Megaron, Vol. 19, No. 1, pp. 1–12, April 2024

Megaron
https://megaron.yildiz.edu.tr - https://megaronjournal.com
DOI: https://doi.org/10.14744/megaron.2024.46034

Article

The effect of window configuration on passive cooling in mosque interiors

Hatice Sena AZKUR[1,*], **Murat ORAL**[2]

[1]*Department of Architecture, Konya Technical University, Konya, Türkiye*
[2]*Department of Interior Architecture, Konya Technical University, Konya, Türkiye*

ARTICLE INFO

Article history
Received: 17 October 2023
Revised: 13 January 2024
Accepted: 08 January 2024

Key words:
ANSYS Fluent; building simulation; CFD; natural ventilation; passive cooling.

ABSTRACT

Cooling energy demand in buildings has more than doubled since 2000. Typically, the energy cost of a naturally ventilated building is 40% less than that of an air-conditioned building. Especially, a typical mosque's cooling energy needs are the biggest part that is consumed in the summertime. Mosque buildings are designed as buildings where the floor height is 5-6 times higher than the human scale. This height allows openings at various levels to be designed that can be used for natural ventilation. However, today, the windows that are at higher elevations in mosque buildings in Türkiye are designed as fixed windows with aesthetic concerns, and the potential for natural ventilation is ignored. Within the scope of the study, three different window configuration scenarios were modeled in ANSYS Fluent software, and the effect of natural ventilation on temperatures was tested. The first is the type in which openings close to the ground are designed, which represents the common design used in Türkiye; the second is ventilation with openings designed only at a higher level; and the third is ventilation with openings designed at two separate levels. In three different models, the inlet and outlet openings are the same size, but their places change. Velocity and temperature contour maps show that stack ventilation is quite efficient for mosque buildings. This study indicates that designing openings at higher elevations in mosque buildings creates significant differences in natural ventilation and lowers the air conditioning needs.

Cite this article as: Azkur, H. S., Oral, M. (2024). The effect of window configuration on passive cooling in mosque interiors. Megaron, 19(1), 1–12.

INTRODUCTION

Buildings and the building construction sector account for 30% of total worldwide final energy consumption and 27% of total energy sector emissions, according to the International Energy Agency's "Buildings" report (2022). Cooling energy demand in buildings has more than doubled since 2000, making it the fastest-growing end-use in buildings, driven by a combination of warmer temperatures and increased activity. It is crucial to make sure that cooling demands are fairly met as the world warms. One of the most important criteria for avoiding ineffective activities is efficiency standards. Efficiency standards, along with better building and district design,

*Corresponding author
*E-mail adres: senaazkur@gmail.com

This publication is a part of an ongoing doctoral dissertation of the first author under the supervision of the second author.

and passive, natural, and alternative solutions to air conditioners, which need to be prioritized where possible to mitigate the growth in demand for active technologies, are key measures to avoid the lock-in of inefficient air-conditioning units in the coming decades (International Energy Agency, 2022). Natural ventilation is now gaining popularity as an alternative to building air conditioning. The most economical and environmentally friendly method for ventilation of buildings is natural ventilation (Darçın, 2008). The energy cost of a naturally ventilated building is 40% less than that of an air-conditioned building (Allocca et al., 2003). Natural ventilation especially provides cooling when it is designed properly. Lowering the cooling loads is important as it is the most energy-consuming operation in summertime. Brager & De Dear (2000) measured and compared the thermal intervals of people in buildings with mechanical ventilation and natural ventilation. It has been determined that people are satisfied with a narrower temperature range in air-conditioned buildings, while satisfaction is provided in a wider range in naturally ventilated buildings. This can be seen as another advantage of natural ventilation.

Mosques are buildings that were born from the need of people to worship collectively in the religion of Islam. The use of these buildings is in the form of short-term uses at certain time intervals (five times a day), but when it is occupied, many people worship in the same space and the occupancy rate is 0.5 m^2/person. Compared to other building types, mosques have a higher occupancy rate, so it is important to provide the indoor environmental quality at the desired level in the sanctuary section. In almost all mosques in Türkiye, air conditioning is used for cooling in summertime, and it consumes a huge amount of energy. Budaiwi et al.'s (2013) study shows that 73% of the total energy consumed in mosques is for cooling in summer. In contrast to other building types, such as office, institutional, and residential buildings, little research has been conducted on the energy and thermal performance of mosque buildings.

Studies on natural ventilation in mosques are as follows: Imam (2003) suggested that sufficient flow rates can be achieved by testing with various thermodynamic equations that the minarets of mosques can be used as wind chimneys for the city of Dhaka, Bangladesh. It has been proposed that a technical function be assigned to the minarets, which today have only a visual function. Al-Homoud et al. (2009) conducted an energy consumption analysis on three existing mosques in Saudi Arabia. Cooling and air conditioning devices have had the largest share in energy consumption. For this reason, energy consumption has increased significantly, especially in the summer months. Asfour (2009) measured two types of mosques, classical Ottoman style and Arabic style, for thermal performance in Ecotect software. The results of the study revealed that the Ottoman-type mosque performed better in the summer months, but the Arabian-type mosque gave more successful results in the winter months. In the study by Maarof (2014), the effect of different roof designs on thermal comfort in Malaysian mosques with typical natural ventilation was evaluated. The hipped roof and the domed type were compared. The study was carried out on four existing mosques. As a result, while the dome type gave better results in mosques with 5000 people or more, the hipped roof type gave more positive results in mosques with a capacity of less than 5000 people. Al Sudany (2015) evaluated the minaret of a mosque in Baghdad as a windcatcher, adding a water spray system to the minarets, and both humidification and cooling effects were tested with computational fluid dynamics (CFD) simulation. The results revealed that this system is a sustainable and successful system for mosques. Mushtaha and Helmy (2017) examined the effects of the forms of mosque structures on thermal performance in a hot humid climate with simulation modeling via Ecotect software. Square, rectangular, and polygonal plans were evaluated. The results revealed that the building form with the least surface area gives the best temperature performance. Nordin & Misni (2017), in their study in Malaysia, selected a historical and a newly built existing mosque and examined their thermal performance. The study was carried out by measuring the airflow rate, temperatures, and humidity with the help of devices. While temperatures fluctuate throughout the day in the new mosque, a certain temperature increase was observed in the old mosque in the afternoon. Ray et al. (2017) evaluated natural ventilation design in the design process of a real mosque project with CFD analysis models. Nordin & Misni (2018) evaluated the thermal performance of three mosques in Malaysia by making device measurements. Alhasan & Yuning (2019), in their research on mosques in China, measured the thermal performance of mosque courtyards with CFD analysis and evaluated which courtyard types are more efficient according to directions. Atmaca & Gedik (2019) conducted a comparative study by examining the energy consumption and thermal comfort conditions of two mosques in a temperate humid climate. Othman et al. (2019) tested how the interior comfort of the building is affected by different opening types in a typical domed mosque in Malaysia in Flow Design software. It has been observed that the flow rate in the building increases when small inlet and outlet openings are used. On the other hand, it has been observed that the speed decreases slightly when small inlet and large outlet openings are designed. Consequently, it would be more appropriate to prefer large inlet openings in areas with high prevailing wind speed, and smaller inlet openings in areas with low wind speed. Rahim & Marassabessy (2019) examined in detail the natural ventilation features of an existing mosque in Indonesia. Sanusi et al. (2019) evaluated three mosques built during the British colonial period in

Malaysia in terms of environmental performance. Thermal performances were measured with the help of devices, and ventilation performances were obtained by simulation.

Yusoff and Jaafar (2019) selected a historical mosque in Malaysia and evaluated the thermal comfort conditions by measuring them with the help of devices. Mohammed et al. (2020) modeled an existing historical mosque structure in Egypt and tested it in a wind tunnel. Yüksel et al. (2021) made an indoor comfort assessment by measuring CO_2 and temperature values in an existing mosque. Azmi et al. (2021) collected the factors affecting energy efficiency in mosques in a review article. Diler et al. (2021) evaluated the thermal performance of a historical mosque in Manisa through measurements. In addition, simulations were carried out in the Design Builder program and evaluated together with real measurements. Raslı et al. (2021) studied the thermal performance of 21 mosques in Malaysia. It has been seen that the factors affecting thermal comfort the most are the window-to-wall ratios and the type of ventilation. Yüksel et al. (2021) compiled studies on thermal comfort, indoor air quality, and energy consumption in religious buildings.

The literature review shows that thermal comfort and natural ventilation research in mosque buildings were mostly carried out as experimental studies with the help of devices. Evaluation studies with simulation software are very few and have started to increase in recent years. Azmi & İbrahim (2020) stated that with CFD analysis, mosques can be examined more comprehensively, and accurate results can be achieved. In this context, it is important to investigate the effect of different window configurations on ventilation, which will be examined within the scope of this article, in terms of its contribution to the literature.

The sanctuary of the mosques is usually arranged as a single and large volume for collective worship. For this volume to provide a three-dimensional space effect, the ceiling height is determined by its scale. For this reason, mosque buildings are designed as structures where the floor height is 5-6 times higher than the human scale. This height allows openings at various levels to be designed in the shell of the mosque that can be used for natural ventilation. However, today, the windows on these surfaces in mosque structures in Türkiye are not designed as operable windows; they are designed with aesthetic concerns, and the potential for natural ventilation is ignored.

Examining the effect of windows designed at different heights on natural ventilation will encourage designers to evaluate the potential for the evacuation of hot and polluted air by utilizing the interior height of the building. Within the scope of the study, three different window configuration scenarios were modeled in ANSYS Fluent software, and the effect of natural ventilation on temperatures was tested. The data obtained as a result of the study is important in terms of presenting data that can be used by architects in the early design stage of mosque design. As stated in the literature, the thermal comfort performance of mosques is an area that has been started to be investigated in recent years, and further studies will contribute to the literature.

MATERIALS AND METHODS

Natural Ventilation and Passive Cooling of Building Interiors

Natural ventilation is the use of the natural driving forces of wind or temperature difference to achieve ventilation for buildings (Ji et al., 2009). Air flows from a high-pressure point to a low-pressure point. In order to ensure air movement in an interior space, a pressure difference must be created between the point where the air enters the space and the point where it leaves the space. The higher the pressure difference, the more air will flow inside. Airflow within the space is important for the user to sense air movement and to remove air pollutants from the space. The air which is used becomes dirty and hot. As it heats up, it expands, becomes lighter, and thus rises. The rising hot air is replaced by cold and clean air which comes from inlets. Accordingly, in an interior, clean and cold air is located near the floor, and dirty and hot air is located near the ceiling. Precise and slow modification of air movement maintains the orderliness of the airflow, while sudden changes create turbulent currents where airflows swirl and split into unpredictable directions. If the speed of an air stream increases relative to the speed of the adjacent air stream, the pressure of this air stream decreases. Airplane wings take off with this principle. This is called the Bernoulli effect. When a stratified airflow is compressed to pass through an opening, its speed increases, and its pressure decreases. This situation is called the Venturi effect (Darçın, 2008).

Passive cooling is the use of natural wind for ventilation to disperse heat through convection and increase occupants' perception of thermal comfort through evaporation. Cooling occurs in the building by evacuating the hot air from the building with the natural movement of the prevailing wind within the building. The main purpose of passive cooling is to reduce the fossil fuel required to cool the space using a mechanical system (Jaffe et al. 2020).

Wind entering from the surface of a building creates positive pressure on the surface it encounters and negative pressure on the other surfaces. Therefore, air will want to enter through the openings on the surface with positive pressure and go out through the openings on the surface with negative pressure. Temperature differences between the indoor and outdoor environments lead to changes in air density, which causes pressure differences. When the indoor air temperature is higher than the outdoor environment, the indoor air goes out from the highest elevation of the building, and the cooler outdoor air enters from the lower elevations of the building. Thus, passive cooling occurs. Buildings are naturally ventilated to cool the space with three basic principles: single-sided ventilation, cross-ventilation, and stack ventilation.

Single-Sided Ventilation

Single-sided ventilation occurs in cases where the building is in contact with the external environment through a single surface. For the single-sided or single-opening ventilation method to be successful, the room depth should not exceed 2.5 times the interior height (Küçüker, 2019; Yavaş, 2019).

Cross Ventilation

The cross-ventilation system occurs by creating two different pressure zones on two sides of the building. Airflow moves from the high-pressure area to the low-pressure area, meaning air currents around a building create high-pressure areas on the front where the wind comes from and low-pressure areas on the other side. The most effective cross ventilation occurs when windows (inlets and outlets) are located in the high-pressure and low-pressure zones of the building (Habibzadeh, 2018). Cross ventilation occurs efficiently when the depth of the space is at most five times the interior height.

Stack Ventilation

The stack effect uses a combination of convection techniques: Bernoulli's principle and the Venturi effect to ventilate a building. Air moves as a result of air pressure differences, which vary due to temperature and moisture differences throughout the building. Warm air rises through the building to escape through a window at higher elevations or a roof vent (Jaffe et al., 2020). Natural ventilation has been shown to affect substantial reductions in cooling energy by over 40-50% in some metropolises in Europe and the USA (Li & Chen, 2021). Passive cooling and natural ventilation reduce the need for fossil fuel energy-based mechanical HVAC (heating, ventilation, and air conditioning) systems to provide cooling and air circulation. Therefore, carbon emissions decrease, and building operational costs are reduced, which supports the fight against global warming.

The most efficient ventilation and passive cooling strategies are:

- Designing buildings with more openings for natural ventilation,
- Designing openings on opposite sides to have cross ventilation,
- Carefully designing the window-to-wall ratio (WWR) to avoid overheating,
- Using shading strategies,
- Well-designed thermal insulation to reduce heat transfer (Jaffe et al., 2020).

Basically, there are three approaches to studying natural ventilation: empirical models, experimental measurements, and computational fluid dynamics (CFD) simulations. Each of these approaches has its advantages and limitations. Empirical models are often developed from analytical solutions and experimental data. While they are useful for natural ventilation design, they may not provide sufficiently detailed or accurate information about natural ventilation. Experimental measurements are effective in obtaining realistic information about natural ventilation. However, they can be expensive, time-consuming, and may not always provide the level of detail needed to fully understand the natural ventilation mechanism. CFD simulations are gaining popularity due to their ability to provide informative results, lower labor costs, and reduced equipment requirements. CFD simulations can offer detailed insights into natural ventilation processes (Jiang, et al., 2004).

Computational Fluid Dynamics and Architecture

CFD involves expressing partial differential equations with discretized algebraic equations that approximately represent these equations. These equations are then solved numerically to find the flow field at the discretization points created in a certain space and time. Since the Navier-Stokes equations are valid for the flow field at every point in the space occupied by the fluid, an analytical solution of these equations gives the solution for the flow at an infinite number of points. However, analytical solutions are available for a limited number of simplified flows and geometries. To overcome this limitation, the equations representing the flow can be discretized and expressed in an algebraic form that can be solved on a computer. CFD simulations find relevant flow variables only for discretization points. Values at points that do not correspond to discretization points are obtained by interpolation methods (Young et al., 2018).

Computational fluid dynamics (CFD) can be thought of as a numerical experiment. CFD calculates the properties of airstream such as direction, velocity, pressure, and temperature by using partial differential equations. In a typical fluid experiment, an experimental model is created, measurements are taken from the places where the model and the fluid interact, and the results are analyzed. In CFD, model building is replaced by the formulation of equations representing the flow and the development of the numerical algorithm. The process of making measurements is replaced by simulating the flow by creating an algorithm on the computer. One of the most important advantages of using CFD modeling is the time and cost savings it provides in design. In the past, designs required manufacturing and testing many prototypes, but with CFD, flow problems can be revealed without manufacturing the prototype. Another advantage is that complex flows can be demonstrated visually with CFD (Young et al., 2018).

CFD has been extensively used in the aerospace and automotive sectors since the 1970s. Therefore, it has potential for architectural design. Structural load testing, lateral winds, wind uplift forces, and natural ventilation design are just a few of the potentials to use CFD in building design. Airflow has a direct effect on designing a building form, opening, and different spaces.

CFD was introduced to the architectural field in the 1990s, and the number of studies using CFD has been increasing since 1997 (Zhai, 2006). The increase in numbers related to CFD in research shows that architects are realizing the potential of CFD. It also appears that CFD can be used not only to evaluate a finished project but also in the architectural decision-making phase. Figure 1 shows the studies that are CFD-related in the architectural field (Jo et al., 2018).

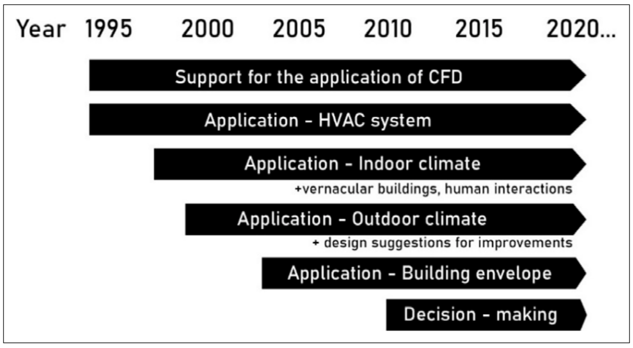

Figure 1. CFD-related research in the architectural field in years (Jo et al. 2018).

Method

The study focused on the cooling effect of natural ventilation in mosques during the summer months. The methodology in Figure 2 was applied to evaluate natural ventilation potentials suitable for mosque buildings and to create design criteria for architects by finding the right window configuration.

The primary aim of the study is to evaluate the natural ventilation potentials of mosques and to create a design criterion for architects by finding the most suitable window configuration for wind-driven natural ventilation. Initially, a prototype mosque was designed based on current practices and regulations in Türkiye and the international literature. Wall, floor, and roof details of the building were drawn, and the U-values of these surfaces were calculated according to TS825. The U-value is the amount of heat passing per unit of time through 1 m^2 of a building element consisting of different material layers. Thermal insulation applications aim to reduce the U-value as much as possible. The smaller the U-value, the less heat loss the building has. Five-year climate data (wind and temperature) for July, which represents the hottest time of the year in Konya province, were obtained. The model loaded into the CFD software was shaped in line with these data, and analyses were

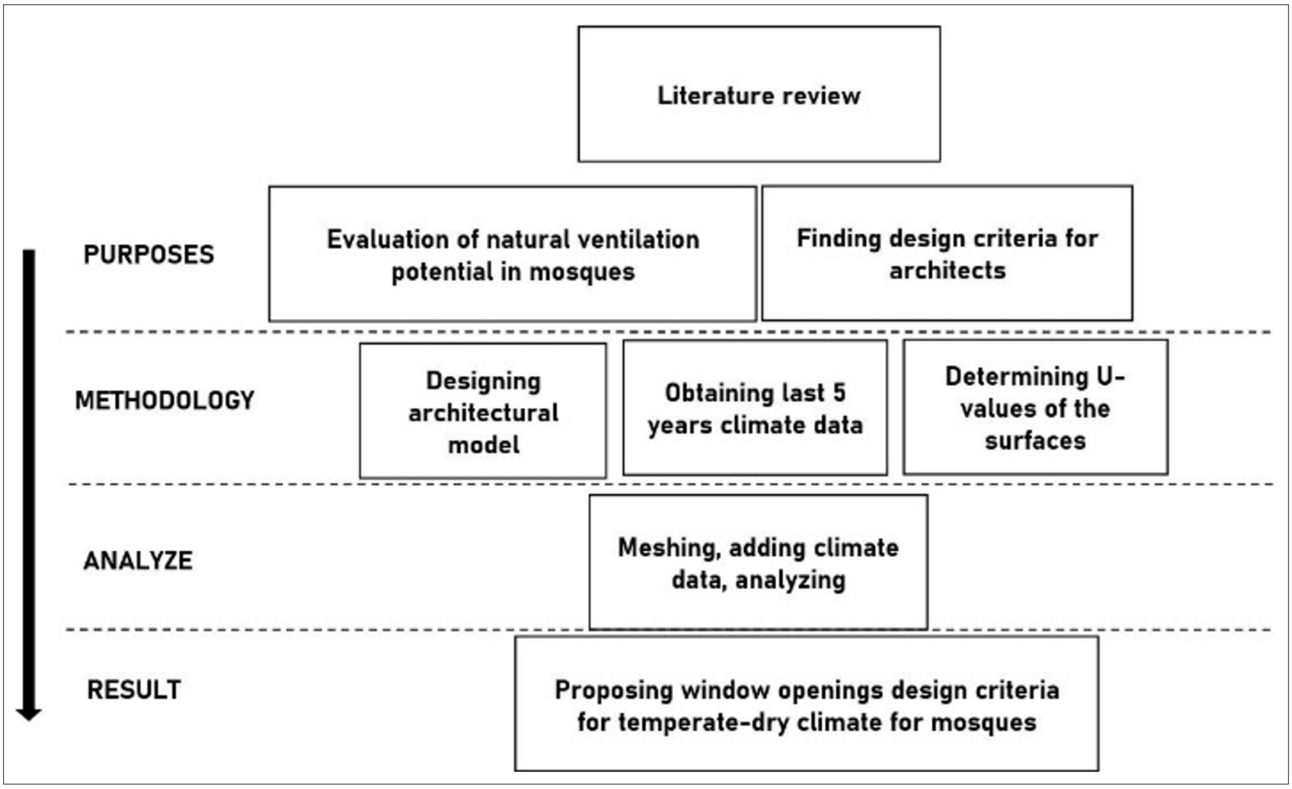

Figure 2. Methodology of the study.

carried out. Finally, the analysis outputs were interpreted comparatively, and a design criterion that architects could use at the design stage was proposed.

Within the scope of the study, a prototype mosque was designed to be analyzed in the climatic conditions of Konya, which represents a temperate dry climate in Türkiye. The size of the mosque was determined after a meeting with the Turkish Presidency of Religious Affairs. The Presidency of Religious Affairs stated that the most commonly used type is mosques with a capacity of 500 people. A mosque with a central square plan, the most used plan type in Türkiye, and a capacity of 500 people, was designed for the study. According to the "Mosque Planning and Design Guide" of the Presidency of Religious Affairs, when designing mosques, it is necessary to allocate 0.5 m² of space for each person. Therefore, a 250 m² prayer area was designed for the prototype building that can accommodate 500 people.

Windows are considered weak points in the structure because they offer less resistance to heat transfer than opaque parts of the structure. Therefore, by reducing the window-to-wall ratio (WWR), unwanted overheating can be minimized. However, reducing the window ratio also risks increasing the energy consumed by artificial lighting as the daylight received into the building will decrease. Thus, using the optimum WWR is crucial for reducing energy consumption (El-deeb, 2013). For this study, the WWR was set at 35% for the north, east, and west directions based on the value determined for a temperate dry climate from Goia's (2016) study. The southeast direction in Türkiye is the qibla direction for mosques. During worship, prayers are performed facing this direction (qibla), and since there should not be any distracting elements in this direction, there are generally no windows. In the prototype mosque, no openings were arranged in this direction either. The mosque's building height was designed using the ratios determined by the General Directorate of Foundations of Türkiye, compiled in the study by Gürsoy (2018).

Since natural ventilation and cooling in mosques are being examined, the analysis was carried out for the hottest month of the year. The temperature and wind data for five years (2018-2022) of July, which is the hottest month of the year for Konya, Türkiye, were obtained from the General Directorate of Meteorology. The average daytime temperature for these five years in July is 25.7 °C, and the average wind speed is 3.8 m/s with the prevailing wind direction being northwest. This means the prevailing wind will enter from the mosque's entrance façade, which is on the northwest side that air inlets are three doors and three windows on the entrance façade. Air outlets are designed as windows on other facades, except the qibla façade. Mosque thermal insulation details were drawn to obtain each surface's U-values. The U-values are determined as 0.275 W/m²K for walls, 0.255 W/m²K for ceilings, 0.363 W/m²K for floors, and 1.80 W/m²K for windows (12-4-12 mm double-glazed low-E coating). These values comply with the ranges specified for Konya in TS825:2013 (Turkish Standards Institution, 2013), which is the standard in Türkiye that indicates thermal insulation requirements.

Mosques are buildings that are used intermittently at five different times during the day. During these times, the usage duration is between 15 minutes and half an hour on average. Intermittent use is a characteristic feature that distinguishes mosque buildings from other building types and creates the potential for effective natural ventilation. During the summer months, windows can be kept fully open except during prayer times. In this way, the prevailing wind can be harnessed and effective cooling achieved inside the mosque. During prayers, the openings that let the prevailing wind in will be closed to prevent unwanted rapid airflow inside, and only the windows on the upper level will be kept open, which will allow for the evacuation of the heated air. However, the common practice in Türkiye is to provide ventilation with windows arranged close to the floor level. Since this type of ventilation is not supported by the stack effect, it is insufficient in the worship area and results in the use of intensive air conditioning. Traditionally, windows are not designed at upper elevations of the walls, which average 10-15 meters in height, because it was believed that occupant access was needed to open and close the windows. However, with the advent of automation technology, these windows can now be controlled remotely, which may significantly reduce the need for air conditioning in mosques by utilizing the high ceiling height to enhance the stack effect.

Based on this hypothesis, three different types of ventilation scenarios were prepared (Figure 3). The first scenario features openings close to the ground, representing the common practice of ventilation used in Türkiye; the second involves ventilation with openings designed only at the upper level; and the third includes ventilation with openings designed at two separate levels. In the three different models, the inlet and outlet openings are the same size, but their locations vary. As mentioned previously, the air inlet is at the prevailing wind's direction, which is

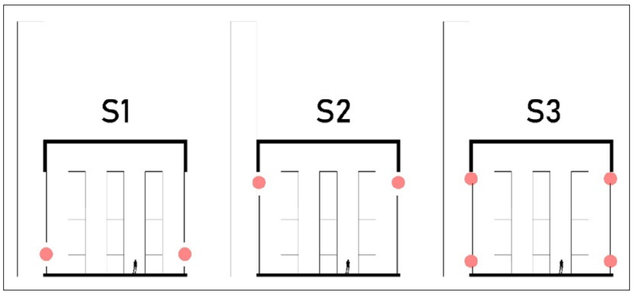

Figure 3. Three ventilation scenarios prepared with different window configurations.

the mosque's entrance façade. Air outlets are the windows designed on the northeast and southwest façades, which are three large windows that allow natural light inside. The evaluation considered how ventilation was affected when the openings' positions changed, including airflow velocities and interior temperatures.

All analysis processes were carried out in ANSYS 2022. Flow and structure geometries were drawn, edited, and made suitable for meshing with the SpaceClaim module. Its geometry and mesh structure were created in the ANSYS mesh module. The total number of elements of the model transferred to the solution is approximately 2.5 million. Models were created from quadrilateral cells only. The mesh structure of the model was created so that all edges, surfaces, and volumes had a minimum element size of 0.2 m. Conservation, energy equations, initial, boundary conditions, and loadings are determined in the Fluent module. The "Shear-stress transport (SST) k-ω model" was used as the turbulence model as it gives better results and convergence in viscous regions. The "Solar ray tracing" model was used for solar radiation, which helps to see both the effects of direct solar illumination and diffuse solar radiation in the model.

The coordinates of Konya province were entered into the solar ray tracing model, and the direction and intensity of solar rays were determined for the specified date and time. The time determined for this study is July, which is determined as the hottest month of the year, obtained from the General Directorate of Meteorology. The time has been determined as 14:00. This time was chosen to represent the afternoon hours when mosques are used intensively. Additionally, it aims to see the effect on the mihrab façade, which is heated by the afternoon sun, in the analysis.

RESULTS

Flow velocities and indoor temperatures are measured with the help of the software. Velocity contour maps and temperature contour maps were obtained. The color range of maps was arranged to represent the same temperatures with the same colors and the same velocities with the same colors to compare the scenarios accurately. Temperatures and air speeds are taken at an altitude of 1.10 meters since the measurement height is determined as 1.10 m in the ASHRAE-55 standard (Al-Homoud et al., 2009; ASHRAE, 2004; Çalış et al., 2017).

Flow Velocities

Scenario 1 (S1)
Scenario 1 represents the common design in mosques in Türkiye. At the southwest and northeast façade, six window openings were designed in total (three windows for each façade). The air enters from the windows and doors of the entrance façade and exits through these six windows. To make an accurate evaluation, the total size of the openings was kept the same in all scenarios. Only the positions of the windows change to understand how it affects air circulation and lowers interior temperatures.

S1's flow velocity diagram shows that air enters at approximately 5 m/sec speed (Figure 4). The airflow that comes from the middle door reaches the Mihrab area and bends towards the ceiling, creating circulation inside the mosque and flows out from the windows at +0.90 cm elevation. The airflow from the other doors decelerates faster compared to the airflow from the middle door. This scenario forms cross ventilation.

Scenario 2 (S2)
Scenario 2 has windows close to the ceiling to provide stack ventilation. The windows from S1 were simply moved to a higher elevation to assess the difference. S2's flow velocity diagram shows that the airflow on the southwest side of the interior is faster than the other two main air streams (Figure 5). Since the southwestern façade heats up more than the northeastern façade and there are no openings at ground level in this scenario, the airflow accelerates and increases due to the low pressure formed in this area.

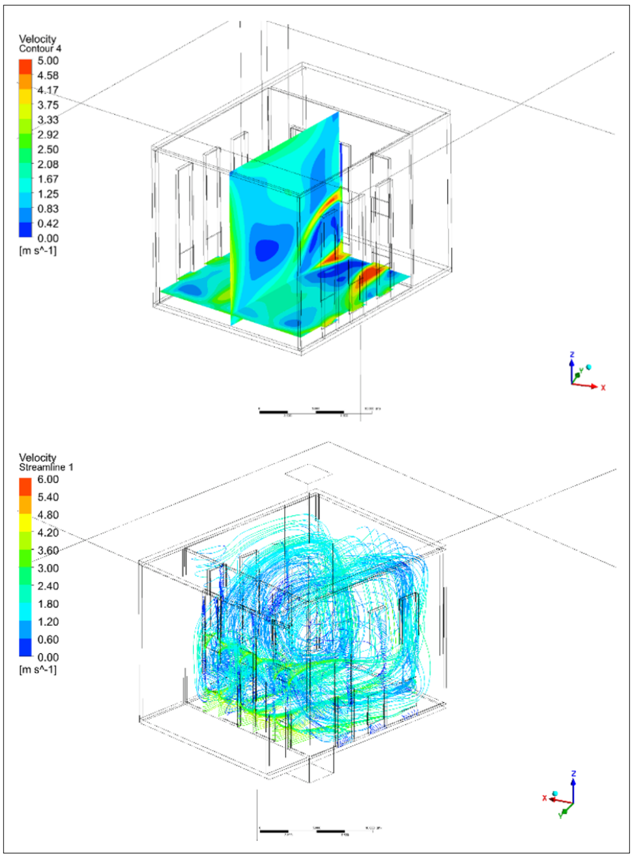

Figure 4. S1 flow velocity diagram and velocity streamline.

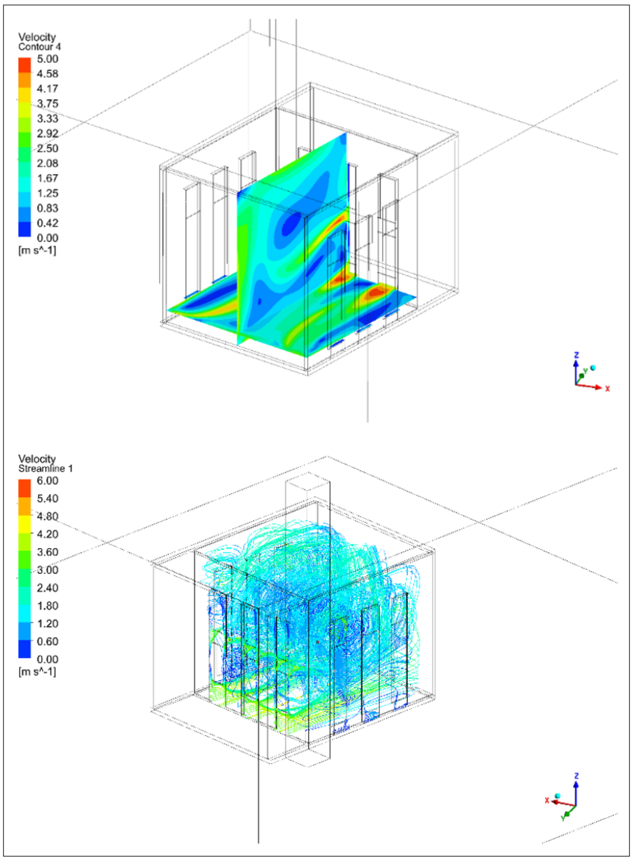

Figure 5. S2 flow velocity diagram and velocity streamline.

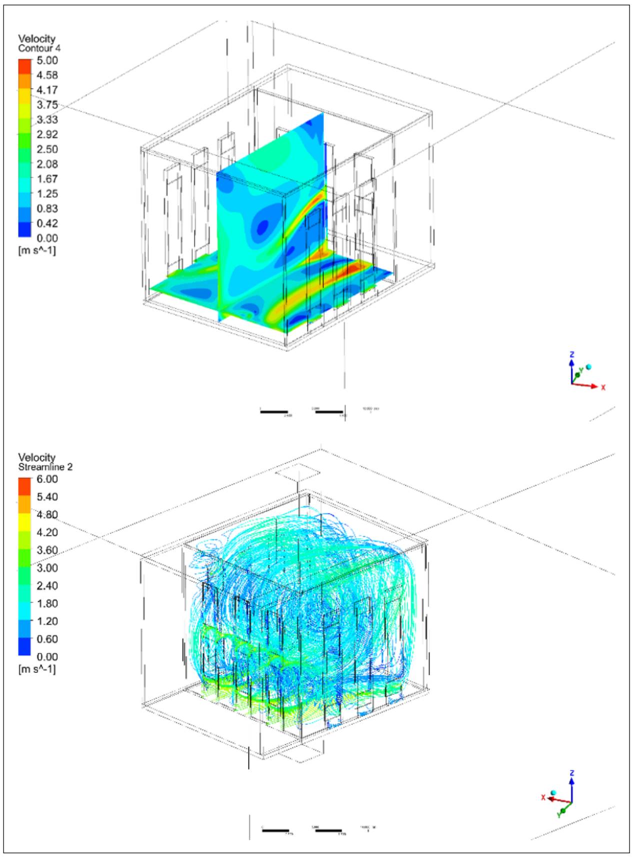

Figure 6. S3 flow velocity diagram and velocity streamline.

Scenario 3 (S3)

Scenario 3 has more openings compared to S1 and S2, but the sizes of the openings are smaller. It is important to note that the total size of the openings remains unchanged. In this design, each opening of a single window is split into two, with one at ground level and one at a higher elevation, effectively forming both stack and cross ventilation (Figure 6). S3's airflow velocities are higher than those in S1 and S2, as the two main air streams that enter from the middle door and the door near the northeast façade reach the mihrab wall at higher speeds, indicating more effective ventilation.

Scenario 1 (S1)

The analysis results indicate that the minimum interior temperatures start at 25.7 °C, which was established as the average outdoor temperature for July during the daytime, as obtained from the General Directorate of Meteorology. The solar model heats the building to higher temperatures, while the prevailing wind enters at 3.8 m/s, the average wind speed for July, which helps to cool down the temperatures. Figure 7 illustrates the building's exterior surface temperatures, which are significantly high.

Figure 8 displays S1's temperature contour diagram. The temperature map indicates that the entrance area of the mosque is cooler than other parts due to the faster airspeed. The air temperature increases towards the Mihrab wall. The diagram reveals that 37.09% of the space registers temperatures between 27.80-28.33 °C, which constitutes the largest percentage, while 29.25% of the space falls within 28.33-28.85 °C. Additionally, 17.05% of the space is within 27.27-27.80 °C, and 11.49% is within 26.75-27.27 °C. The remaining parts comprise less than 10% of the space.

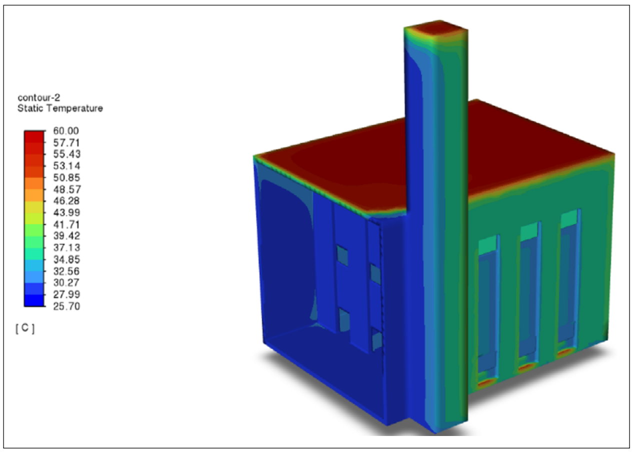

Figure 7. Exterior temperatures.

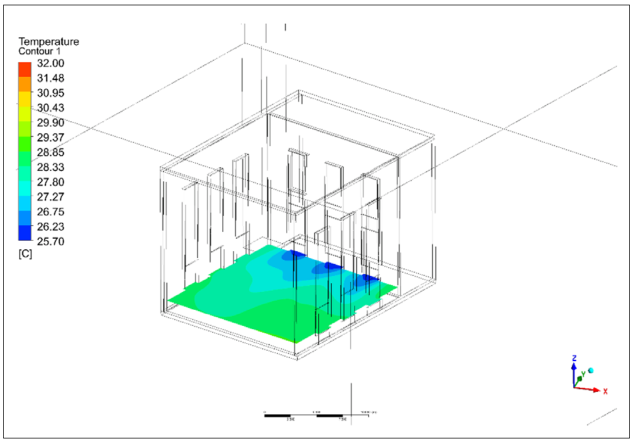

Figure 8. S1 temperature contour diagram.

Scenario 2 (S2)

Figure 9 presents S2's temperature contour diagram. The temperature map reveals that the southwest façade heats up more, indicating that measures must be taken at this façade to prevent overheating and to help achieve a more uniform temperature distribution throughout the building. According to the diagram, 42.93% of the space falls within the range of 27.27-27.80 °C, which constitutes the largest percentage. Furthermore, 25.96% of the space is between 26.75-27.27 °C, and 17.36% is between 27.80-28.33 °C. The remaining parts comprise less than 10% of the space.

Scenario 3 (S3)

The S3 temperature contour diagram is depicted in Figure 10. The interior temperatures are similar to those in S2, but the temperature map for S3 is more uniform. The ground floor level window openings, absent in S2, have helped to prevent overheating at the southwest façade by facilitating airflow. According to the diagram, 37.97% of the space falls within the range of 27.27-27.80 °C, which constitutes the largest percentage. Additionally, 31.99% of the space is between 27.80-28.33 °C, and 20.83% is between 26.75-27.27 °C. The remaining areas comprise less than 10% of the space.

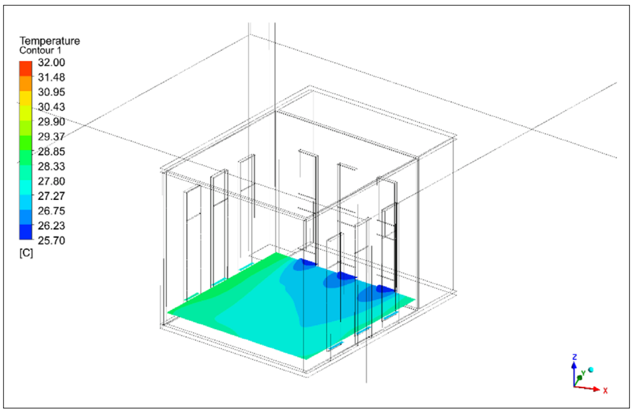

Figure 9. S2 temperature contour diagram.

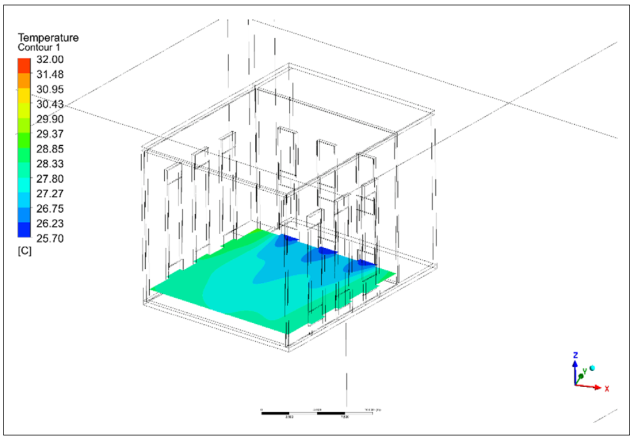

Figure 10. S3 temperature contour diagram.

Comparing the window configurations, temperature contour maps and velocity contour maps demonstrate that the S2 and S3 scenarios provide better ventilation and lower temperatures than the S1 scenario (Figure 11). This highlights the significance of stack ventilation for mosque buildings. The S1 scenario, which relies solely on a cross-ventilation strategy at ground floor level, is insufficient for achieving efficient air circulation to reduce temperatures effectively. The temperature maps for S3 are more uniform than those for S2, yet the temperatures are comparable. Air velocities in the S3 scenario are higher; the three main air streams reach the Mihrab wall more quickly than in the other scenarios.

Figure 12 presents a comparative view of the percentage of space within each temperature range for all three scenarios. As can be seen, S2 and S3 have similar temperature distributions, but S1 exhibits higher temperatures. When comparing the temperature ranges where most of the space in the different scenarios falls, 86.25% of the space in the S2 scenario and 90.79% of the space in the S3 scenario are within the range of 26.75-28.33 °C. In contrast, 83.39% of the space in the S1 scenario falls within the range of 27.27-28.85 °C.

CONCLUSION

Within the scope of this study, three different window configurations on a mosque prototype were examined. The first configuration (S1) featured ground-level openings, reflecting the common practice in Türkiye. In the second configuration (S2), openings were positioned near the roof to test the stack effect. The third configuration (S3) investigated the impact of windows at both ground and upper levels on passive cooling. Temperature comparisons show that S2 and S3, which utilize the stack effect, maintain lower temperatures than the S1 configuration. Specifically, 86.25% of the space in S2 and 90.79% of the space in S3 fall within the temperature range of 26.75-28.33 °C, while 83.39% of the area

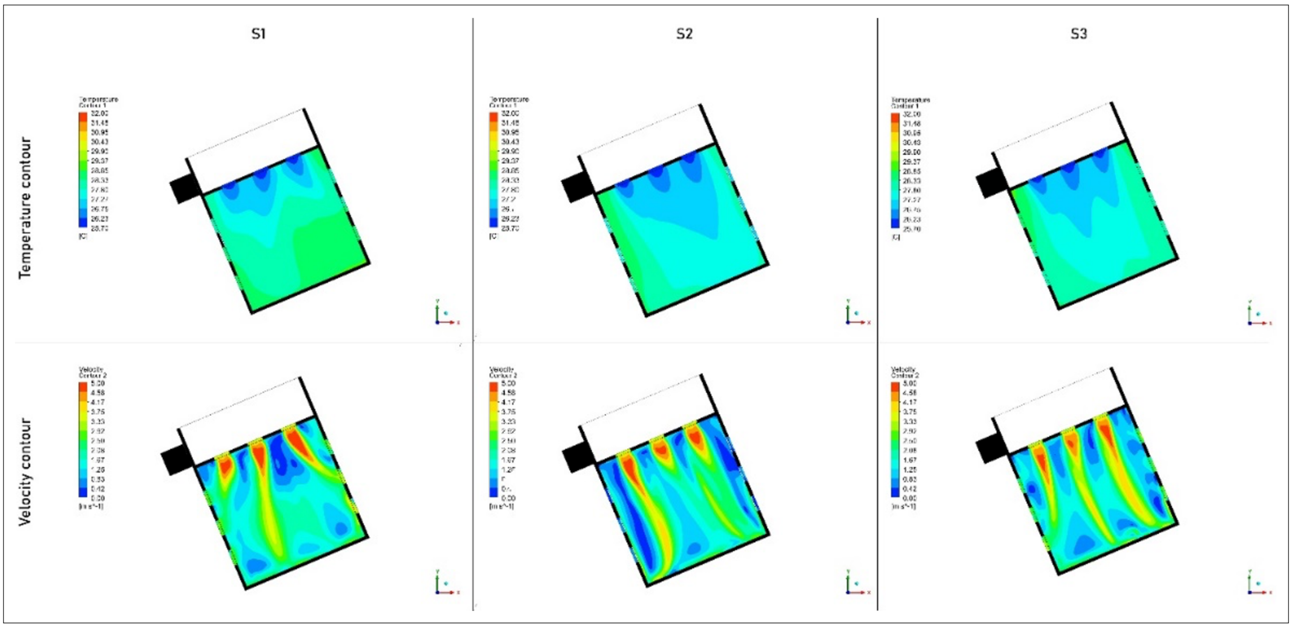

Figure 11. S1, S2, S3 temperature contour and velocity contour diagrams.

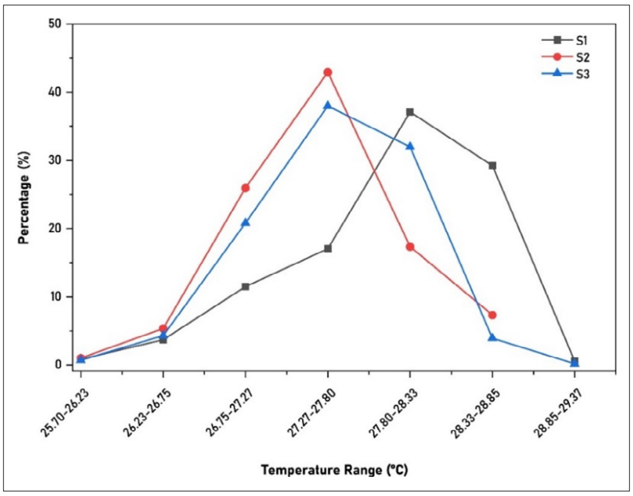

Figure 12. Temperature range – percentage of the space chart.

in S1 is within the range of 27.27-28.85 °C. These findings underscore the significance of incorporating stack effect ventilation in mosque designs. The S1 scenario, with only ground-level cross-ventilation, does not provide adequate passive cooling for mosque buildings. The results indicate that stack ventilation is highly effective for mosques, which typically have much taller floor heights than other building types. Therefore, this study suggests that designing openings at higher elevations in mosque buildings significantly enhances natural ventilation and reduces the reliance on air conditioning. Architects can utilize this criterion to design more sustainable mosque buildings.

For future research, analyses could be extended to include strategies to prevent overheating, such as the implementation of sunshades on the southwest façade or the creation of a protective shell around the building. Such modifications could further improve the efficiency of natural ventilation and cooling.

ETHICS: There are no ethical issues with the publication of this manuscript.

PEER-REVIEW: Externally peer-reviewed.

CONFLICT OF INTEREST: The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FINANCIAL DISCLOSURE: The corresponding author of the study, Hatice Sena Azkur, is supported as a YÖK 100/2000 PhD program scholar.

REFERENCES

Al Sudany, J. A. A. W. (2015). Employment minarets wind-catcher natural ventilation and passive cooling in the mosques of Baghdad. Int J Curr Eng Technol, 5(5), 3186–3192.

Al-Homoud, M. S., Abdou, A. A., & Budaiwi, I. M. (2009). Assessment of monitored energy use and thermal comfort conditions in mosques in hot-humid climates. Energy Build, 41(6), 607–614.

Alhasan, W., & Yuning, C. (2019). Environmental analysis of Nanjing Mosque courtyard layout based on CFD simulation technology. E3S Web of Conf, 136, 04040.

Allocca, C., Chen, Q., & Glicksman, L.R. (2003). Design analysis of single-sided natural ventilation. Energy Build, 35(8), 785–795.

Asfour, O. S. (2009). Effect of mosque architectural style on its thermal performance. Islam Univ J Ser Nat Stud Eng, 17(2), 61–74.

ASHRAE. (2004). Thermal environmental conditions for human occupancy (ASHRAE Standard 55).

Atmaca, A. B., & Gedik, G. Z. (2019). Evaluation of mosques in terms of thermal comfort and energy consumption in a temperate-humid climate. Energy Build, 195, 195–204.

Azmi, N. A., & Ibrahim, S. H. (2020). A comprehensive review on thermal performance and envelope thermal design of mosque buildings. Build Environ, 185, 107305.

Azmi, N. A., Arıcı, M., & Baharun, A. (2021). A review on the factors influencing energy efficiency of mosque buildings. J Clean Prod, 292, 126010.

Brager, G., & de Dear, R. (2000, October 01). A standard for natural ventilation. UC Berkeley Center for the Built Environment. https://escholarship.org/uc/item/3f73w323

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. Build Simul, 6, 33–50.

Çalış, G., Kuru, M., & Alt, B. (2017). Bir eğitim binasında ısıl konfor koşullarının analizi: İzmir'de bir alan çalışması. Uludağ Üniv Müh Fak Derg, 22(2), 93–106.

Darçın, P. (2008). Yapı içi hava kirliliğinin giderilmesinde doğal havalandırma ilkeleri [Unpublished master's thesis]. Yıldız Technical University.

Diler, Y., Turhan, C., Arsan, Z. D., & Akkurt, G. G. (2021). Thermal comfort analysis of historical mosques. Case study: The Ulu Mosque, Manisa, Türkiye. Energy Build, 252, 111441.

El-Deeb, K. (2013, September 10-12). Combined effect of window-to-wall ratio and wall composition on energy consumption [Paper Presentation]. PLEA 2013 - 29th Conference, Sustainable Architecture for a Renewable Future, Munich, Germany.

Goia, F. (2016). Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential. Solar Energy, 132, 467–492.

Gürsoy, E. (2018). Cami tip projelerinde ölçü-oran ilişkisi. Türk Dünyası Araştırmaları, 118(232), 211–228.

Habibzadeh, A. (2018). Konut yapılarında doğal havalandırmanın önemi ve badgir bağlamında günümüz koşullarında değerlendirilmesi [Master's Thesis]. Yıldız Technical University.

International Energy Agency. (2022). Buildings. https://www.iea.org/reports/buildings

Imam, S. N. (2003). Ventilation in a mosque – an additional purpose the minarets may serve [Paper Presentation]. The 7th International Conference Healthy Buildings, Singapore.

Jaffe, S. B., Fleming, R., Karlen, M., & Roberts, S. H. (2020). Sustainable design basics. John Wiley & Sons.

Ji, Y., Lomas, K. J., & Cook, M. J. (2009). Hybrid ventilation for low energy building design in south China. Build Environ, 44(11), 2245–2255.

Jiang, Y., Alloca, C., & Chen, Q. (2004). Validation of CFD simulations for natural ventilation. Int J Vent, 2(4), 359–369.

Jo, S. J., Jones, J., & Grant, E. (2018, September 25). Trends in the application of CFD for architectural design. ARCC Conference Repository. https:// www.arcc-journal.org/index.php/repository/article/view/489/392

Küçüker, S. (2020). Mimari tasarım sürecinde doğal havalandırma ilkeleri [Master's Thesis]. Yıldız Technical University.

Li, W., & Chen, Q. (2021). Design-based natural ventilation cooling potential evaluation for buildings in China. J Build Eng, 41, 102345.

Maarof, S. (2014). Roof designs and affecting thermal comfort factors in a typical naturally ventilated Malaysian mosque [Unpublished Doctoral dissertation, Cardiff University].

Mohammed, A. G., AbdelGawad, A. F., & Nassief, M. M. (2020). Artificial neural networks to assess the effect of window parameters on indoor natural ventilation in Sultan Al-Ashraf Qaytbay Mosque. Egypt Int J Eng Sci Technol, 30, 51–65.

Mushtaha, E., & Helmy, O. (2017). Impact of building forms on thermal performance and thermal comfort conditions in religious buildings in hot climates: A case study in Sharjah city. Int J Sustain Energy, 36(10), 926–944.

Nordin, N. I., & Misni, A. (2017). A comparative study on the indoor thermal performance of new and old mosques. Environ Behav Proc J, 2(5), 23.

Nordin, N. I., & Misni, A. (2018). Evaluating the interior thermal performance of mosques in the tropical environment. IOP Conf Ser Earth Environ Sci, 117(1), 012014.

Othman, F. Z., Ahmad, S. S., & Hanapi, N. L. (2019). The relationship between ventilation and opening strategies of domed mosque for indoor comfort. e-Academia J, 8, 85–91.

Rahim, M., & Marasabessy, F. (2019). Evaluation of natural ventilation characteristics on the Sultanate of Ternate Mosque. IOP Conf Ser Mater Sci Eng, 506(1), 012035.

Raslı, N. B. I., Ramlı, N. A., Ismail, M. R., Zainordin, N. S., & Razman, M. R. (2021). Effectiveness of ventilation strategies in reducing the temperature in the main prayer halls of mosques in Malaysia. J Eng Sci Technol, 16(4), 2960–2979.

Ray, S. D., Sadaba, S., & Leung, L. (2017). Intelligently controlled naturally ventilated mosque - a case study of applying design tools throughout the design process. Int J Vent, 16(2), 124–133.

Sanusi, A. N. Z., Abdullah, F., Azmin, A. K., & Kassim, M. H. (2019). Passive design strategies of colonial mosques in Malaysia. In Green Build Renew Energy: Med Green Forum 2019-Part of World Renew Energy Congr Netw (pp. 247-262). Springer International Publishing.

Turkish Standards Institution (2013). Thermal insulation requirements for buildings (Standard no. TS 825:2013).

Yavaş, F. (2019). Binalarda doğal havalandırma performansının bina bilgi modelleme yöntemi ile incelenmesi [Master's Thesis]. Fırat University.

Young, D. F., Munson, B. R., Okiishi, T. H., & Huebsch, W. W. (2018). Akışkanlar mekaniğine giriş. (N. Yücel, H. Türkoğlu, Z. Altaç, & N. Dinler, Trans.) Nobel Academic Publishing.

Yusoff, W. F. M., & Ja'afar, N. H. (2019). Preliminary evaluation of indoor thermal comfort in Malaysia heritage mosque. MATEC Web Conf, 277, 02016.

Yüksel, A., Arıcı, M., Krajčík, M., Civan, M., & Karabay, H. (2021). A review on thermal comfort, indoor air quality and energy consumption in temples. J Build Eng, 35, 102013.

Zhai, Z. (2006). Application of computational fluid dynamics in building design: Aspects and trends. Indoor Built Environ, 15(4), 305–313.