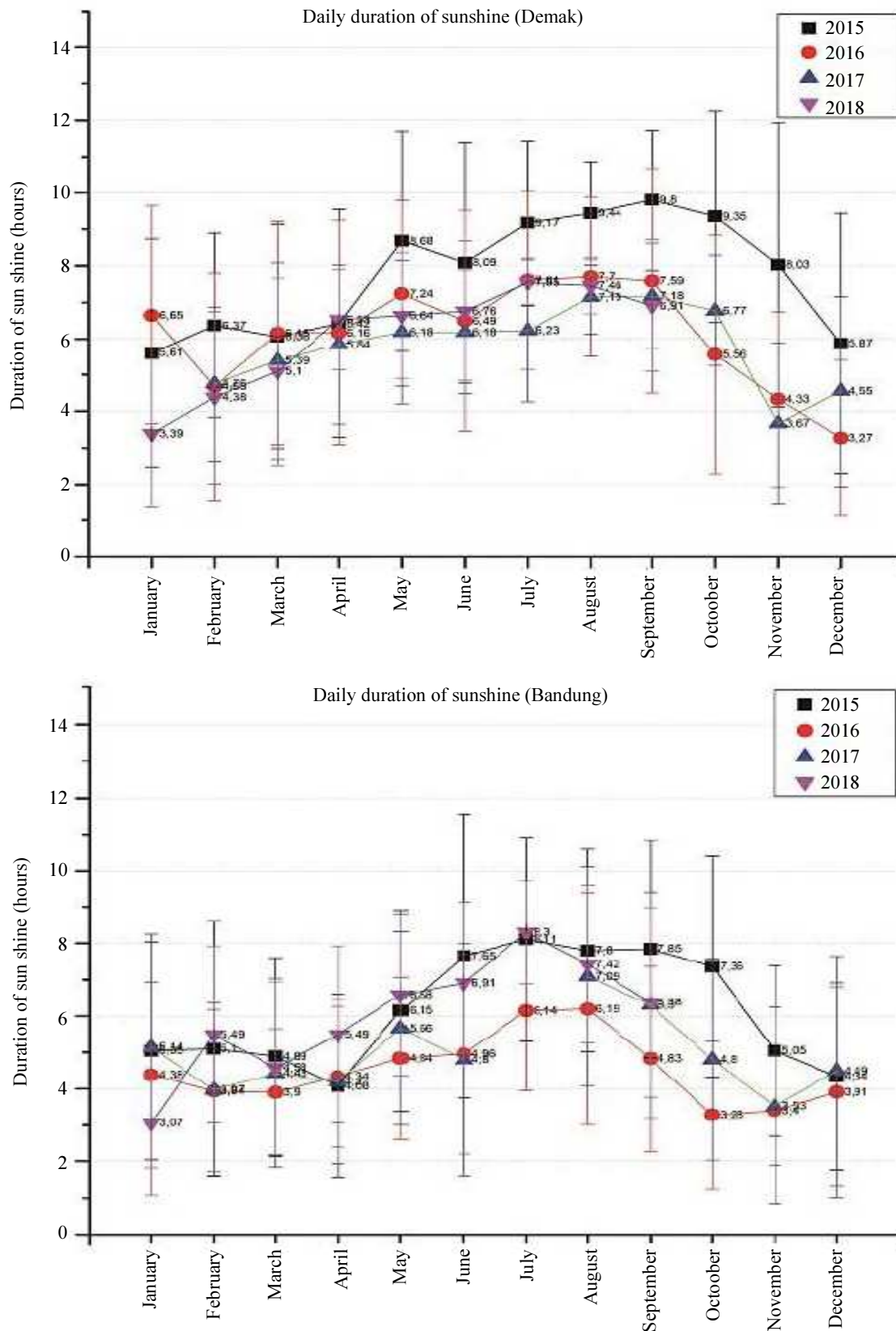


Fig. 1: Patterns of daily sunshine in the cities of Demak (left) and Bandung (right)





The measuring tools were wet and dry thermometers, globe thermometers and digital anemometers. The thermal environments in the mosques were measured on Friday before 11:00 and after Friday prayer (12:00) and in the afternoon before 14:00 and after the ashar prayer (at 16:00). Measurements were taken at three measuring points: the 1st floor of the main hall, the 1st floor porch and the 2nd floor porch.

### Analysis Method

This study examined the relationships between the thermal qualities of two mosques built in different ways and locations. The physical aspects of the buildings and their surrounding environmental factors were investigated. Correlation analysis was performed to identify the influence of the position and area of openings/ventilation in each mosque on the speed of airflow entering the mosque spaces. Airflow patterns were obtained by interpreting air humidity in both mosques and were confirmed through a digital simulation using ANSYS R 15.0 CFD (computational fluid dynamics). Interpreting airflow in terms of thermal comfort values can explain the role of these aspects. The role of materials in both mosques was gathered by interpreting surface temperature values. The interpretation results were used to explain the accuracy of the materials used in both mosques.

### Analysis and Results

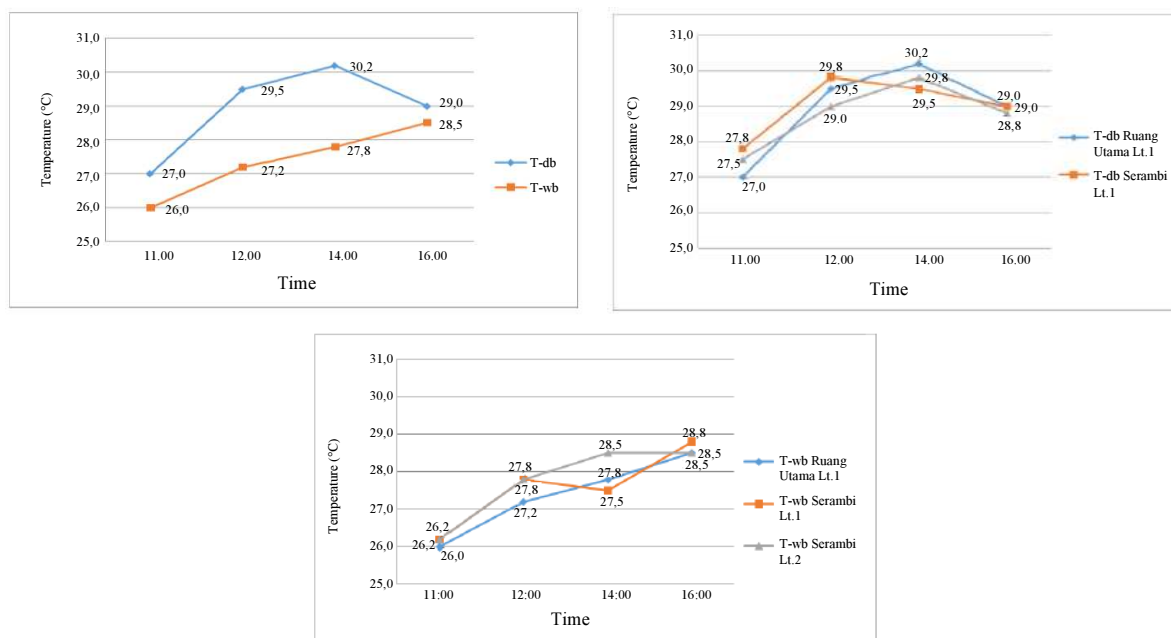
The Cabean mosque was built independently by the community. The half-vaulted mosque is made of concrete material that adopted its design from the areas

around it. The mosque was built over a period of 10 years through a cooperative system involving craftsmen from the village. The construction process was carried out by dismantling the old mosque and building a new one on the grounds of the old mosque.

The Pesantren mosque was designed professionally by an architectural consultant. Structural calculations were done by a structural expert and construction was carried out by a professional contractor. Construction took six years using a Pesantren fund collected through Wakaf Ummah. The construction sought to minimize changes to the contoured tread. This is seen in the presence of the east yard of the mosque, which is located 3-4 meters from the surface of the site, while the west yard is on the surface. The mosque was designed to be on the 1st floor of the building; there are support facilities on the 1st floor, such as the boarding school office, a multipurpose room, a canteen and other facilities.

Thus, in the construction process, the 1st floor was built first, followed by the construction of a mosque located on the 2nd floor (Table 1).

Different building designs influence the thermal comfort of mosque spaces. Based on the results of the  $T_{DB}$  and  $T_{WB}$  measurements at the Cabean mosque between 11:00 and 14:00, comfort quality decreased from morning to afternoon because of rising air humidity. The highest air temperature was at 14:00, which decreased at 16:00. However, air humidity tended to rise in the afternoon due to poor ventilation (Fig. 3). This condition was perceived as sultry by users.



**Fig. 3:** TDB and TWB of the Cabean mosque (left); TDB 1st floor main hall, 1st floor porch and 2nd floor porches of the Cabean mosque (center); TWB 1st floor main hall, 1st floor porch and 2nd floor porches of the Cabean mosque (right)

**Table 1:** Development process of the mosques of Cabean and Eco pesantren

	Age of building (years)	Source of funding	Design process	Stakeholders	Development process
Cabean Mosque	10	Independent	Adoption from design of mosques in the areas around it	Society	Dismantle old buildings and build a new mosque
Eco Pesantren Mosque	6	Pesantren	Professional designer	Contractor	Build the 1st floor mosque facility and continue to build the 2nd floor mosque

**Table 2:** ET measuring points of the Eco Pesantren and Cabean Mosques

	ET 1st floor main hall (°C)	ET 1nd floor porch (°C)	ET 2nd floor porch (°C)
Eco Pesantren mosque	24.3	23.3	24.2
Cabean mosque	28.5	28.8	28.5

The temperature of the indoor air space tended to be higher than on the porch. This shows that air ventilation plays an important role in air temperature (Fig. 3). The wet ball thermometers also showed values that tended to be lower for the porch than the main hall of the mosque. Air movement on the porch was better than in the main hall, meaning the humidity value of the porch was lower (Fig. 3).

Meanwhile, in the Eco Pesantren mosque, designed by architects and located in the highlands of Bandung, the highest  $T_{DB}$  temperature did not occur at 14:00 but at 12:00 (Fig. 4). Air temperatures on the 2nd floor tended to be higher at 12:00, showing the effect of solar radiation penetrating the roof (Fig. 4).  $T_{WB}$  showed declining values after the peak at 11:00.

This indicates that airflow inside the mosque was very good (Fig. 4). Humidity and air temperature on the porch were lower than in the inner chamber. This condition was influenced by a good ventilation factor and the relatively open environment setting in this mosque.

The thermal comfort of the Cabean and Eco Pesantren mosques can be measured by the Effective Temperature (ET) using a nomogram. The ET measurement of the Cabean mosque showed that the main hall on the 1st floor was 28.5°C, the 1st floor porch was 28.8°C and the 2nd floor porch was 28.5°C. In the Eco Pesantren mosque, meanwhile, the 1st floor main hall was 24.3°C, the 1st floor porch was 23.3°C and the 2nd floor porch was 24.2°C (Table 2). The measuring point of the 1st floor porch was lower because of the effect of the airflow rate (Fig. 5 left and right).

The quality of thermal comfort was influenced by the relative humidity factor in the mosque spaces. The average relative humidity in the main hall of the Cabean mosque was 94%; in the Eco Pesantren mosque, it was 75% (Fig. 6). This indicates that the quality of ventilation at the Eco Pesantren mosque was better than at the Cabean mosque.

The quality of thermal comfort is influenced by the flow of air coming into rooms through openings/vents in the walls. On the north and south sides of the main hall of the Cabean mosque, there are wide glass windows that

can be opened for airflow. The west wall is completely covered with brick while the eastern wall is glass and there are two glass doors that can allow for airflow (Fig. 7).

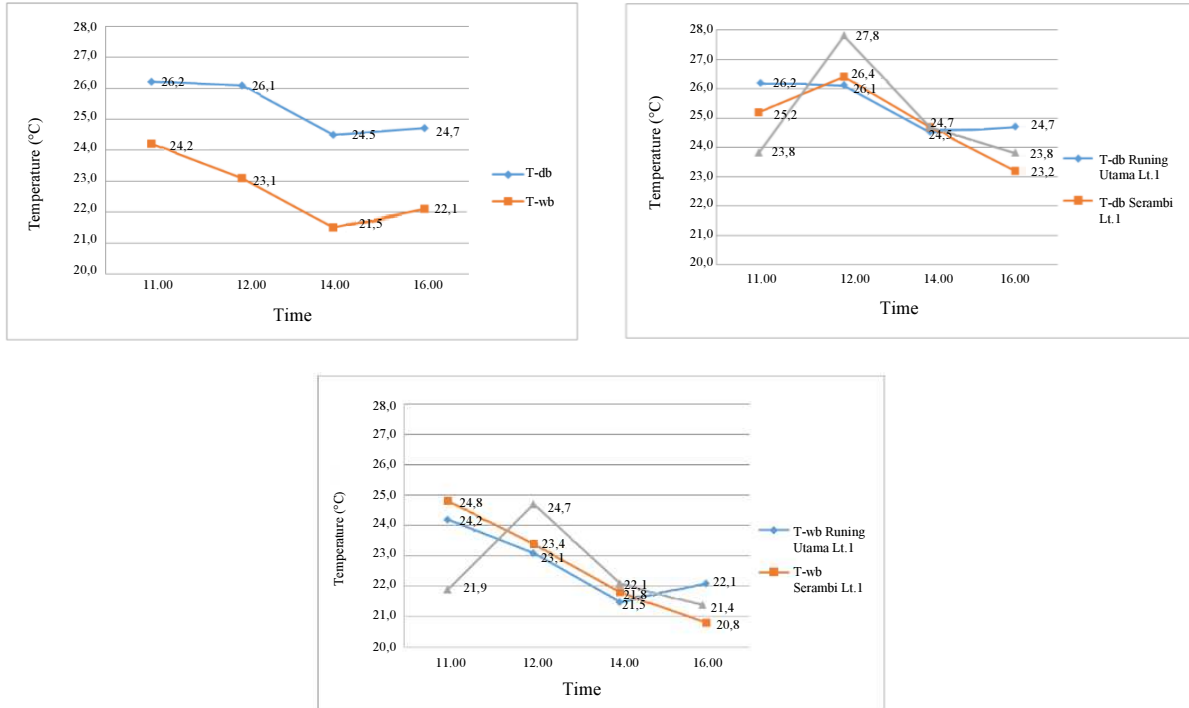
The Eco Pesantren mosque is designed to drain as much air as possible into rooms. The western side is not walled and directly open to the natural environment. The north, south and east sides consist of glass windows that can allow light and air to enter when opened (Fig. 8).

The percentages of openings in the walls of the 1st floor of the Cabean mosque are as follows: the west side is 0% covered with a brick wall, the east side has a glass wall with openings in the form of an entrance comprising 8.3% and the north side wall, equal to the south side wall, has window openings, 41.3% of which cannot be opened. On the 2nd floor, the west side has the same ratio as the 1st floor, while the east side is 100% open; the north and south sides have the same opening ratios of 39.7% (Fig. 9). Meanwhile, the opening percentages for the Eco Pesantren mosque are 26.7% for the north side, 43.3% for the south side and 52.7% for the east side. The west side has a 100% open area. The percentages of open space on the 2nd floor are north side 7.8%, south side 7.8% and east side 8.3%. The open area on the west side is 100% (Fig. 9).

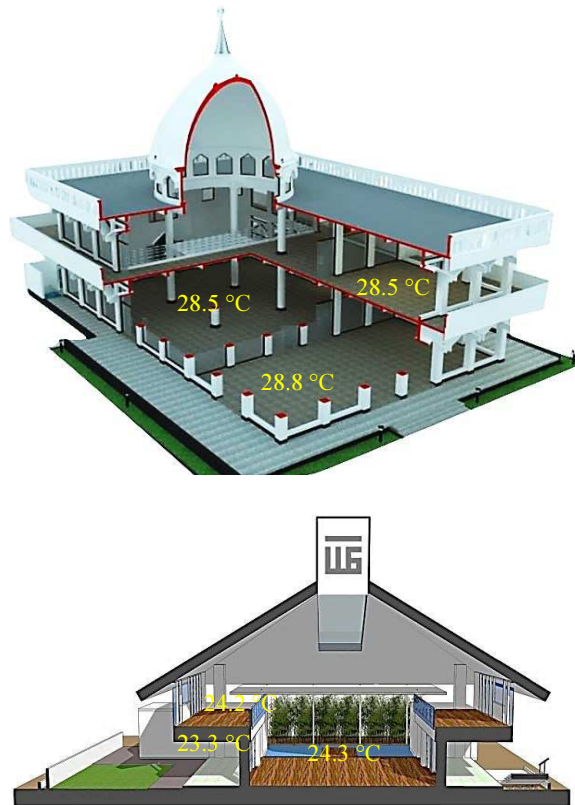
These design differences in the walls of the mosques influence the quality of airflow in the main rooms. The Cabean mosque has fewer openings but can provide more light because the walls are made of glass. Meanwhile, the Eco Pesantren mosque adapts to the cool environment in the highlands of Bandung with many openings on the north, south and east walls. The open west side facilitates airflow through the mosque's central room.

The widths of the openings in the mosques have different ratios. The Cabean mosque has a total opening area of 34% while the Eco Pesantren mosque has 79%. The small openings in the Cabean mosque affect the quality of airflow in the rooms (Fig. 10 left and right).

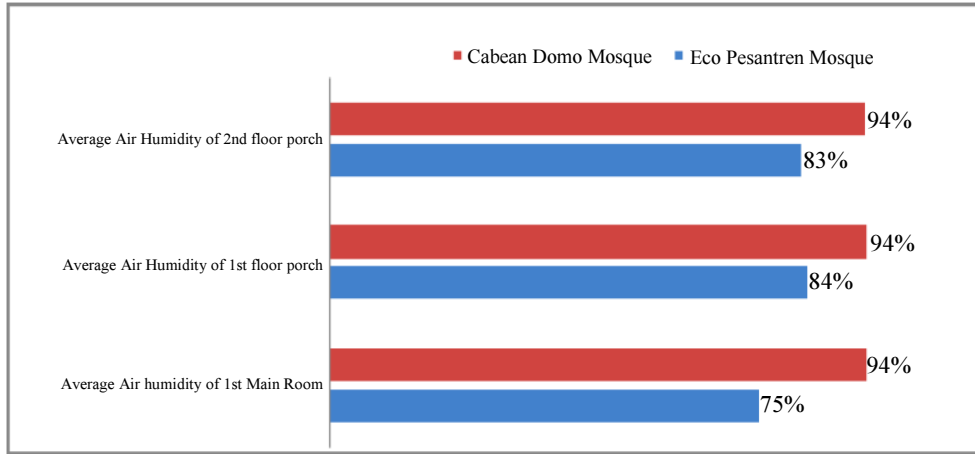
The speed of airflow in the buildings is influenced by the surrounding environment. The Cabean mosque is located in a densely populated residential area that impedes airflow around the mosque. The Eco Pesantren mosque, meanwhile, is located in an open area with an environment contoured with high trees (Fig. 11 left and right).



**Fig. 4:** TDB and TWB of the Eco Pesantren mosque (left); TDB of the 1st floor main hall, 1st floor porch and 2nd floor porches of the Eco Pesantren mosque (center); TWB of the 1st floor main hall, 1st floor porch and 2nd floor porches of the Eco Pesantren mosque



**Fig. 5:** ET measuring point of the Cabean mosque (left), ET measuring point of the Eco Pesantren mosque (right)



**Fig. 6:** Average air humidity in the 1st main hall, 1st floor porch and 2nd floor porch of the Cabean and Eco Pesantren mosques

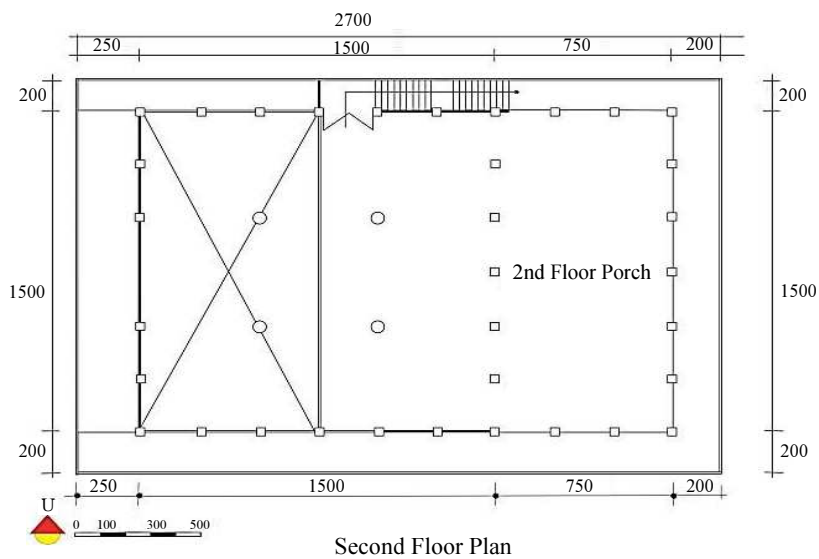
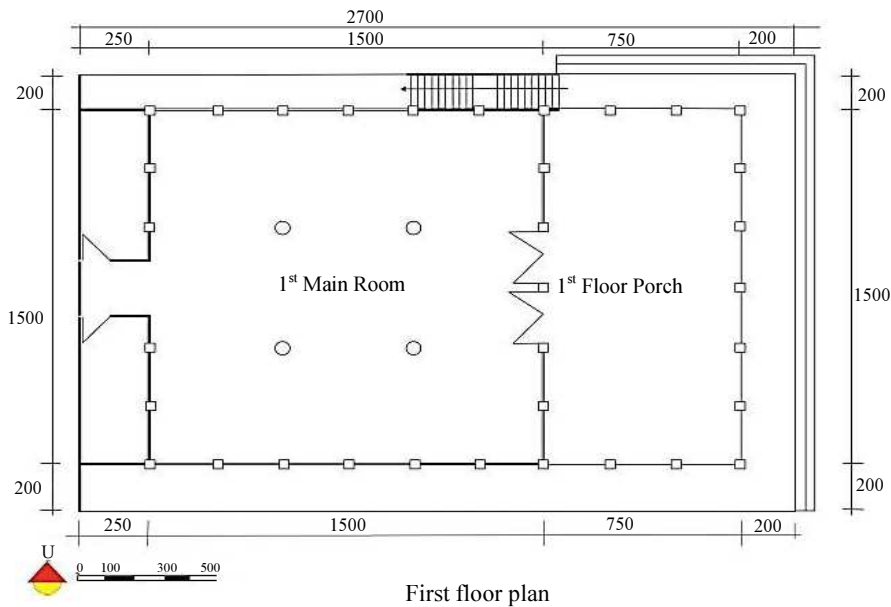
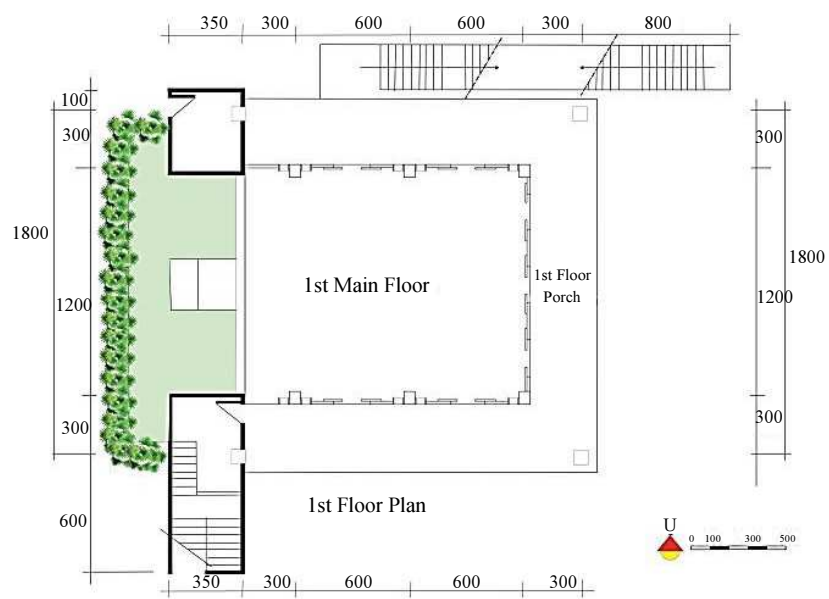
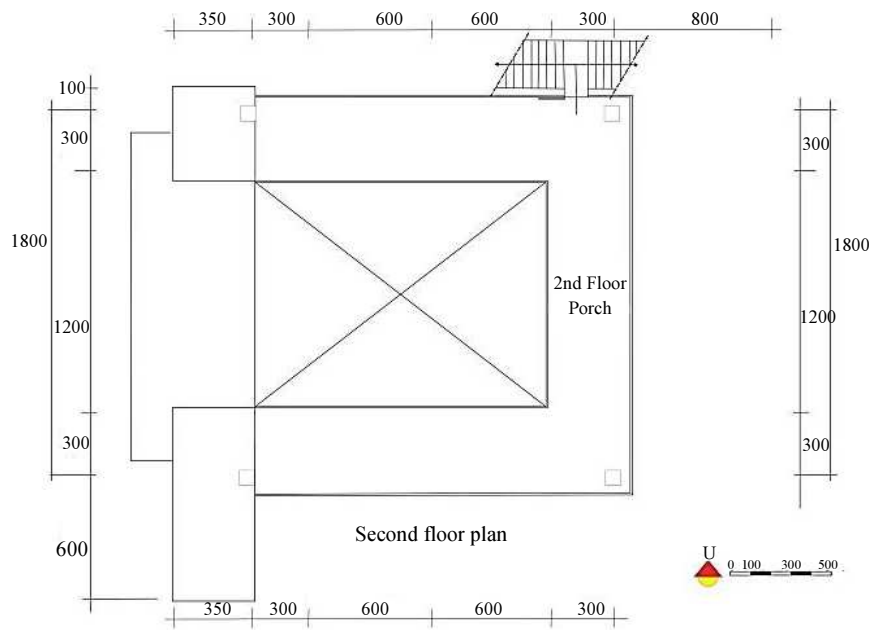




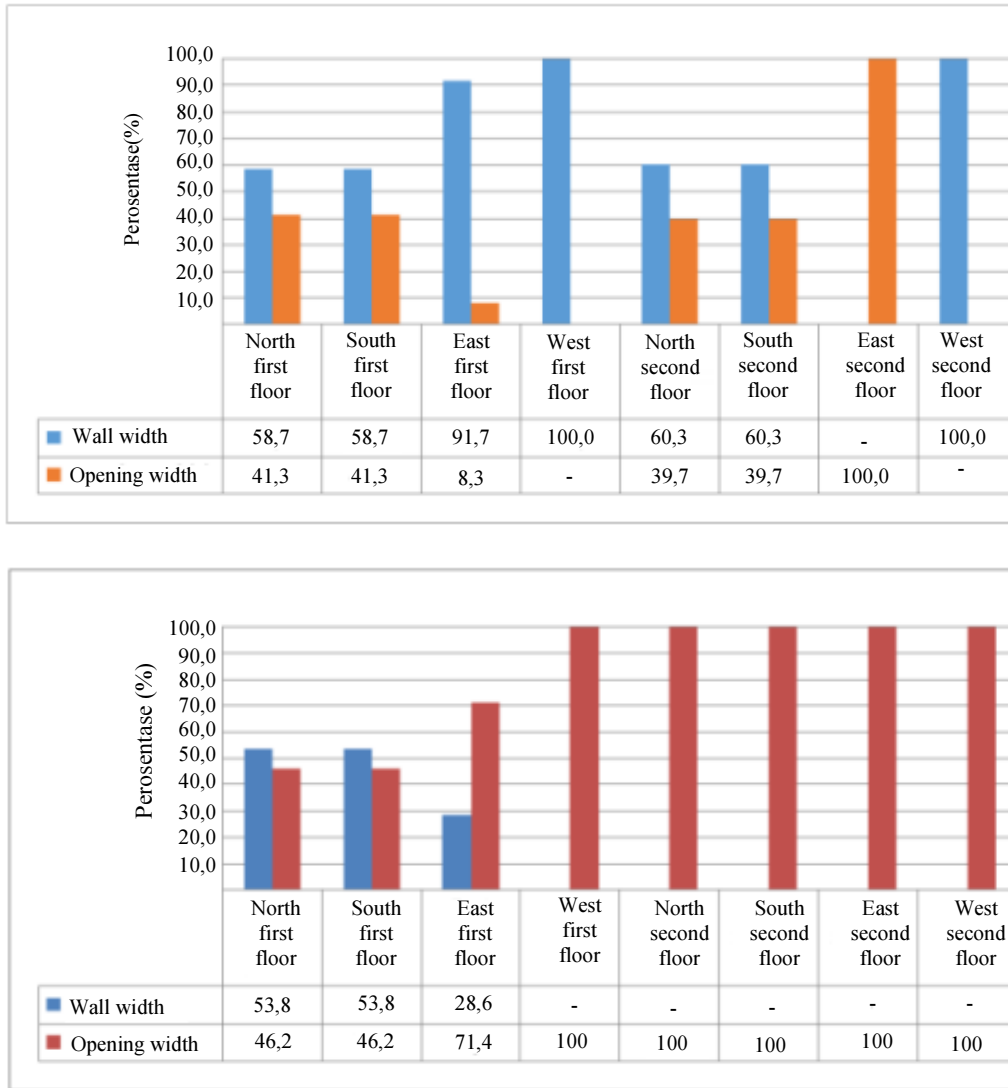


Fig. 7: 3D illustrations and photos of the Cabean mosque showing the locations of openings on the side of the building

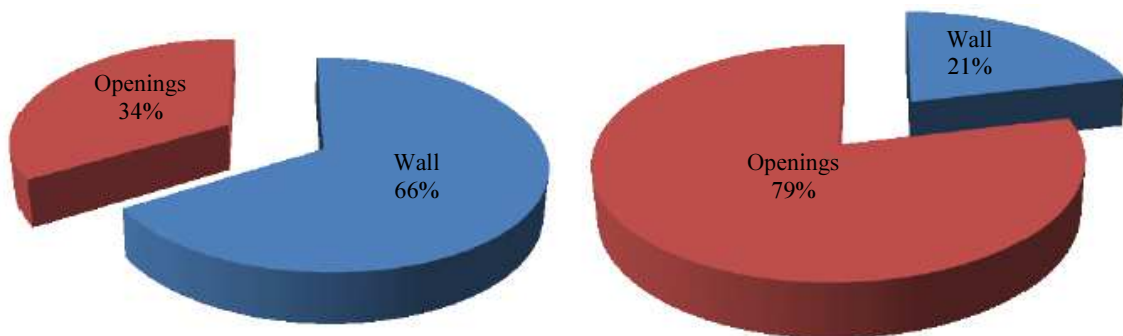




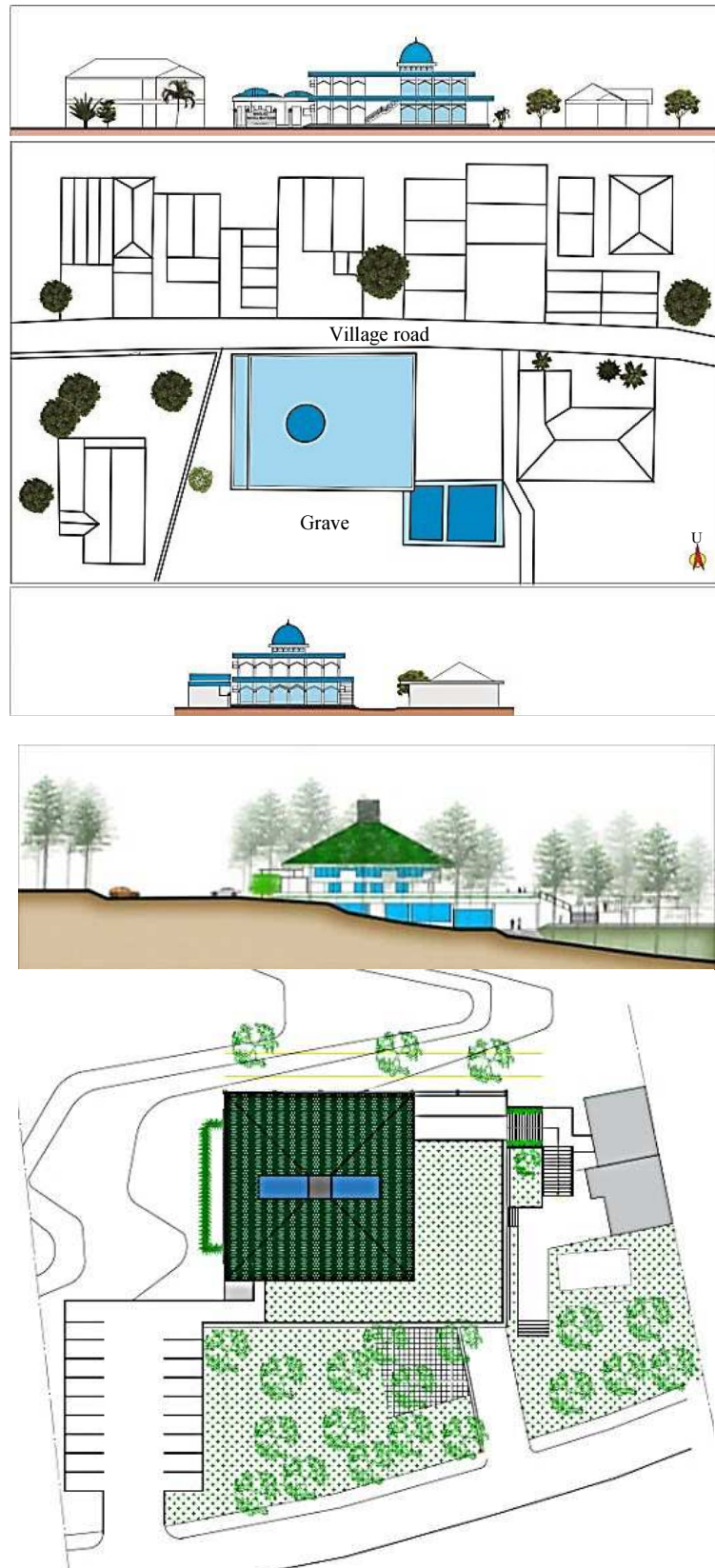
**Fig. 8:** 3D illustrations and photos of the Eco Pesantren mosque showing openings at the side of the building



**Fig. 9:** Ratios of wall width and opening width for each room in the Cabean mosque (left); the same ratios for the Eco Pesantren mosque (right)

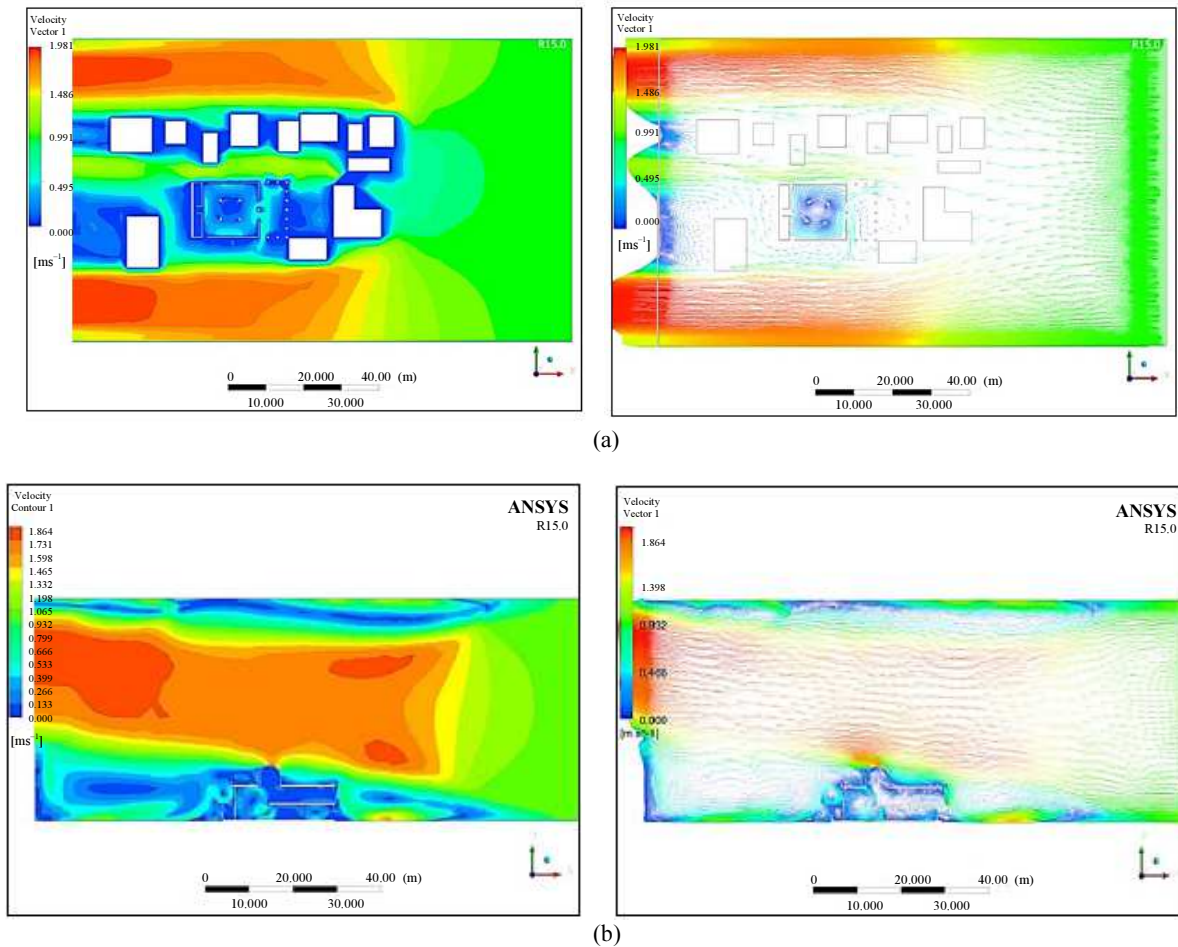


**Fig. 10:** Ratios of width area and overall openings in the Cabean mosque (left); the same ratios for the Eco Pesantren mosque (right)



**Fig. 11:** Site of the Cabean mosque (left); site of the Eco Pesantren mosque (right)





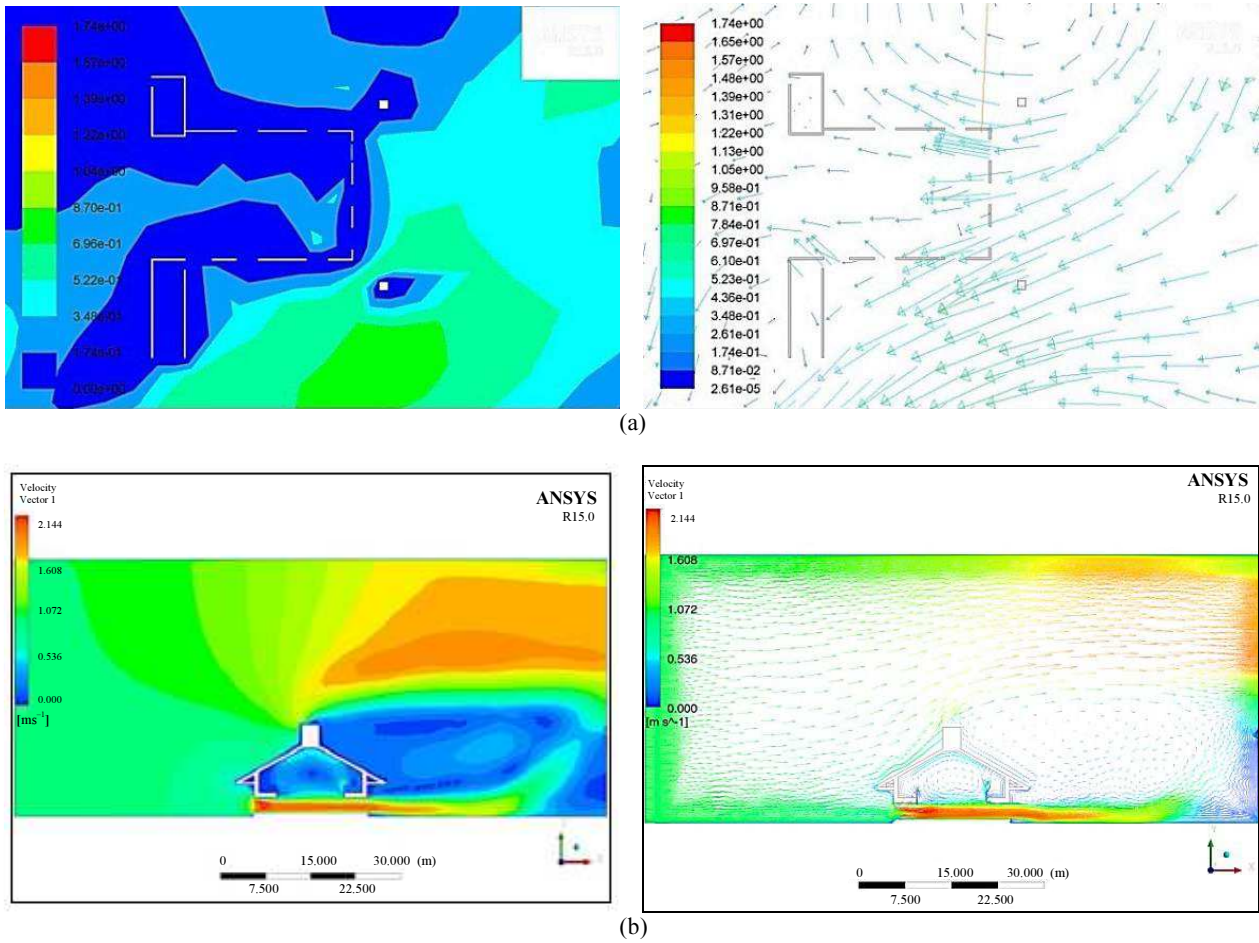
**Fig. 12:** (a) Airflow rate in the Cabean mosque and its surrounding area; (b) airflow rate of the Cabean mosque space in cross-section

Airflow around the mosques was simulated from east to west. Air in the Cabean mosque mostly flows through the aisles. Some airflow turns to the front porch of the mosque on its northern side. Changes in direction occur because the flow of air is blocked by houses east of the mosque. Airflow in the mosque’s porch can enter the main hall and partly flow to the south side. Airflow inside the mosque’s main chamber experiences turbulence. Air does not flow through the window openings on the north and south sides. Air temperatures in the courtyard are higher because airflow is blocked by the houses. The temperature around the column in the main hall of the mosque is higher because there is no airflow in the area (Fig. 12a). The simulation results showed the flow of air from outside into the main hall in Fig. 14b, on the 1st floor porch entering through the main hall door. Turbulence takes place on the west side wall of the mosque. Airflow occurs from the floor to the space below the dome, causing turbulence in the dome due to the absence of ventilation holes under the dome (Fig. 12b).

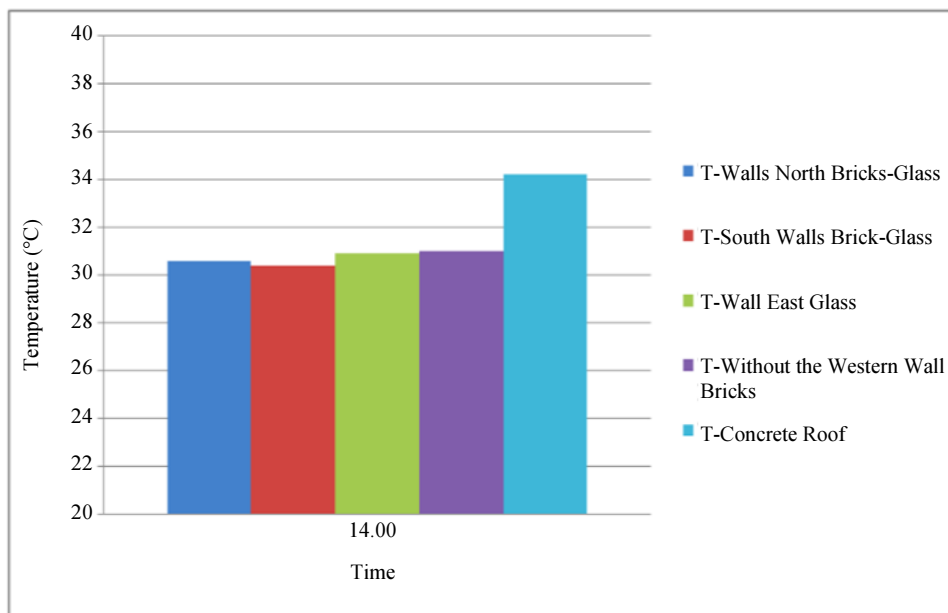
Airflow at the Eco Pesantren mosque was simulated from east to west, where the air enters through the porch, partly flows into the main hall and partly flows into the north and south sides of the mosque. Air flowing into the mosque’s main hall exits through windows on the north and south sides and openings on the western side. The movement of airflow from outside into the mosque is not blocked by other buildings because the mosque is located away from the settlement environment (Fig. 13a). In the simulation shown in Fig. 15b, air enters and exits through the mosque rooms through openings on the north and south sides of the building so that the 1st floor main hall feels cool. The only partial airflow rises through the 2nd floor voids (Fig. 13b).

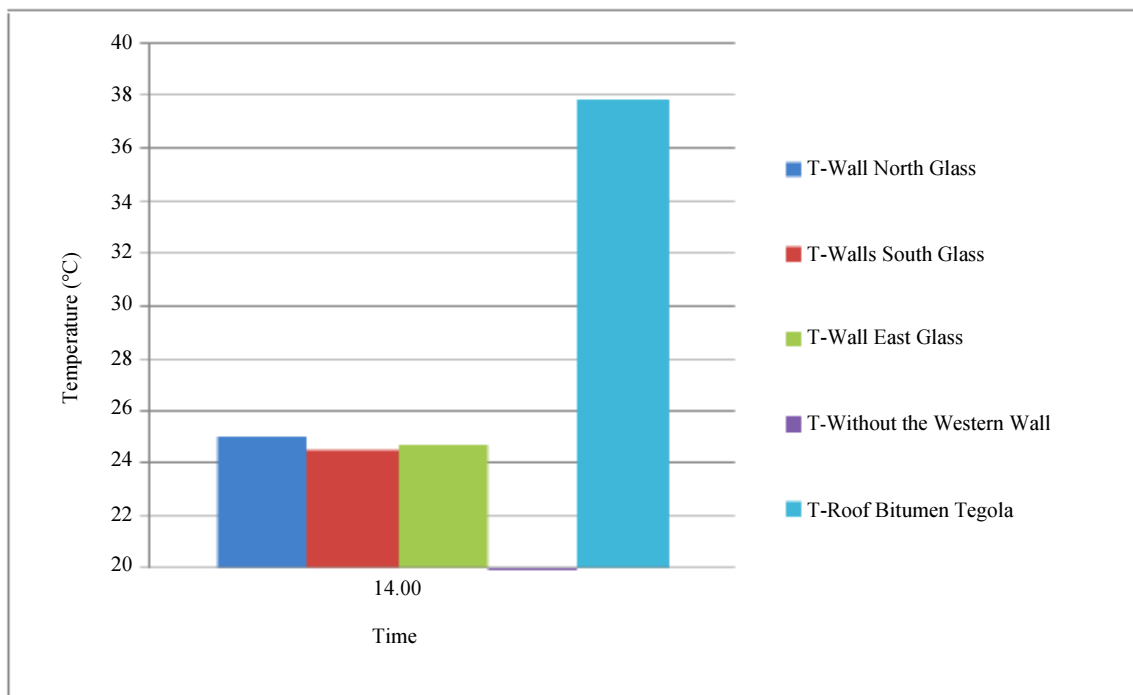
Roof surface temperatures were higher than wall temperatures in both mosques. This indicates that the mosques’ roofs are exposed to more sunlight than the walls. The Cabean mosque uses more brick, glass and concrete materials, which have greater thickness and density, than the Eco Pesantren mosque, which uses more wood and glass materials. The higher the density of the material, the greater the capacity to store heat.





**Fig. 13:** (a) Airflow rate of the Eco Pesantren mosque and the surrounding environment; (b) airflow rate of the Eco Pesantren mosque room in the longitudinal section





**Fig. 14:** Surface temperatures of the walls and roofs of the Cabean (above) and Eco Pesantren mosques (below)

The thicker the material, the more heat stored and the longer the heat transfer process. Heat stored during the day is released at night, so the room is potentially warm and not thermal (Fig. 14 above and 14 below).

## Discussion

The two mosques have differences in space quality, especially in terms of thermal comfort. Differences in space quality are revealed by the relative humidity analysis results, air temperatures and surface temperatures of the building envelopes. The Cabean mosque-which was built independently using mosque typologies from other regions that employ concrete domes-becomes more stuffy from noon to early afternoon. The mosque's design places ventilation on the north, east and south sides, while on the west side there are massive brick walls with no openings. Typologies from other places are not always appropriate for local sites. It is necessary, therefore, to adjust designs to existing site conditions. Apparently, designing buildings appropriately in consideration of the distance factor between buildings and ventilation openings is poorly understood by the community.

The Eco Pesantren mosque, meanwhile, was designed by an architect and is integrated with the surrounding environment. One innovation of this mosque is that it opens the west side and provides a barrier on the east side. East-west airflow has the potential to cause discomfort because the airflow is too tight, but this is not the case here because there is a bamboo plant barrier on the west side, which keeps the air from flowing directly to the mosque users. The

bamboo plants on the west side have the following functions: (1) filtering the afternoon sun so that the air temperature is cool; (2) blocking direct sunlight and avoiding glare, limiting the view of the outer space, providing privacy in worship and blocking unwanted views; and (3) forming a comfortable microclimate (Carpenter *et al.*, 1975; Febriarta *et al.*, 2012; Hakim, 2006; Sintia and Murhananto, 2004).

Air circulation in the Cabean mosque flows along the alley formed between buildings. Some of this airflow cannot be continued and so turbulence occurs in the yard of the mosque, creating a wind shadow area (Boutet, 1987; Melita *et al.*, 2017). Airflow enters the building through a mosque opening, which has an open area of less than 40% compared to the surface area of the wall. The open-area percentage does not reach 40%-80% of the wall surface area, causing less thermal comfort indoors (SNI DPU No. 1728-1989).

Airflow to the Eco Pesantren mosque is not obstructed by buildings and it enters the building through the mosque opening. The percentage of openings is 79% of the surface area of the walls-a percentage that provides thermal comfort in the mosque space. This type of opening design has a great influence in terms of the quantity or direction of airflow that enters the building (Damiati *et al.*, 2016; Melita *et al.*, 2017). The presence of voids on the 2nd floor of both mosques provides sufficient space for vertical air circulation (Hanan and Wonorahardjo, 2012). This air movement helps reduce air humidity so that spaces become more comfortable. The

area of the openings in a mosque greatly influences ventilation. Mosques with wide openings are better ventilated and more comfortable.

In general, mosques around the world, as in Saudi Arabia, Africa, Turkey, Iran and India, have domes and the western walls are closed (Michell, 1978; Frishman and Khan, 1994). Meanwhile, traditional mosques in Indonesia do not use domes. Today, however, many mosques in Indonesia are built using domes and towers like mosques in the Middle East and North India (Nas, 2009).

In a mosque, airflow enters from the east side on the 1st and 2nd floors through the main room and exits through openings on the north and south sides. Airflow also occurs through a void from the 1st floor to the 2nd floor. Meanwhile, airflow from the west turns along the north and south edges of the building. Airflow enters through the openings on the north and south sides and exits through the eastern side openings (Fig. 15).

In the Eco Pesantren mosque, the west side of the building is open, causing intense interaction with the natural environment. This design creates a large ventilation opening, so airflow is very smooth in and out of the building. Openings on the east and west sides guarantee that good ventilation and air exchange take place in the mosque. The openings on the north and south sides on the 2nd floor become the exit paths for airflow. The existence of a void in the mosque also facilitates airflow and ventilation (Fig. 16 left and right).

The concrete dome roof of a mosque acts as a thermal mass that absorbs and stores heat from sunlight. The heat is released at night, which indirectly warms the space (Wonorahardjo *et al.*, 2018). The more heat stored, the more energy released to the environment and for a longer time (Balaras, 1996). This is different from thin roofing materials, which tend to continue the heat received from sunlight.

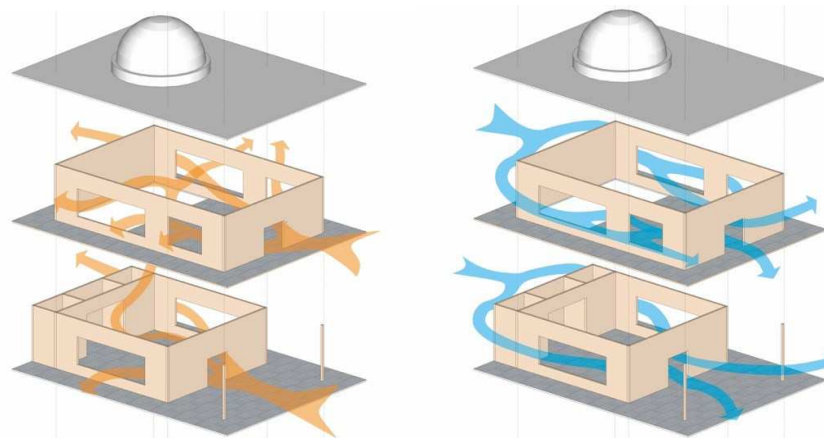


Fig. 15: Open fields and speed of airflow in the Cabean mosque: eastern airflow (left); western airflow (right)

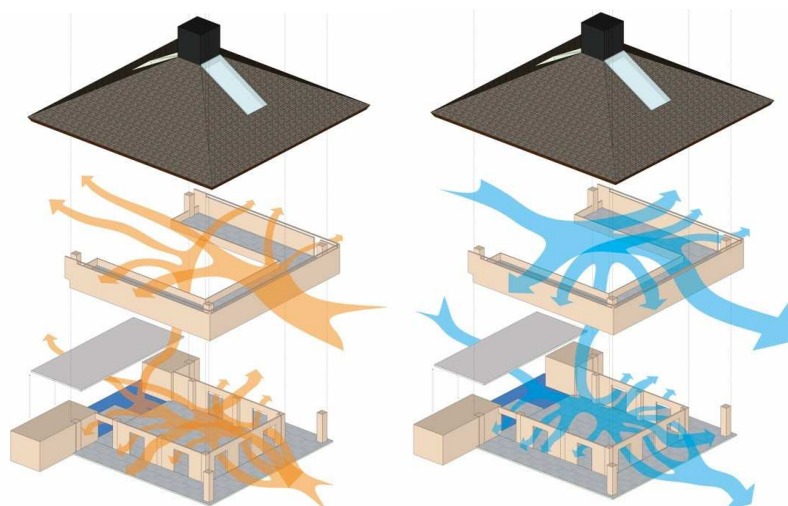
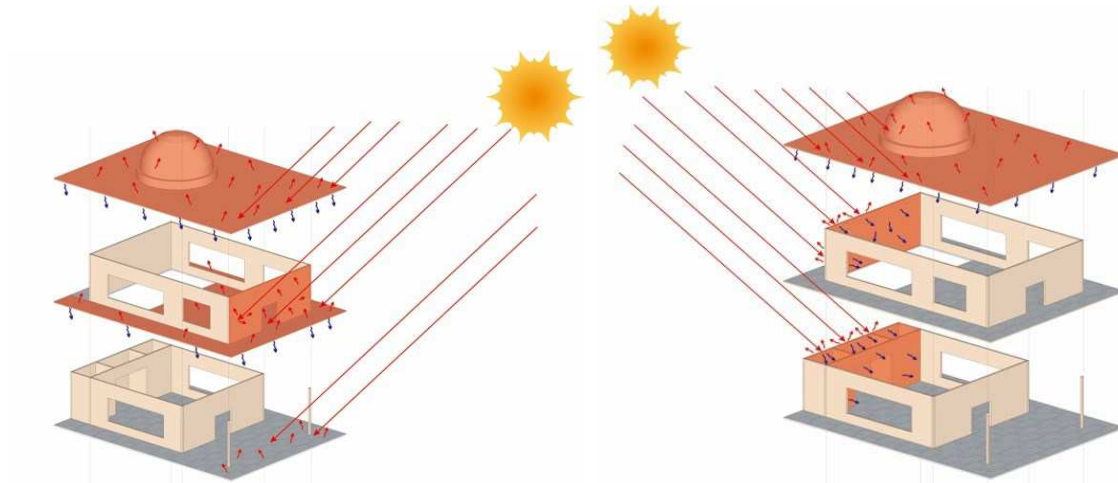
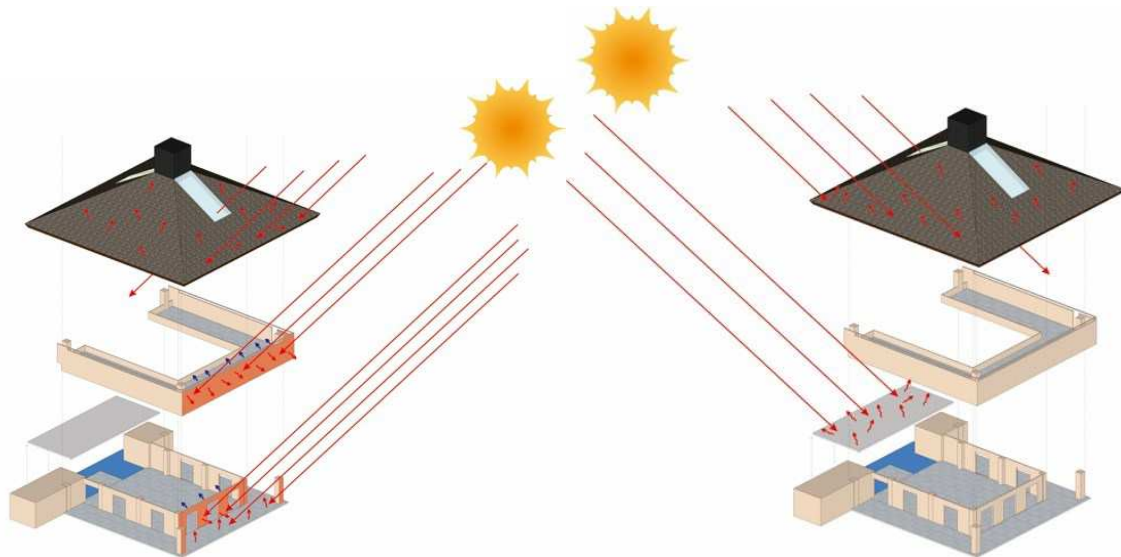


Fig. 16: Open fields and speed of airflow in the Eco Pesantren mosque: eastern airflow (left); western airflow (right)



**Fig. 17:** Heavyweight-lightweight materials of the Cabean mosque: in the morning (left) and in the afternoon (right)



**Fig. 18:** The heavyweight-lightweight materials of the Eco Pesantren mosque: in the morning (left) and in the afternoon (right)

In general, the roofs, walls and floors of domed mosques are made from heavy materials such as concrete and brick, so they act as a thermal mass when receiving sunlight in the morning and evening. The building components release the heat so that the air temperature on the 1st and 2nd floor spaces increases (Fig. 17 left and right). With lightweight roofing materials, however, there is no heat storage, so the air inside the mosque decreases as the temperature outside decreases (Fig. 18 left and right). This shows the low role of thermal mass in mosque design (Wonorahardjo, 2012). The thermal quality of mosque spaces in Indonesia is determined by material use factors and ventilation openings. A suitable thermal mass composition and ventilation system can provide a comfortable thermal quality in the mosque.

## Conclusion

In this study, a mosque built by the community using architectural styles adopted from other regions was found to be less integrated with the local environment and lacking in qualities suited to the environment. This differed from a mosque designed by an architect that was more integrated with its surrounding environment.

Adapting a mosque's design to its location can include providing greater between-building distances as well as wind-catching features that facilitate the flow of air into the main hall.

The design and use of roofing materials are also worth noting. Dome roofs generally use concrete, which has a large heat capacity and is better able to dampen solar radiation than sloping roofs made from lighter



materials. Sloping roofs generally indicate poor insulation, except in cases where adequate heat insulation materials are added.

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## Author's Contribution

**Mohammad Kusyanto and Imam Adlin Sinaga:** organization of ideas, data requisition and analysis, interpretation of the results and article write up.

**Sugeng Triyadi, Budi Faisal and Surjamanto Wonorahardjo:** Contributed to revision and final approval.

**Aldissain Jurizat:** Participated in the data-analysis.

## Ethics

All authors have provided assurance that this paper is original research and has not been published elsewhere and all the author has read and approved the manuscript.

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