Creative city design / Vol. 6, No. 3, 2023, 16-36

The Effect of Canopy Protrusion Amount on Energy Consumption and Thermal Comfort in the Dome Structure (Case Study: Sheikh Lotfollah Mosque)*

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Submit Date: 26 April 2023, Accepted Date: 10 July 2023
DOI: 10.30495/ccd.2023.1983578.1204

Abstract

The present research aimed to investigate the relationship between the canopy performance and the gable openings of the dome structure (Sheikh Lotfollah Mosque, Isfahan City) and considered the determinants of energy consumption and thermal comfort to provide a solution to improve thermal comfort and optimize energy consumption while using clean energy in ventilation. Modeling of different modes was performed with the help of Design Builder Energy Simulator software. Further, the computational fluid dynamics (CFD) method was used to evaluate thermal performance. The parameters of the research included air velocity, relative humidity, dry air temperature, and amount of canopy protrusion. Based on the results, the lack of necessary facilities for natural ventilation led to uncomfortable conditions and lower air-flow circulation in the building, causing unfavorable thermal conditions for worshippers. Moreover, the total consumption of energy decreased by increasing the fixed-canopy protrusion amount (up to 1.5m). On the other hand, a higher amount (more than 1.5m) led to better conditions in warm months, but worse conditions were created and total energy consumption greatly increased in cold months. The research results indicated that as the protrusion of fixed canopies increased up to 1.5 meters, then the amount of total energy consumption also decreased. Furthermore, the protrusion of greater than 1.5 meters gently increased the total energy consumption. The thermal comfort index was more tolerable in hot months and a little more difficult in cold months.

Keywords: Dome structure, Thermal comfort, Canopy, Sheikh Lotfollah Mosque

Introduction

Thermal comfort regarding climatic conditions is an important issue that has long affected the people's lives [1]. Thermal comfort, consumption, and use of energy affect all stages of construction. Nowadays, dealing with energy and optimizing its consumption and thermal comfort despite environmental crises and limited reserves of fossil fuels is important for the construction of buildings. Furthermore, it is necessary to determine how much energy is used during and after the construction of buildings for heating and cooling. Moreover, the materials of the buildings should be taken into consideration [2]. Optimizing the energy consumption of buildings is a key strategy in reducing the risks of climatic changes worldwide [3].

According to the optimization statistics of fuel consumption in Iran in recent years, reported by the National Iranian Oil Product Distribution Company (NIOPDC), the construction sector has the highest energy consumption (one-third of the energy consumption) among other sectors both in terms of cooling and heating [4]. This amount of consumption and waste of resources and an increasing construction process with various uses and functions do not leave any traces and patterns of the local historical, cultural, and architectural identity of this area. The body does not reflect itself [5]. The architecture and building construction

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[*] This manuscript is taken from the Ph.D. thesis titled "Investigating the effect of the physical characteristics of grave dome valves on natural ventilation in hot and dry regions of Iran" by Mrs. Najmeh Tavazo, guided by Dr. Mansour Nikpour, and advised by Dr. Mohsen Ghasemi and Dr. Hadi Farzan in the Islamic Azad University of BAM.

**Corresponding Author: Mansour.nikpour@iau.ac.ir patterns in Iran in the past periods, both in terms of the form of the building, and the materials and the construction patterns, indicate a strong balance of the relationship between the natural and the man-made environment. Further, the pattern of architecture and building construction was previously formed in line with sustainable architecture. Considering that Iran is located in a dry desert belt, most cities are involved in thermal comfort and relevant issues. The examination of the history of cities, form, and architecture of Iran throughout history, and climatic conditions indicates the problems arisen in this regard for human life. Therefore, architects and designers have taken measures towards energy control and its optimal consumption to create thermal comfort. Due to the obsolescence and high cost of facility solutions, which are conducted to reduce energy consumption in buildings [6], decisions should be made and types of designing the architectural projects should be taken into consideration to provide optimal solutions, achieve an optimal model in the field of energy consumption reduction, reduce costs, and optimize energy consumption. It can be also very effective in achieving an optimal model in the climate-compatible architectural design process [7] Considering that mosques in Iranian-Islamic cities greatly contribute to shaping social relations as basic elements in the general structure of cities, providing and creating comfort in this space are significantly important to increase the public presence in society, and investigate the thermal behavior of such a space where a dome cover is a valuable element [8] According to the advances in sciences and new methods of architectural design in recent years, new methods have been created in the process of designing dome covers and their new styles. The modern models in Western countries are used for building mosques with new techniques and based on new needs and materials, for example, there are several cases in Iran, like the work of Jahangir Mazloum Yazdi (Al-Ghadir Mosque), Tehran University Mosque with modern design by architect Abdulaziz Farmayan, and engineer Ebrahimi (Jawad Mosque) as is the first modern Iranian mosque based on the characteristics of modern materials, painted with air conditioning paint and spirituality along with the requirements, except for the dome. The present research evaluated the influence of vent protrusions or groove openings of domed buildings on the amount of energy consumption and thermal comfort of Sheikh Lotfollah Mosque in Isfahan only as a model to explain the role of architect's knowledge and expertise and modern design methods in providing thermal comfort. Undoubtedly, changes in protrusion affect the amount of solar radiation or heat energy loss through windows; however, the amount of influence is different on these factors. Considering the importance of the subject, the location of Isfahan, and its location in a hot and dry climate, it is necessary to analyze the protrusion amount of certain canopies of the hatches of Sheikh Lotfollah Mosque. Furthermore, the present study sought to determine the extent of influence of opening canopy or vents on the amounts of heating and cooling energy consumption, in addition to the level of worshipers' thermal comfort. This research aimed to evaluate two factors (energy and thermal comfort), and finally, provide solutions to improve thermal comfort. This is possible by optimizing energy consumption as the result of higher efficiency than clean energy in terms of ventilation. Therefore, the main research question is stated as follows to achieve these goals: Does the design of the canopy protrusion of mosques in hot and dry areas affect the reduction of energy consumption and establishment of thermal comfort?

2- Research background and theoretical principles

Thermal comfort refers to a condition in which a person does not feel extreme heat and cold and is thermally favorable for 80% of people [9]. In the subjective dimension, "ASHRAE" defines thermal comfort as the level of human satisfaction with the heat of the environment and emphasizes that it can be measured by a subjective evaluation [10]. Thermal comfort can be classified into three dimensions, first, the mental-psychological dimension in which a person feels mentally satisfied with the space under thermal conditions; second, the thermo-physiological dimension which is more correlated to the physiological and biological aspects, and thermal receptors on the human skin compared to the surrounding environment; and finally, the energy dimension which depends on the flow of energy from one body to another [11]. In 1970, Finger introduced a method for calculating thermal comfort, known as the Finger model. In this model, the Predicted Mean Vote Index (PMV), and the predicted percentage of unsatisfied people are used to measure thermal comfort [12]. Energy analysis considers all modes of energy loss from the body of people and assumes that a person has a stable thermal compromise with the surrounding environment [12]. There are seven categories of PMV. The PMV value is based on the ASHRAE thermal sensation ranging from the coldest (-3) to the hottest (3+). This thermal index has been used for thermal comfort in the dome structure of mosques [13]. PMV value increases as it changes positively or negatively from zero in such a way that the acceptable range for the PMV index is in the range of -0.5 to +0.5 for public comfort, according to the "ASHRAE" standard, and 0 to 1 for the PPD index. The calculation of PPD can be strongly affected by hourly-average physical parameters (air temperature, air velocity, and humidity) in mosques [14]. Table 1 presents the thermal comfort index of Fanger's PMV.

Table 1. Range of measurement area

(Fanger index)	Feeling
-3	Cold
-2	Cool
-1	A little cool
0	Neutral
1	A little warm
2	Hot
3	Too warm

Despite the importance of thermal comfort, few studies have evaluated it in dome structures such as mosques. The empirical literature review indicates the evaluation of the closest topics so that a standard and basis can be provided for comparing the results of the present research.

Ebrahimpour et al. [15] investigated the methods of optimizing energy consumption in the structure of the University of Tabriz using the Energy Plus software. Based on the evaluation and analysis of the research data, the use of a canopy with a depth of 50 cm and the light color of windows decreased energy consumption. Nikofred et al. [16] investigated the effects of canopy installation on heating and cooling energy consumption and greenhouse gas production using ESPR software in a residential building. The research results indicated that only the use of automatic roller shutters decreased energy consumption. In an article titled "Double-shell dome from the perspective of thermal performance in the desert climate of Kashan", Fuladi et al. [17] used computer simulation to achieve an optimal model for the dome in terms of maintaining the air temperature in the space. The researchers concluded that the best geometrical shape to cover the roof of the building in the desert climate of Kashan and similar climates was a two-shell dome with an outer shell in the image of Nari and an inner shell in the image of the Korean sector similar to the dome of Chehel Dokhtaran mausoleum in Kashan. Asghari et al. (2016) [36] investigated the effect of canopy and thermal insulation on the cooling load of an office building in hot (Ahvaz), humid (Tehran), and moderate and cold (Tabriz) climates. Design builder software simulated two different strategies, and their effects were investigated on energy consumption. The first strategy was to use the radiant heat transfer equation and reduce the irradiated cross-sectional area of the building, using the canopy with different depths in six modes, and the second strategy was to use the Fourier equation which calculated the amount of heat flux reduction in a building, using thermal insulation with different thicknesses in five modes. Based on the results, the second strategy was preferable to the first strategy for Ahvaz and Tehran, but the difference between the two strategies was small in Tabriz. The results of Ahvaz city indicated that the reduction of energy consumption by awnings was often not correct and the use of thermal insulation with a thickness of one centimeter had a good effect on the reduction of energy consumption. Niu et al. (2022) [18] investigated the effect of trees in the open space around the university structure on the natural ventilation of the building and used casmphor tree and Metasequoia. The research results were important in two aspects, first, it was found that compared to the situation without trees, outdoor trees had a great effect on the natural ventilation performance of the university building. It was also found that the blocking effects of camphor in internal ventilation were more than Metasquia. The mean ventilation flow rate increased by 14.89% in Metasquia cases compared to camphor cases. Efor (2022) studied the effect of natural ventilation on the internal comfort of residents of general hospital wards in Nigeria [19]. He classified the weather into hot and humid and then measured the comfort indices with thresholds. Then he compared the comfort offered by the American

Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and finally, analyzed data using the correlation coefficient and linear regression models. The mean temperature in the four thermal zones was higher than the standard threshold recommended by ASHRAE [10]. The results of the correlation coefficient indicated a strong negative correlation between indoor air speed and temperature. The regression analysis also indicated that as the value of the independent variable (X) increased, the value of the dependent variable (Y) decreased.

Given a few theories about the principles and regulations of the manner and extent of interference of surrounding buildings, and the intensity and direction of wind distribution on a dome-shaped structure and building, Lin Sheng et al. [20] used the fluid dynamics method computationally and simulated the mean wind pressure of a dome-shaped structure in interference with a building with a rectangular cross-section. This research process measured the effects of height, different widths of the building, and the distances between both buildings. The research results also indicated that the mean wind pressure caused by interference increased the suction in a domed roof. Further, the height ratio had the greatest effect on the mean wind pressure. The closest area of the domed roof to the interfering building had the highest suction considering all wind directions.

The following points are obtained according to the empirical literature review:

The residential, administrative, university, and medical buildings were investigated and the details of buildings, especially the mosque buildings, were addressed in a smaller way. In other words, the mosque building was studied. Most of the buildings had flat roofs, and a few had domed roofs.

Most of the articles aimed to provide a theoretical and experimental basis for a more accurate calculation of the ventilation of the interior spaces of buildings. In this regard, various simulations were performed to create the most efficient ventilation conditions to help complete this research, look at the research objectives in providing natural ventilation in domed buildings, and better understand the way the canopy overhung the window openings. In this research, Design Builder computer simulator software was used to analyze CFD calculations. Furthermore, the fluid turbulent flow prediction algorithm (k-e) was used to solve the turbulence model, and it provided better performance for predicting the turbulent flow in the indoor space. This software enabled the ability to provide calculations for the internal and external conditions of the building model in any season and specific time of year.

3- Materials and methods

The researcher inserted Isfahan's weather information into the Design Builder Simulation software to check the extent of the canopy over the opening or window and reach reliable results. Considering that this sample is located in the east of Naqsh-e Jahan Square and faces the west wind from the wide Naqsh-e Jahan Square, and there is an empty space on the east side of the building, it is a unique example in the entire Islamic and even non-Islamic world, and we do not see such a thing in any dome, even non-religious ones. This building has no courtyard, porch, or minaret, indicating its exceptionality. Therefore, they should be measured from this point of view and not enter into other issues such as aesthetics, and pollution. This is a sample that can be used for laboratory work, modeling, and simulation. It is worth mentioning that the validity of the work depends on the accuracy of the primary and basic information, and it is not possible to compare the two climates in the upcoming work because the validation criterion is the sameness of the information, and this has been fully considered in the research evaluation. The weather information of Isfahan was given to the software to check and reach reliable results. Therefore, the proportions and geometry used in the modeling of the test on Sheikh Lotfollah Mosque did not cause this dome to go out of proportion because the researcher had chosen the real model only to investigate the research objectives. In other words, the researcher chose this topic to go into details in a specific field (energy and thermal comfort), evaluate a discussion transparently, and avoid generalizations. This issue should not be considered after phenomenology. Therefore, a meaningful symbolic building such as Sheikh Lotfollah Mosque was evaluated with a modern functionalist approach, and the achievements of these types of approaches were presented quantitatively. Given that the result of the functionalism approach in the form of computational data can be used in other aspects of building analysis [21] by preserving the style and trend of the past architecture, ancient values, and traditions to use and maximize the efficiency of natural wind power, reduce fuel and energy consumption, achieve as much thermal comfort as possible for users, and investigate and implement changes. In this regard, the effective parameters were discussed and a level increased the science of construction with dome roofs.

4- The role of ventilation in promoting thermal comfort and satisfaction

The provision of clean and enjoyable air was very important in ancient civilizations, and they used natural ventilation systems in the indoor environment and various architectural elements and techniques, such as domes, windbreaks, and courtyards. They invented ventilation, and in recent decades, they preferred natural ventilation in many high-rise buildings instead of mechanical ventilation as an effective solution for the contemporary period. Further, the natural ventilation system is effective in controlling environmental conditions [22].

It should be noted that natural ventilation is an important basic principle in sustainable buildings, and one of its main goals is to provide healthy air for breathing in buildings [23] without consuming energy. It can be used in small and large buildings such as mosques. On this basis, the present study evaluated the role of natural ventilation in domed mosques and the optimization of the energy consumption pattern in the design of windows to determine the effect on the quality and comfort of the worshipers in the mosques.

Using computer simulation, the function of Grave Dome windows is explained to provide the desired air temperature and control the amount of sunlight entering through the windows and controlling these two issues. It had a significant impact on the thermal comfort of the building. Furthermore, the use of specific climate strategies and designing more sustainable buildings provided thermal comfort to the residents without using a mechanical ventilation system. Since it is almost impossible to solve heat transfer equations in dome-shaped roofs due to the instability of solar radiation and ambient temperature, it is almost impossible to solve them with analytical methods. In recent years, Computational Fluid Dynamics (CFD) is considered as the most suitable method for airflow modeling and analyzing the airflow state, and the way of heat transfer inside and inside the buildings. It is widely used and accepted to measure thermal comfort [24]. In the present research, calculations were made to determine the amounts of wind pressure, air speed and direction, and the temperature prevailing in the space, especially at a distance of 0.5 m from the floor inside the mosque (the distance where the worshipers perform their activities). These simulations were carried out for the design conditions of summer between 12:00 and 14:00, and the various indoor air quality parameters were also taken into consideration to determine the boundary conditions inside the mosque and evaluate the natural ventilation in the building.

4-1- External CFD analysis

The effectiveness of the dome roof of the mosque against climatic conditions was an important issue in this study. About one-third of the heat enters the buildings through the roof. Therefore, the roof form, the type of materials, and the region climate are effective in improving the thermal performance of the roof. Arch-shaped domes rely on the free movement of air on the surface and they can reduce the transfer of heat absorbed by the sun through the roof due to the spatial connection of the spherical dome with the surrounding space, exposed to the wind all the time. Therefore, the convective heat transfer coefficient increases, and less heat enters the building. On the other hand, the heat that radiates from the roof at night is quickly removed and has a natural cooling effect on the building. The first way to cool the roof is to pay attention to the proper direction of the roof, its shape, and shade [25]. It is considered an important moderator in terms of nature [26]. Better natural ventilation can regulate the movement of incoming air in the entire interior spaces of the building by a suitable opening, a correct placement, and arrangement of the building [27].

According to the external CFD simulation, and the weather data of Isfahan City, the wind speed around the dome roof of the Sheikh Lotfollah Mosque was analyzed and evaluated, and the potential of natural ventilation was evaluated in the summer season. The results indicated that air circulation around the dome roof caused positive and negative pressure on both sides of the dome. Positive pressure occurred on the surface of the dome facing the wind, and the other surface had negative pressure. This pressure difference accelerated the wind flow around the dome and removed heat from its surface. Therefore, wind speed and direction were important in reducing the heat of the dome surface and the surrounding space. Figure 1 shows the air pressure and speed at heights of 5 m and 15 m (for windows of the grave). This causes the air to enter the building through openings in high-pressure areas. There is no problem in accepting wind pressure for spaces that are ventilated only from one side.

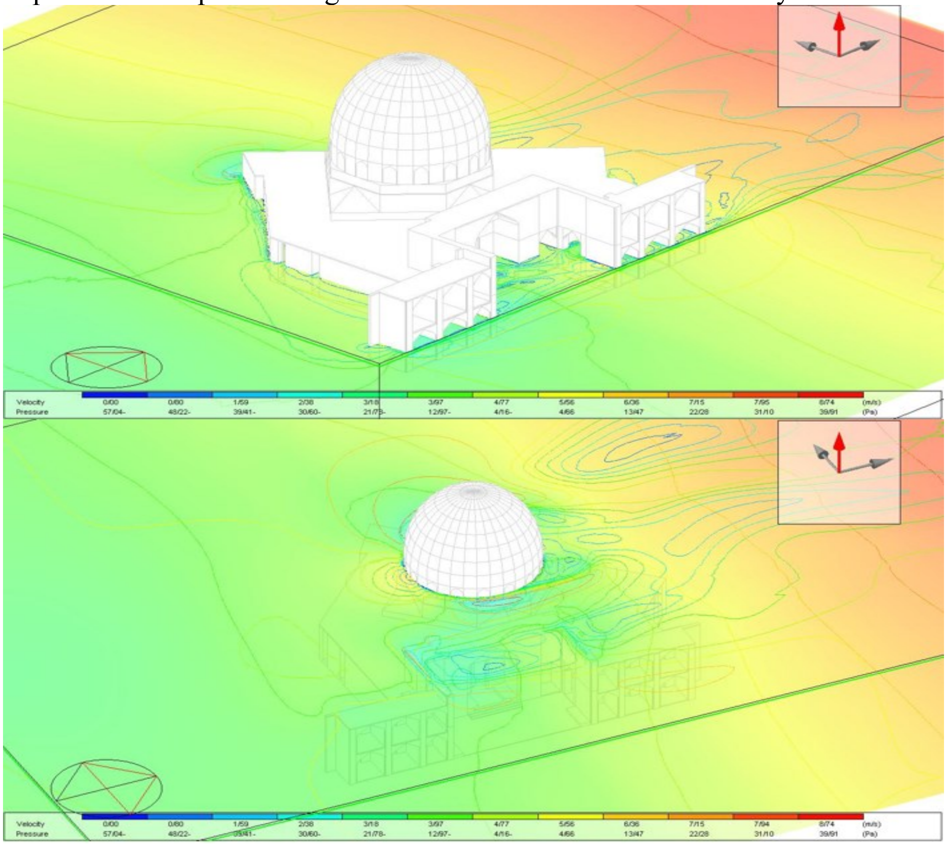


Figure 1. (From top to bottom): The external airflow of the building at heights of 5 and 15 meters (author)

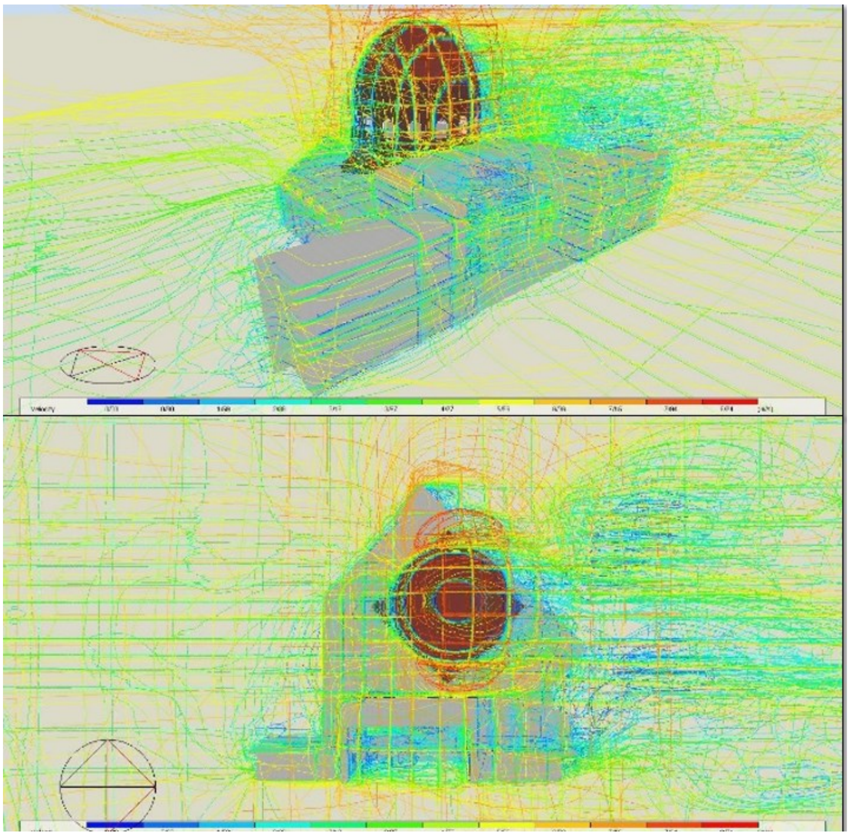


Figure 2. The external wind flow on the building and its changes according to Design Builder software

As shown, there are two rotational movements in Figure 2, and the fluid movement is much more behind the domed roof area. Airflow patterns around the mosque structure create a vortex in some parts of the dome roof. Further, the speed distribution and density of the flow are especially prominent at the top of the dome roof. Due to the low pressure at the top of the dome roof, it is possible to ventilate air in tropical areas by opening the top of the dome to allow the internal air to drain.

4-2- Internal CFD analysis with closed windows

Various indices of internal ventilation were included in the sample model, and the internal simulation of the building was analyzed to assess the behavior of air fluid flow. The speed of the incoming wind in real conditions was extracted by the speedometer and it decreased to less than 1 m/s according to the building scale, indicating the actual amount of air entering from the windows. During the hours, when the sunlight reached its peak, the worshipers came to perform their noon prayers. Figure 3 shows the temperature distribution when the windows of the mosque are closed. Since the external wind inlets are blocked, the air flies at a low speed through the seams and doors of the mosque, and thus the mosque's space increases the people's metabolism due to the entry of sunlight. The noon prayers face thermal flux to a great extent. Therefore, a temperature-driving flow is slowly created.

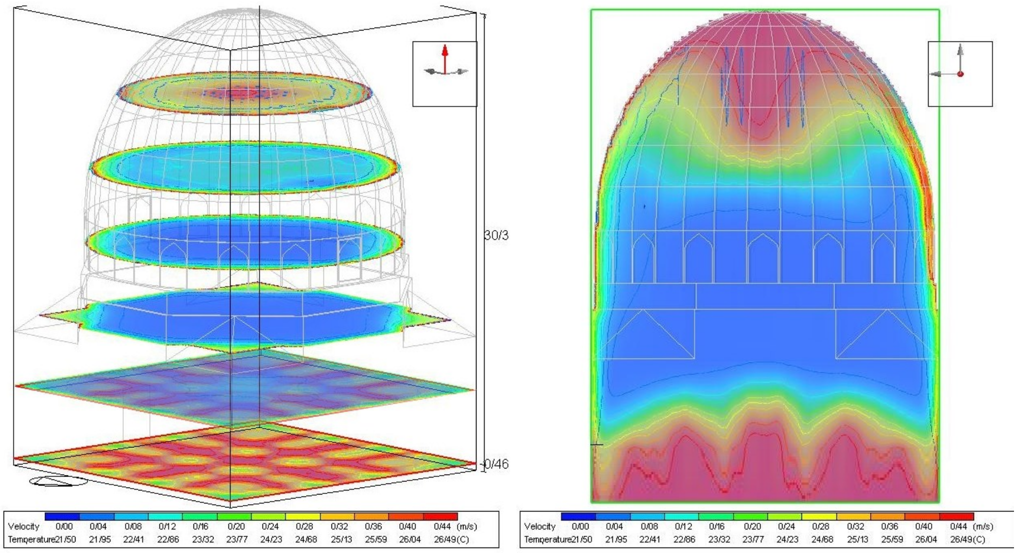


Figure 3. The flow of external wind on the building and its changes using Design Builder software from a high angle

The results of computational fluid dynamics (CFD) indicated that the amount of sunlight absorption in the nave space was more than required, and thus the temperature of the interior of the mosque increased in hot months, especially in the middle of the day due to the lack of balance between the ventilation and the volume of the nightstand. Therefore, airflow could not reduce the room temperature. The areas shown in red have hot air in that space. According to the temperature distribution, if the mosque windows are closed, then the temperature at a distance of 0.5 m from the mosque's floor is about 26ºC. Due to the large vertical distance between the mosque's windows and floor, the proportionality of the overall volume of the mosque with the percentage of light-transmitting windows, as well as the better performance of the dome roof compared to the flat roof in this building, the interior space receives less heat and the temperature of the non-ventilated units in many similar studies reach above 30 ºC. Due to the slanting angle of the sun and the shorter day length in the winter, the sun can enter the building for a shorter period; hence, there is no need to cool the interior of the mosque's nave in winter.

4-3- Internal CFD analysis using natural ventilation

Figure 4 shows the results of pressure and airflow distribution from 12:00 to 14:00 on the first day of July when all windows are opened. The results indicate that when the windows are open in the summer, the fresh air is exchanged with the trapped air inside. Despite the accumulation of hot air at the top of the roof, they are prioritized for exit, and the outside air replaces the hot air under the roof. With the exit of the hot air, the negative pressure appears at the lower heights of the building, attracting the air from the lower part of the mosque to the top. This movement of air buoyancy changes the temperature of flowing air and goes towards the low-pressure opening after traveling the static path in the space inside the mosque so that people in the mosque can experience this airflow. The presence of squinches in the mosque helps speed up the moving process of the airflow. Due to combining the air outside and inside of the mosque, the airflow moves against the wind direction. This optimal method is useful for changing the air inside. According to the software output, the temperature reached 23.76ºC at a height of 0.5 m from the floor, and it was considered "slightly warm".

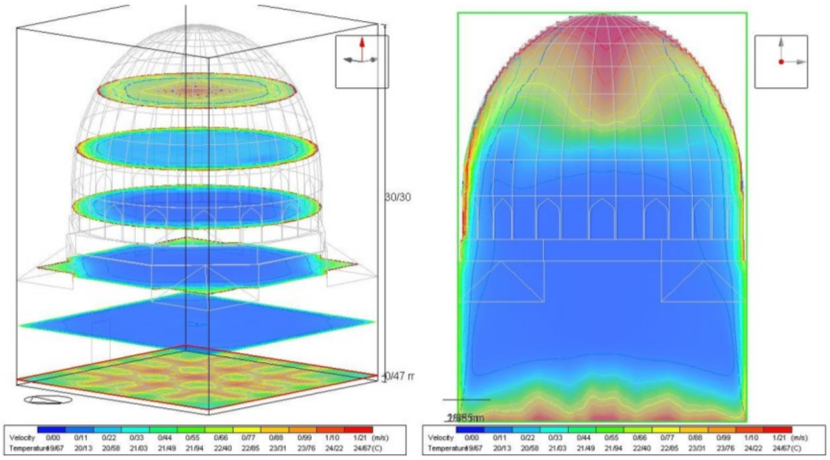


Figure 4. Airflow speed and temperature in a building without natural ventilation (author)

If no process is carried out in the mosque at night, then the opening of the windows creates negative pressure inside and night ventilation. In the early hours of the next day, the temperature of the air inside the mosque increases slowly. As a result of the gradual increase in temperature, it decreases by 1 ºC at noon.

5- Thermal comfort index and software analysis

Design Builder software is an advanced building thermal analysis tool using the Energy Plus simulation engine [28]. This software calculates temperature comfort based on Finger's comfort indicators in two formats: The predicted percentage of dissatisfied (PPD) index and the Predicted Mean Vote Index (PMV). This software performs mathematical calculations and causes relationships between six parameters, including Activity (MET (body metabolism) or W (activity) of a person or Btu (British thermal unit in hours), clothes (Clo), air temperature (°C or °F), and calculates the mean radiant temperature (°C or °F), air speed (m/s or ft/min), and humidity (percent). The following equations indicate the relationships between the parameters of the heat index [38].

$$pmv = (0.303^{e-0.036M} + 0.028\,[(M - W) - H - E_C - C_{rec} - E_{rec}] \qquad (1)$$

$$E = 3.05 \times 10^{-3}\,(256_{sk} - 3373 - P_a) + E_{SW} \qquad (2)$$

$$EC = 3.05 \times 10^{-3}\,[5733 - 6.99 \times (M - W) - P_a] + 0.42(M - W - 58.15) \qquad (3)$$

$$C_{rec} = 0.0014M(34 - Ta) \qquad (4)$$

$$H = K_{cl} = t_{SK} - t_{cl} \,/\, I_{cl} \qquad (5)$$

$$PPD = 100 - 95_e - (0.03353PMV4 + 0.2179PMV2) \qquad (6)$$

Where Crec is the convective heat exchange of transpiration (W/m2); Erec is the evaporative heat exchange perspiration (W/m2); Ec is the evaporative heat exchange on the surface of the skin when it is in a neutral thermal state (W/m2); Icl is the average clothing radiation for the whole body (W/m2); M is the body metabolic rate (W/m2); tcl is the clothing surface temperature (°C); tsk is the average skin temperature (°C); W is the effective mechanical force (W/m2); e is the evaporative heat exchange on the skin surface (W/m2); H is the dry heat loss in the form of convection, conduction, and radiation (W/m2); Pa is the partial vapor pressure of air (Pascal); and Ta is the air temperature (ºC) [37]. The amounts of basic activity level and clothing coverage of worshipers were measured based on the ISO 7730 standard by examining people during prayer time when they prayed in the mosque and performed movements such as standing, bowing, prostrating, and sitting in a very calm process. The metabolic rate used for the worshipers was estimated to be 1.2 and the mean overall value of the clothing used in this research was 0.70 and the relative humidity was 50%.

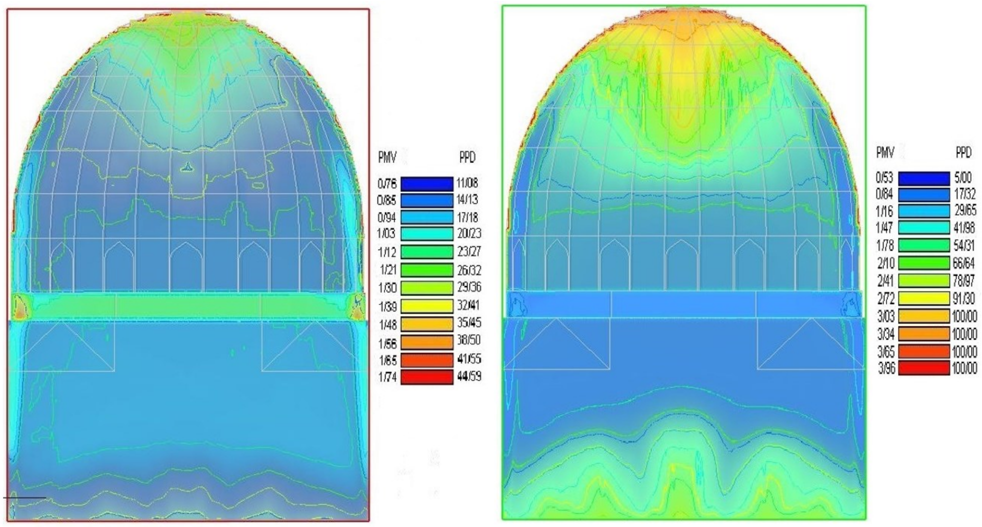


Figure 5. The thermal comfort index in two formats (PMV) and (PPD) in a building with natural ventilation

According to Figure 5, the PMV and PPD are calculated using computational fluid dynamics (CFD) in a situation where internal ventilation is not possible due to the closed windows of the mosque structure, then the hot air in the area near the mosque's floor prevails and hot weather leads to people's dissatisfaction. Thereafter, the measurement is performed by applying natural ventilation and looking at the fluid dynamics analysis output. It is determined that the grave windows of the mosque play an important role due to their locations as they reduce air temperature and provide proper ventilation in the building. Even though the PMV values in summer are closer to the optimal temperature range of the index (+0.5 and -0.5) and make the space tolerable for maximum worshipers, complete thermal comfort is not achieved yet. The results indicated that the presence of the worshiper was also effective in increasing the mosque's temperature in such a way that the temperature increased from 12:00 to 14:00 as the time of noon prayer because the human body produced the necessary energy for keeping warm through metabolism. Therefore ventilation systems must work with more power to remove excess heat. According to the extracted temperature information, the relative humidity of air decreased as its density decreased due to the heat generated from the prayer body, especially at noon. On the other hand, the relative humidity decreased more at the lower temperatures and increased air speed of the mosque during prayer.

6- Introduction of the research principles

Sheikh Lotfollah Mosque, a historic building in Isfahan, was built in the Safavid era by the prominent architect and scientist Sheikh Bahai. This mosque is located in the eastern Naqsh-e Jahan Square, opposite the Ali Qapu Palace, and was built on the ruins of an old mosque. [29] Like the Imam mosque, Sheikh Lotfollah Mosque is located in the Qibla direction with a deviation of 45 degrees from the north-south axis [30].

6-1- Architectural, structural, and facility characteristics

Based on the authors' field observations, the materials in the structure of Sheikh Lotfollah Mosque in Isfahan are made of pressed bricks and glazed tiles. Table 2 presents the characteristics of this building regarding the architectural, structural, and facilities aspects.

Table 2. Characteristics of the base model

General characteristics	Details	Building characteristics
Architectural and structural characteristics	Shabistan plan geometry	Square
	Plan proportions	1:1
	Plan dimensions	21/70 * 21/70 meters
	Spatial arrangement of the plan	Open plan

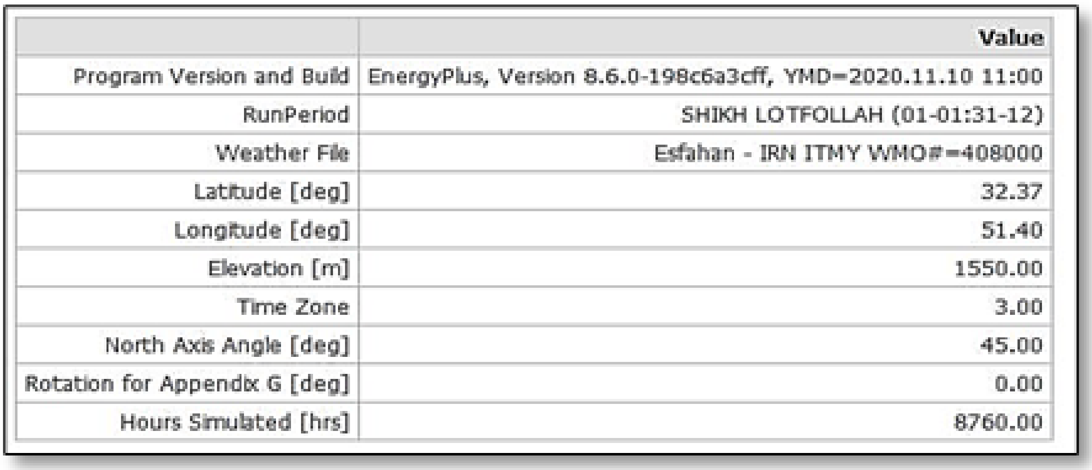
	Number of floors	One floor
	Floor height	30.8 meters from the floor to the top of the dome
	Type of skeleton	brick
Shell characteristics	External wall structure	Brick and tile
	Roof structure	Brick and tile
	Exterior wall color	Blue
	Type and material of openings	Latticed openings without windows
Typical facilities of similar mosques	Energy source	Gas and electricity
	Hours of use	Continuous use
	Heating system	Ceiling or standing radiant heating
	Cooling system	wall split (9000-30000)
	Brightness	400 lux
	Ventilation	natural and mechanical Hours of use: 19-5

7- The software data

Design builder software was used in this study. Like other energy simulation software, it has input and output data [31]. Changing the project time by 1 hour is a point that should be specified in the software position section. This time change means that the clock is moved back and forward by one hour to increase the efficiency of daylight hours, and it is done by ticking the option (use daylight) in the software. Further, the changed data is compared to the initial format of the software according to the upcoming project.

7-1- Climatic data

Several climatic parameters are necessary, including air temperature, relative humidity, amount of radiation, wind speed, direction, and air pressure to simulate the energy in the building. These data should not be available as an average or only for some days and months of the year but for all days and hours of the year. In this research, the climatic data of Isfahan (with longitude coordinates of 51.40 east and latitude of 32.37 north) were collected from the website of the Meteorological Organization of Isfahan Province, and then the collected data along with the longitude and latitude of Isfahan were compiled into a climate document and entered into the software. (Figure 6) (Meteorological Organization of Isfahan Province, 2022)

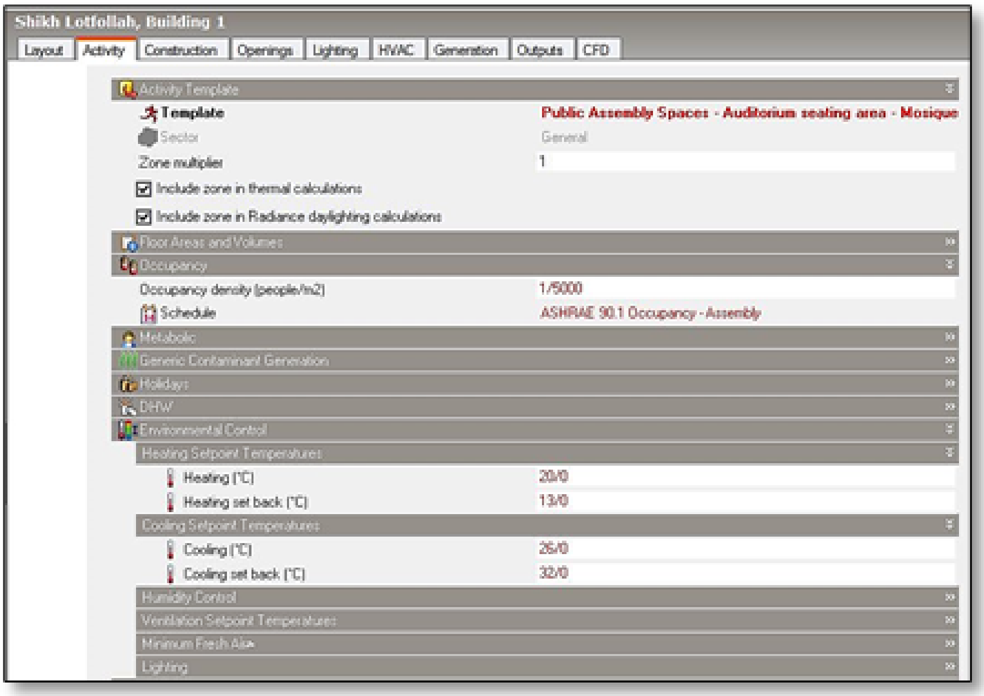


	Value
Program Version and Build	EnergyPlus, Version 8.6.0-198c6a3cff, YMD=2020.11.10 11:00
RunPeriod	SHIKH LOTFOLLAH (01-01:31-12)
Weather File	Esfahan - IRN ITMY WMO#=408000
Latitude [deg]	32.37
Longitude [deg]	51.40
Elevation [m]	1550.00
Time Zone	3.00
North Axis Angle [deg]	45.00
Rotation for Appendix G [deg]	0.00
Hours Simulated [hrs]	8760.00

Figure 6. The climatic file of Isfahan City in Design Builder software

7-2- Base temperature of cooling and heating in the building

The range with the minimum and maximum consumption of cooling and heating energy is the comfort range of the human body. With the reduction of consumption in this range, there will be no noticeable change in the body comfort [32]. The interaction between the components of ambient air temperature, the average radiation temperature, wind speed, and humidity form a structure that creates a thermal environment for residents in that environment. These components have direct and effective effects on residents' health, thermal comfort, efficiency, and performance in the building. To reach thermal comfort conditions in the human body, we must be able to adjust and create the body's reaction to changes in the components. The psychrometric chart of Isfahan City was used to calculate the appropriate air temperature as the comfort range in the simulation of the building, and it was obtained using the climate software and weather information of the region. Temperatures of 20ºC to 26 ºC (comfort range) are considered according to the psychrometric chart (Figure 7).



Template: Public Assembly Spaces - Auditorium seating area - Mosique
Sector: General
Zone multiplier: 1
☑ Include zone in thermal calculations
☑ Include zone in Radiance daylighting calculations
Occupancy density (people/m2): 1/5000
Schedule: ASHRAE 90.1 Occupancy - Assembly
Heating (°C): 20/0
Heating set back (°C): 13/0
Cooling (°C): 26/0
Cooling set back (°C): 32/0

Figure 7. The thermal comfort temperature for the interior space of the building in the Design Builder software

7-3- Lighting

The lighting section is analyzed using various types of lighting systems that are used inside and outside the building. To analyze this section, among the options available in the lighting section, the lighting, which is related to the artificial light inside the building, should be turned on because the lighting is among the alternatives that are not only in old buildings and cannot be also removed in new buildings [33]. Additionally, any lighting which provides light also produces heat, affecting the thermal comfort of the building's residents, as well as the ambient temperature.

7-4- Schedule

Regarding the scheduling, it is obligatory to enter the hours when the users (prayer) are present in the mosque according to the months of the year and the days of the week. To insert the dates into the software, these dates must be converted from solar to Gregorian. For all months of the year, the morning and evening calls to prayer time are set, and the basis of the software is based on the sunrise and sunset time. Therefore, the schedule of thermal comfort systems is included from 5 am to 7 pm.

7-5- The building structure

The construction materials in this part are similar to those used in the executive part of the mosque building in Isfahan city. In most of the mosques, which were built in different historical periods, pressed bricks were used in walls and ceilings, and glazed tiles were used on facade surfaces in the interior and exterior spaces. According to the layers of the brick wall of Sheikh Lotfollah Mosque, it is possible to understand the thermal resistance and thermal conductivity of the materials, which are very important regarding energy consumption. The two components, U-Value (thermal conductivity), and R-Value (thermal resistance) are correlated and both of them indicate the total resistance of layers that make up that shell. The higher the amount, the lower the cooling and heating energy consumption. In Sheikh Lotfollah Mosque, the resistance of the brick wall shell is equal to 1.355 square meter kelvin per watt ($m^2 \cdot K/W$) and the thermal conductivity coefficient of the shell is equal to 0.738 Watt Per Square Meter Per Kelvin (W/m^2-K), indicating the relatively good resistance of this shell to thermal conductivity. Regarding the roof section, the thermal resistance of the shell decreases and the resistance of the brick roof shell of the base building is 0.607 $m^2\cdot K/W$ and the thermal conductivity of the shell is 1.648 $W/m^2\text{-}K$. The values indicate that there is a lot of energy that is wasted from the shell in this section (Table 3).

Table 3. Thermal characteristics of the shell of the building in the Design Builder software

Thermal conductivity coefficient (U-Value)	Thermal resistance (R-Value)	Building components
0.738	1.355	Wall
.648	0.607	Dome roof

7-6- Holes in the building

Elements such as heat transfer coefficient in glass and window frame, sunlight transmission coefficient, and shading elements are among the determinants of the effect of building windows on the amount of energy consumption. Therefore, it is necessary to have functional features related to the openings in the building, canopies, the optimal ratio of the windows to the walls, and different directions and fronts to minimize the amount of energy consumption in different weather conditions and climates. The directions of windows affect the amount of sunlight during the day and in different years; hence, a building should have different ratios of different sizes and different areas of windows to walls in different directions. Therefore, the ratios of the areas of windows and openings to the surface of the walls are variable and can be changed in Design Builder software [34]. In the Sheikh Lotfollah Mosque building, 16 openings are installed as windows in the interior space of the nativity scene according to field observations and referring to architectural plans. The input data of the software are taken into account. The dimensions of the valves are 2 meters wide and 2.20 cm high all around the grave part of the mosque. These valves are arched with a rectangular base.

7-7- The type and amount of air conditioning equipment in the building

Entering air conditioning equipment information is a difficult part of working with most simulation software for architects and designers. Given the direct effect that air conditioning systems have on providing thermal comfort to building residents and the amount of energy consumption in the building, it is mandatory to define the characteristics of air conditioning equipment in most energy simulation software to carry out energy simulation, but in some other software, one of the default systems can be selected for the software [35].

7-8- Cooling, heating, and air conditioning systems

In this part of the software input, all systems such as mechanical ventilation, cooling systems, and heating are considered to be on because ventilation occurs mechanically in similar buildings in Isfahan city. There are two ways to compare samples in terms of reducing energy consumption. One of these methods covers all equipment, including cooling, heating, lighting, and hot water consumption. In the second method, only the amounts of heating and cooling energy consumption are mentioned. In this research, the second method is used and the cooling and heating energy consumptions are used as a basis for comparing the hypotheses. According to the long-term statistical evaluations of the years (1951-2015) in Isfahan city, the average temperature is 3°C in the coldest month of the year (i.e. January), and 29.5°C in the hottest month of the year (i.e. July), and the highest air temperature is 43 ºC in the hottest day of the year. Summer starts at the beginning of April and lasts until the end of October. In addition, its average relative humidity is from 14% to 42% in summer and 42% to 80% in winter, and the maximum number of sunny hours is 350 hours in July and the minimum number of sunny hours is 199 hours. The total average annual sunny hours is equal to 3274 hours in Isfahan. The annual average speed of prevailing winds is about 2.5 m/s, and the prevailing wind direction is east in the summer months of this city, and west in other seasons. Other factors, which affect the amount of energy consumption of the building, are mentioned in this section of research. The upcoming test determines the canopy performance on the grave valves. Even though the sunlight entering through windows affects the amount of energy consumption, and the location of Isfahan City in a hot and dry climate, it is more important to pay attention to these issues. The protrusion amount on the gate valves of Sheikh Lotfollah Mosque was assessed in this section. Table 4 and Figures 8-9 show the window canopy protrusion of 0.5, 1, 1.5, and 2 meters in all directions and the modeling of these sizes, as well as the canopy according to Appendix 10 (Section 19 of the National Building Regulations specific to Isfahan).

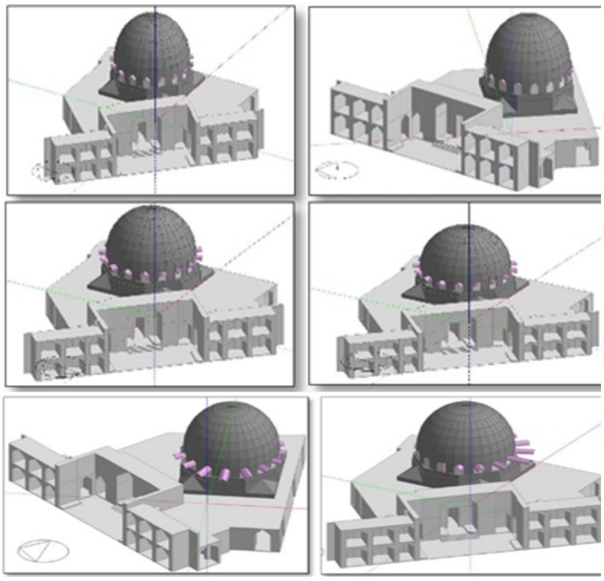


Figure 8. The windows protrusion simulation in the sample building (from left to right) equal to 0.5, 1, 1.5, and 2 meters according to the national building regulations, Section 19 using the Design Builder software

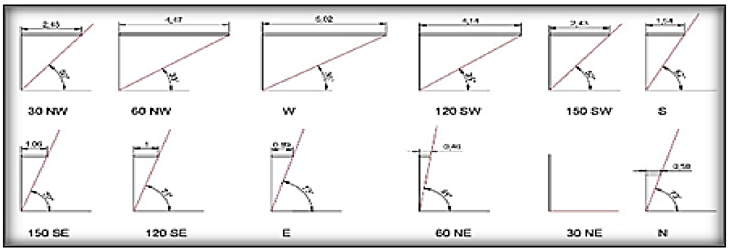


Figure 9. a Schematic view of canopy overhang according to Appendix 10 of the National Building Regulations, Section 19, in different views

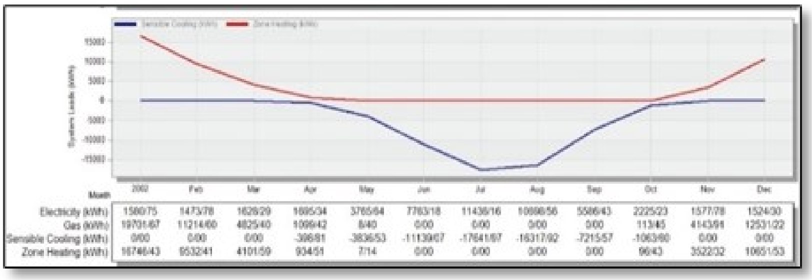
Table 4. The amount of canopy protrusion on different sides of the building in Isfahan

Window direction	**North**		**30 degrees northeast**		**60 degrees northeast**		**East**		**120 degrees southeast**		**150 degrees southeast**	
Canopy angle	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**
	w73	-	-	-	-	81	-	73	-	71	-	70
Window direction	**South**		**150 degrees southwest**		**120 degrees southwest**		**West**		**60 degrees northwest**		**30 degrees northwest**	
Canopy angle	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**	**Horizontal**
	-	62	-	50	-	35	-	30	-	33	-	50

In this building, there are 16 vents in the grave shell and they are implemented in the existing condition. The hatches or openings of the Sheikh Lotfollah mosque do not have canopies, indicating the importance of the canopies in the mosque and the impact of the canopies on the consumption of heating and cooling energy, as well as the thermal comfort of the worshipers. The architects of this building considered the important aesthetic basis of the building without a canopy. While observing the aesthetics of the exterior of the mosque and its overall form, they paid attention to its architectural proportions and created a good appearance. Using the energy simulation, we can get the values of different canopy states with the protrusions of windows located in the grave for reducing energy consumption. Each different state is shown schematically. Then, it is presented separately to simulate the amount of energy consumption. According to the previous results from the current situation in the amount of energy consumption, the amounts of cooling and heating energy consumption were obtained in hot and cold months separately, and it was decided that July, as the hottest month, and January, as the coldest month, should be examined and these two months should be considered as a comparative criterion between the states.

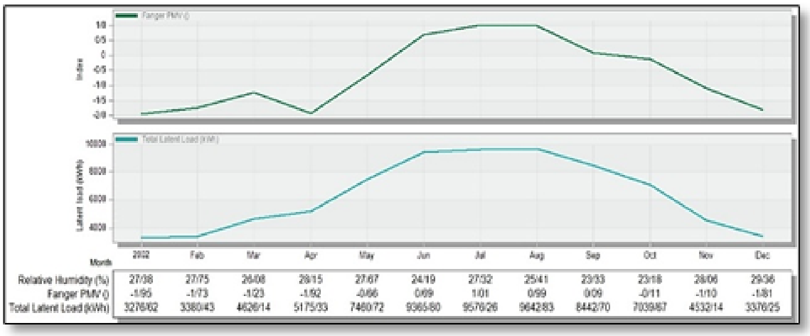
8- Discussion and Conclusion

In this research, it was determined that when the mosque architecture was based on logical principles and rules and in line with the natural desires of humans in harmony with the nature and climate of the region, and provides a beautiful and relaxing space for worshipers, it would result in significant savings in mosque costs due to the use of existing natural factors (wind, water, sun energy). The present research indicated energy saving through natural ventilation using wind renewable energy. The analysis of graphs showed that about half of the ambient weather conditions in summer could be provided using passive techniques. Natural ventilation has a significant effect on the improvement of the thermal comfort process in buildings. Going through the process of solving the thermal comfort between the mosque before and after benefiting from passive natural ventilation techniques led to a reduction of 2.28 ºC in the air temperature at a distance of 0.5 m from the surface of the mosque floor and an increase in the air speed inside the mosque by 3. The above speed and pressure simulation results can be confirmed as the higher speed and pressure difference increase the coolness in the dome roof and the heat transfer coefficient depends on the intensity and speed of the air (Figure 20). Further, this research investigated the canopy performance on the vents and the amount of building energy consumption with changes in the amounts of canopy protrusion, consumption of cooling and heating, and the amount of one-year thermal comfort (Figures 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19). In the model process, the Sheikh Lotfollah Mosque structure was modeled in different states with protrusion amounts of 0.5, 1, 1.5, and 2 meters in all directions. The canopy was according to appendix 10 of topic 19 of the national regulations specific to Isfahan city. Further, all other cases between different fixed and common states were considered.



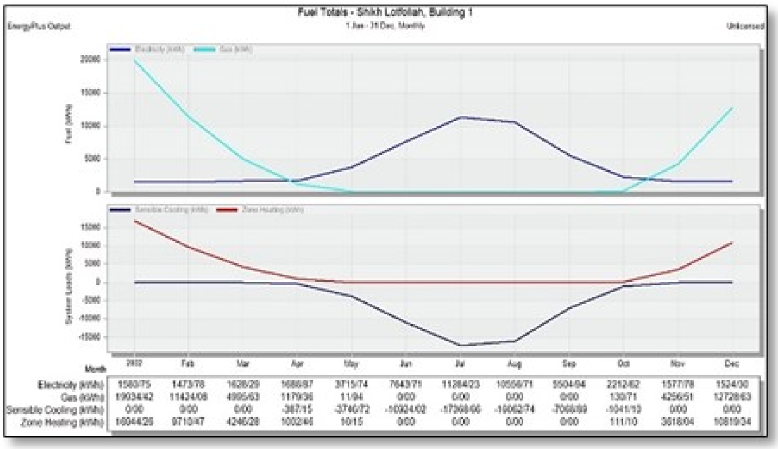
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity (kWh)	1580/75	1473/78	1628/29	1695/34	3765/64	7763/18	11436/16	10698/56	5586/43	2225/23	1577/78	1524/30
Gas (kWh)	19701/67	11214/60	4825/40	1099/42	8/40	0/00	0/00	0/00	0/00	113/45	4143/91	12531/22
Sensible Cooling (kWh)	0/00	0/00	0/00	-396/81	-3836/53	-11139/07	-17641/97	-16317/92	-7215/57	-1063/60	0/00	0/00
Zone Heating (kWh)	16746/43	9532/41	4101/59	934/51	7/14	0/00	0/00	0/00	0/00	96/43	3522/32	10651/53

Figure 10. The graph of heating and cooling energy consumption in the sample building regarding the canopy with a protrusion of 0.5 meters in the graphic form



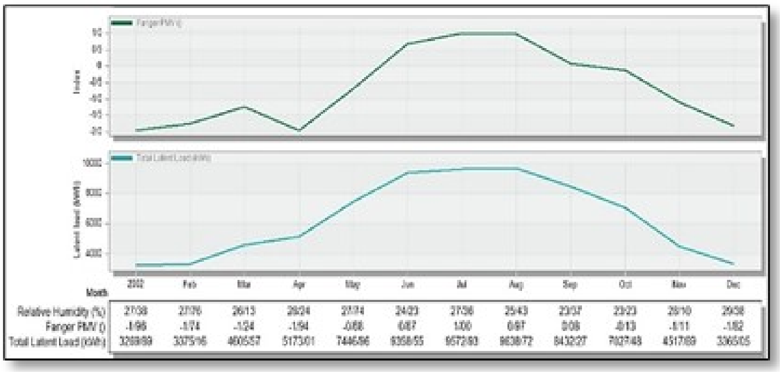
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Relative Humidity (%)	27/38	27/75	26/08	28/15	27/67	24/19	27/32	25/41	23/33	23/18	28/06	29/36
Fanger PMV ()	-1/95	-1/73	-1/23	-1/92	-0/66	0/69	1/01	0/99	0/09	-0/11	-1/10	-1/81
Total Latent Load (kWh)	3276/02	3380/43	4626/14	5175/33	7460/72	9365/80	9578/26	9642/83	8442/70	7039/67	4532/14	3376/25

Figure 11. The graph of one-year thermal comfort in the sample building regarding the canopy with a protrusion of 0.5 meters in the graphic form



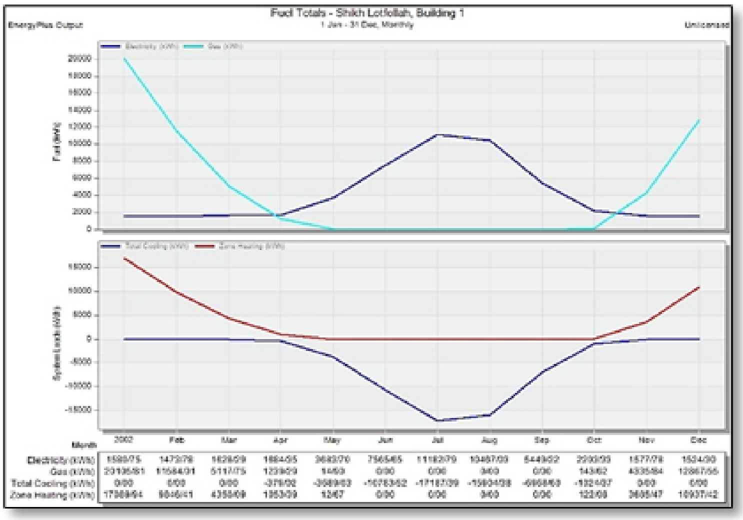
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity (kWh)	1580/75	1473/78	1628/29	1686/87	3715/74	7643/71	11284/23	10556/71	5504/94	2212/62	1577/78	1524/30
Gas (kWh)	19034/42	11424/08	4995/63	1170/36	11/94	0/00	0/00	0/00	0/00	130/71	4256/51	12728/63
Sensible Cooling (kWh)	0/00	0/00	0/00	-387/15	-3740/72	-10924/02	-17368/66	-16062/74	-7068/89	-1041/13	0/00	0/00
Zone Heating (kWh)	16044/26	9710/47	4246/28	1002/46	10/15	0/00	0/00	0/00	0/00	111/10	3818/04	10819/34

Figure 12. The graph of heating and cooling energy consumption regarding the canopy with a 1-meter long protrusion in the graphic form



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Relative Humidity (%)	27/38	27/76	26/13	28/24	27/74	24/23	27/36	25/43	23/37	23/23	26/10	29/38
Fanger PMV ()	-1/96	-1/74	-1/24	-1/94	-0/68	0/87	1/00	0/97	0/08	-0/13	-1/11	-1/82
Total Latent Load (kWh)	3269/89	3375/16	4605/57	5173/01	7446/96	9358/55	9572/93	9638/72	8432/27	7027/48	4517/69	3365/05

Figure 13. The graph of one-year thermal comfort in the sample building regarding the canopy with a protrusion of 1 meter length in the graphic form



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity (kWh)	1580/75	1473/78	1628/59	1884/05	3683/70	7565/65	11182/79	10487/03	5449/02	2200/93	1577/78	1524/30
Gas (kWh)	20135/81	11584/31	5117/75	1239/29	14/69	0/00	0/00	3/60	0/00	143/62	4335/84	12867/56
Total Cooling (kWh)	0/00	0/00	0/00	-379/02	-3589/03	-10783/52	-17187/39	-15934/38	-6958/63	-1324/07	0/00	0/00
Zone Heating (kWh)	17369/94	9846/41	4358/09	1353/39	12/67	0/00	0/00	3/60	0/00	122/08	3695/47	10937/42

Figure 14. The graph of heating and cooling energy consumption in the sample building regarding the canopy with a protrusion of 1.5 meters in the graphic form

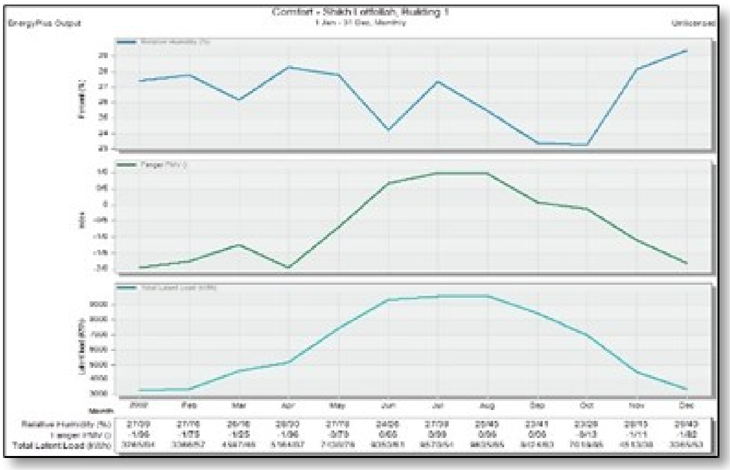


Figure 15. The graph of one-year thermal comfort in the sample building regarding the canopy with a protrusion of 1.5 meters in the graphic form

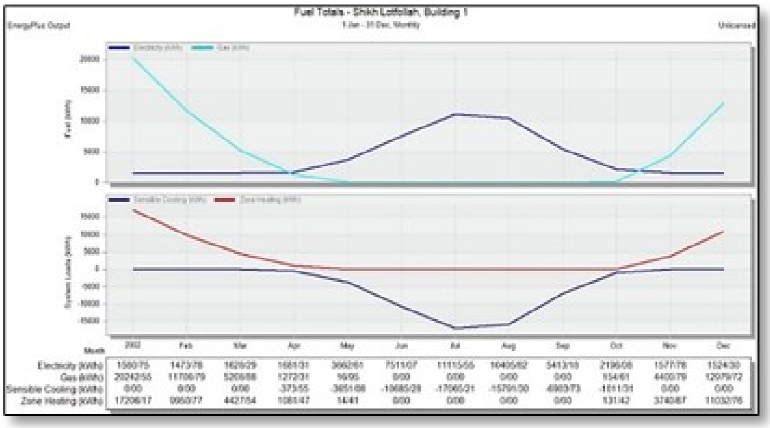


Figure 16. The graph of heating and cooling energy consumption in the sample building regarding the canopy with a protrusion length of 2 meters in the graphic form

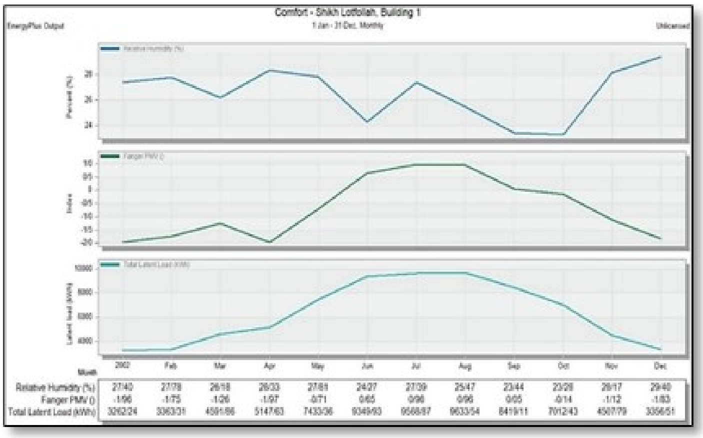


Figure 17. The graph of one-year thermal comfort in a sample building with a 2-meter overhanging canopy in the graphic form

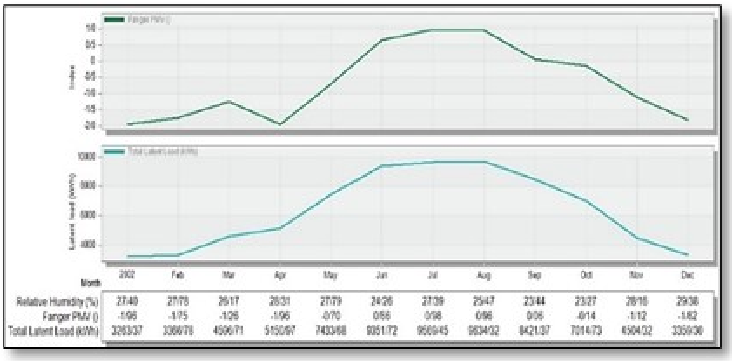


Figure 18. The graph of heating and cooling energy consumption in the sample building regarding the canopy in accordance with the national building regulations in the graphic form

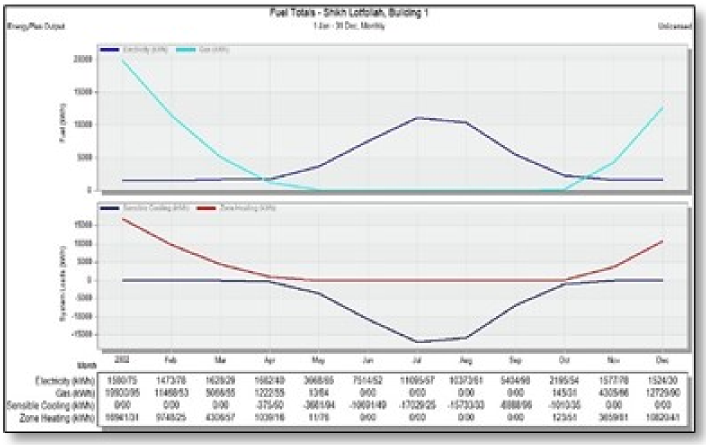


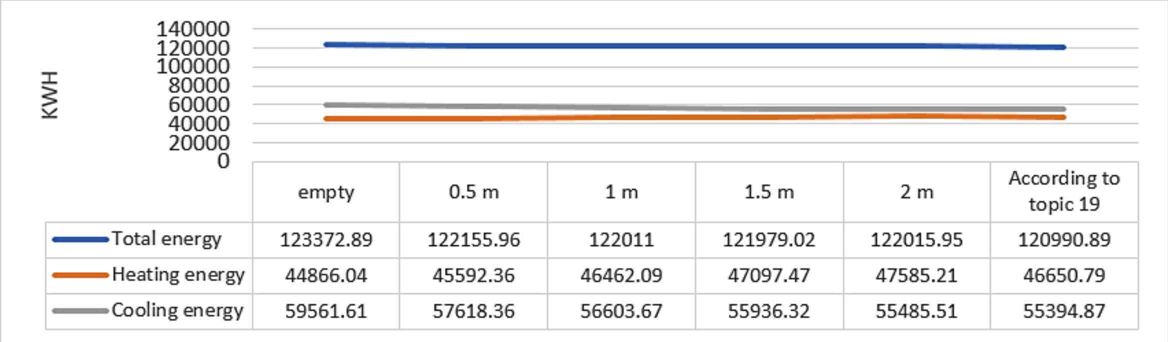
Figure 19. The graph of one-year thermal comfort in a sample building regarding the canopy in accordance with the national building regulations in the graphic form

The hypothesis of canopy protrusion was specifically investigated. Based on simulations, the amounts of total energy consumption and heating and cooling consumption in the cold and hot months were obtained in each case. According to Table 5, as the amount of protrusion of fixed canopies increases up to 1.5 meters, the amount of total energy consumption decreases, and if the amount of protrusion is greater than 1.5 m, the amount of total energy consumption increases gently.

Table 5. Temperature changes and thermal comfort using a canopy with different protrusions

Awning sizes	**Basic building**	**According to Topic 19**	**2m**	**1.5 m**	**1m**	**0.5m**
July air temperature	28.55	28.45	28.46	28.46	28.48	**28.5**
January air temperature	16.35	16.33	16.34	16.34	16.34	**16.35**
July thermal comfort index	1.05	0.98	0.98	0.99	1	**1.01**
Thermal comfort index of January	-1.95	-1.96	-1.96	-1.96	-1.96	**-1.95**

The results obtained from the canopies with sizes simulated according to the national regulations indicate a significant reduction in energy consumption compared to other cases. If this issue is looked at specifically, the obstruction from the arrival of sunlight from the east, south, and west decreases energy consumption in the cooling and heating sectors. Regarding the temperature conditions of the hottest and coldest months of the year, if the awnings are installed in the most optimal mode, the air temperature decreases. Figure 20 shows changes in the thermal comfort index of users and worshipers. Based on this diagram, if the optimal canopy is installed, the thermal index will be more bearable in the hot months and the conditions will be a little more difficult in cold months.



	empty	0.5 m	1 m	1.5 m	2 m	According to topic 19
Total energy	123372.89	122155.96	122011	121979.02	122015.95	120990.89
Heating energy	44866.04	45592.36	46462.09	47097.47	47585.21	46650.79
Cooling energy	59561.61	57618.36	56603.67	55936.32	55485.51	55394.87

Figure 20. Diagram of the total amount of energy consumption, cooling, and heating in the base building with a canopy with different protrusions

After simulating the building with protrusion sizes of 0.5, 0.5, 1, 1.5, and 2 meters according to Appendix 10 of Article 19 of the National Building Regulations, their energy consumption was analyzed. According to the results, the canopies can contribute to reducing the total energy consumption and the cooling energy consumption; however, there is an increase in heating energy consumption in all cases. The best case is according to the standard provided by Isfahan according to Appendix 10, topic 19 with the highest optimization in the cooling section. The outputs of indoor air speed indicate that the canopy does not have much effect on the indoor air speed, and it reduces the cooling energy consumption simply because of the prevention of sunlight. According to the results, changes in air temperature in canopies are mostly manifested in the surroundings and under the vents and do not contribute greatly to the desirability of the interior space (Figure 20).

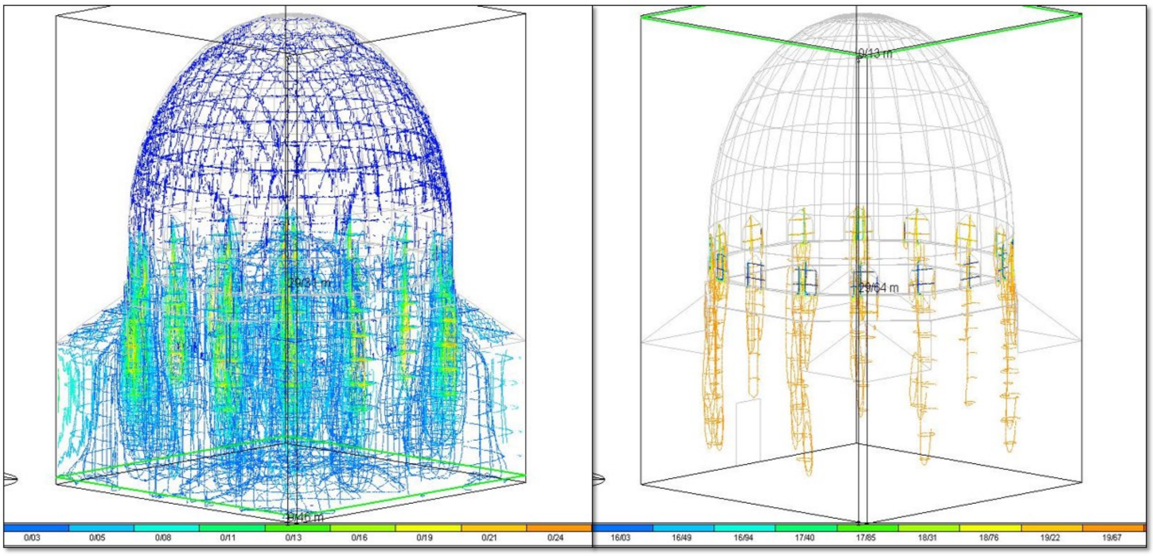


Figure 20. (From right to left)- Indoor air temperature distribution and flow velocity in the building with a canopy using Design Builder software

The most optimal and most responsive mode was selected in the evaluation of the canopy protrusion amount. It was simulated on the base model. Therefore, the energy consumption amount varied in winter and summer, and the energy consumption of the whole building decreased. In the winter, the prevailing weather conditions in January decreased thermal comfort but in the summer, the conditions related to July caused more changes to establish the thermal comfort level. It should be noted that the non-use of the window awning according to Appendix 10 of Chapter 19 by the architect of Sheikh Lotfollah Mosque in the past did not indicate an executive error in his work because according to conditions and requirements of the time, they paid attention to issues such as aesthetics, creating bright shadows, and spiritual sense other than variables in this research. For the construction of new buildings with today's emotional, climatic, structural, and architectural conditions, it is suggested to use this mode of energy saving. In today's situation with noise and air pollution, resulting from the use of vehicles and factories, we can expect that researchers will look for a solution to establish a building's thermal comfort and energy consumption, and heating in winter, and suggest a solution to filter air pollution.

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