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Research Article

A NUMERICAL INVESTIGATION OF THE HEATING OF A 3D MOSQUE MODEL USING PANEL RADIATORS

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ABSTRACT

There are a lot of mosques which have panel radiators for heating purposes since this method is very common in Turkey. In this study, the effect of the efficiency of panel radiators, which are used for heating mosque, was investigated numerically using the STAR CCM+ software. The 3D mosque model which has a 20x20 m floor area and 29.5 m dome height is used for modelling. The temperatures of the radiators are kept at 60 °C. The temperature distribution is investigated at the end of 1 and 1.5 hours. The heating of the volume of space in which worship takes place, which is less than ~2 m in height, can be achieved after the other volume is heated. Given that the heating takes a long time, there are large differences in temperature between these volumes. Therefore, this study has proved numerically that the use of radiators for heating of mosque in heating of mosques of a large internal volume is absolutely unsuitable.
Keywords: Heating, hot-water panel radiator, Energy efficiency, CFD.

1. INTRODUCTION

The most common energy source is fossil fuel and need for energy is increasing rapidly day-by-day. Furthermore, greenhouse gas emissions which are caused by conventional energy sources, is the most important cause of global warming and climate change [1]. Therefore, it is of great importance to use energy efficiently in a country like Turkey which is dependent on energy from external sources. Sometimes, it is possible and easy to get huge energy gains with the insignificant alterations to working practices.

In terms of thermal comfort, the living environment should satisfy the thermal comfort conditions described in ASHRAE standard 55 [2], EN 15251 [3] and ISO 7730 [4]. In Turkey, it is necessary to heat buildings because the temperature is mostly below a comfortable level in winter, fall and sometimes spring. The energy used for the heating the living environment makes up 26 percent of the total energy consumption in Turkey [5]. Heating with the panel radiators is one of the most common heating methods. These types of radiator are commonly used due to their high thermal power, aesthetic appearance, ease of installation and low cost/life ratio [6].

The panel radiator is also frequently used for large atrium buildings such as mosques for practical reasons. In many mosques it is possible to see panel radiators. In some mosques, it can be seen that panel radiators have been installed, but never or very rarely used. This can be due to

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such reasons as not having sufficient knowledge of other heating systems, putting the system into place without planning and calculating their use, not having enough knowledge about energy efficiency etc.

Sevilgen and Kilic [7] performed numerical thermal comfort measurements of a manikin in a room heated by two-panel radiators. They pointed out that thermal comfort can be improved in addition to energy savings by using better-insulated outer walls and windows. Kibar [8] investigated numerically the thermal efficiency of a radiator in a room in terms of obstacles such as the niches around the radiator. A similar experimental study was done by Brady et al. [9] and Ucler et al. [10]. These studies indicated that the efficiency of the radiator may be affected by the covers around the radiator. Faghih [11] studied the thermal efficiency of dome-shaped buildings such as mosques. They stated that in thermal terms a dome-shaped ceiling has a better performance than a flat one. Horikiri et al. [12] studied numerically the indoor thermal comfort of a room with a heat source, furniture and occupants. They noted that there was little difference in terms of temperature between a furnished and an unfurnished room. Noman et al. [13] studied the thermal comfort inside the mosque in terms of ventilation system. They stated that the most effective strategy to improve the thermal comfort inside the mosque is to install exhaust fans above the windows on the west-side wall. Ibrahim et al. [14] investigated the thermal comfort conditions in the mosque. They indicated that the thermal comfort inside the mosque can be improved by using thermal insulation on the roof. In the literature, thermal comfort studies with regard to mosques are mostly made for hot zones where the indoor environment must be cooled. Therefore, there are many studies of the solar radiation effect on a domed roof [15], carbon dioxide and volatile organic compounds [16] and HVAC operations [17] etc. However, the heating of mosques to ensure thermal comfort has received less attention.

The objective of this study is to investigate the efficiency of panel radiators for the heating of large atrium buildings using the computational fluid dynamics. For this purpose, temperature distribution is examined in a 3D mosque model.

2. MESH AND BOUNDARY CONDITIONS

In this study, the heating of a 3D mosque model is investigated numerically using the STAR CCM+ software to examine the efficiency of panel radiators. Figures 1a and 1b show the geometry of the 3D model and the location of the radiators, respectively. The floor area, the height of the dome, and total volume of the model are 20x20 m, 29.5 m and 8885 m^3, respectively. The model has 4 small domes at the corners with a radius of 3.58 m around a big dome which has a radius of 8.75 m. The windows are 20 cm from the inside wall. For the radiators, 12 rectangular prisms of 2x0.6x0.12 m in dimension were subtracted from the 3D domain (Figure 1b). The radiators are located 30 cm above the floor and 10 cm away from the wall. For the modelling, 32 windows, 1 door and 1 mihrab (prayer niche) with 6.5, 12 and 4.75 m^2 of surface area respectively were used.

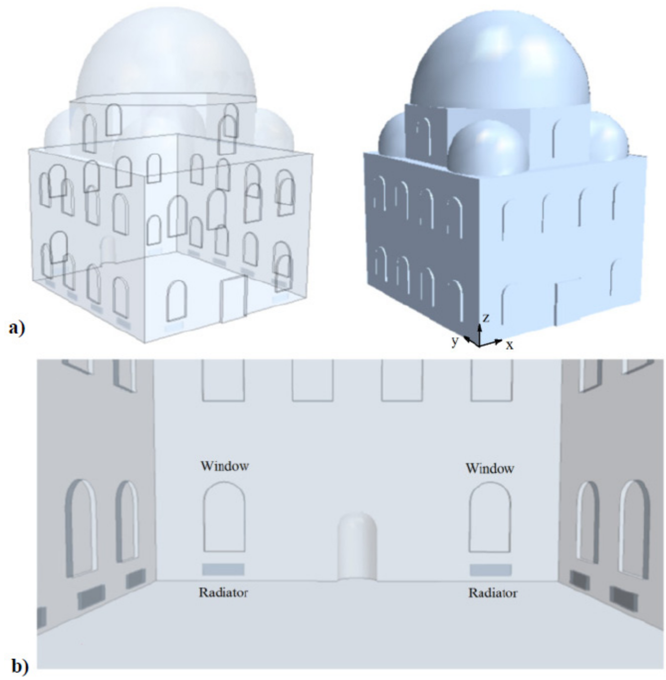

Figure 1. a) 3D domain, **b)** location of the radiators.

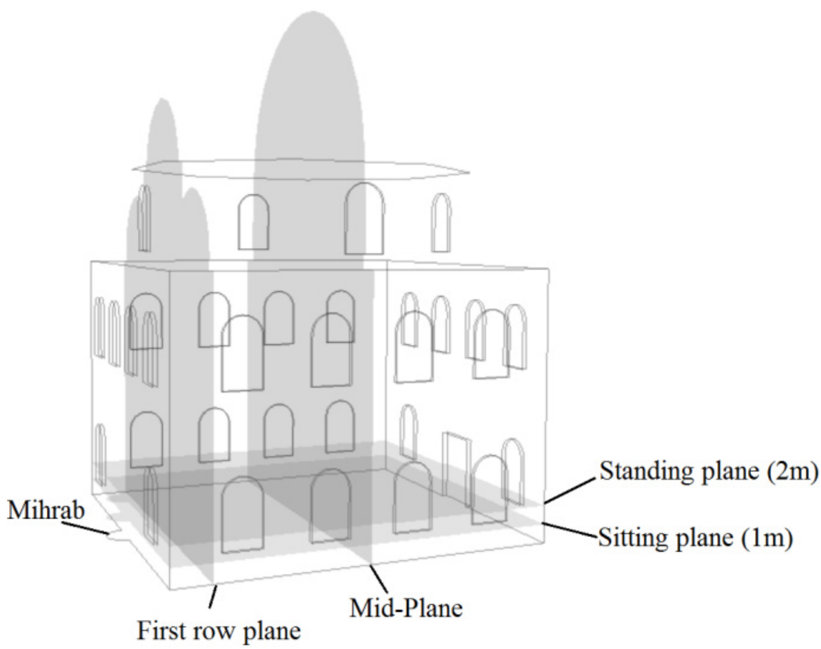

Figure 2. Planes on the models used to analyze temperature distribution.

Figure 2 shows the vertical and horizontal planes which are used to analyze the results. There are two cases considered people standing and sitting on the floor during worship in the mosque. The sitting and standing planes are considered at the height of 1 and 2 m, respectively. During the daily worship, the sequence of the prayer is mostly stated at the first row. Therefore, the first row is considered to show the data using the first plane, as shown in Figure 2. It is 2 m away from the front wall where the mihrab is located. The mid-plane is in the middle, between the door and the mihrab, that is, 10 meters away from each other. The mihrab is where the imam leads the prayers, as shown in Figure 2.

Figure 3 shows the mesh used for the simulation. The mesh structure of the model consists of 11.773.630 hexahedral cells. The largest and lowest sizes of the hexahedral elements are 20 cm and 4 cm, respectively. The temperatures of the windows and door were fixed at 15 °C. The temperatures of the radiators were fixed at 60 °C throughout the analysis. All the other surfaces including walls, edges of the windows, door and all domes and floor, are considered as adiabatic. The initial temperature and pressure of the domain are determined as 15 °C and 1 atm., respectively. The time step is determined as 1 second.

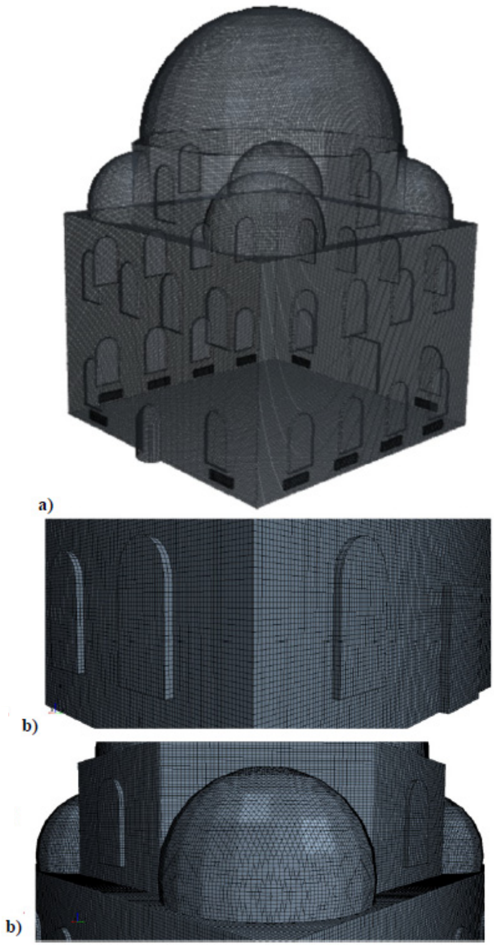

Figure 3. a) The transparent appearance of the mesh**, b)** the mesh of the small domes and walls.

3. MODELLING

Incompressible Navier–Stokes equations with the buoyancy force are solved numerically to determine the heating effect with regard to a 3D mosque model. The Boussinesq approximation is used for the buoyancy term. The differences of the fluid densities caused by the differences in temperature are used for this approximation. The ideal gas is used as the fluid. Thus, natural convection is provided by the change in the fluid density, depending on the temperature. The buoyancy force term is estimated according to Boussinesq model as a flow [18]:

$$F_g = \rho g \beta \left(T_{ref} - T\right) \tag{1}$$

where β is the thermal expansion coefficient, T_{ref} is the operating temperature, ρ and g are the density and gravitational acceleration in a (–z) direction, respectively. There is no fluid entrance and exit to the system since it is considered as being a closed system. The fluids physical properties are determined as a constant, except for the buoyancy force term. The conservation equations of the continuity (Equation (2)), momentum (Equation (3)) and energy (Equation (4)) are the governing equations of the simulation.

Continuity equation:

$$\frac{d(\rho)}{dt} + \nabla \cdot (\rho \vec{v}) = 0 \tag{2}$$

Momentum equation:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.(\rho \vec{v}\vec{v}) = -\nabla p + \nabla.[\mu(\nabla \vec{v} + \nabla \vec{v}^T)] + f_b \tag{3}$$

Energy equation:

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(\rho \vec{v} H) + \nabla.(\vec{v} p) = \nabla\left(k_{eff} \nabla T\right) + \nabla(\overline{\tau} \vec{v}) + f \vec{v} + S_U \tag{4}$$

where $\vec{v}$, μ p and f_b are the velocity vector, the dynamic viscosity, the pressure and the external force, respectively. E and H are the total energy and total enthalpy respectively. T, $\overline{\tau}$ and k_{eff} are the temperature, the viscous stress tensor and the effective thermal conductivity respectively. S_U is the energy source.

The heat transfer occurs mostly between the panel radiator and the environment by natural convection [19]. However, a small amount of heat transfer also occurs by radiation. In the present study, the heat transfer due to natural convection is only considered, and the amount of radiation heat transfer is ignored.

The convective heat transfer from the human body or radiator (C), can be basically expressed by using Equation (5).

$$C = h_c\left(T_h - T_{h,\infty}\right) \tag{5}$$

where h_c is the convective heat transfer coefficient, T_h and $T_{h,\infty}$ are the mean temperature of the human body/radiator and the air temperature surrounding the human/radiator, respectively.

The characteristic of fluid flow (turbulent or laminar) can be determined by the Rayleigh number (Ra), which is defined as the product of the Grashof (Gr) and Prandtl (Pr) numbers:

$$Ra = GrPr = \frac{\beta g L^3 (T_s - T_{r,\infty})}{\upsilon^2} Pr \tag{6}$$

where g is the acceleration of gravity, L if the radiator height, υ is the kinematic viscosity of air, T_s and $T_{r,\infty}$ are the surface and surrounding temperatures of radiator, respectively.

The transition of fluid flow from laminar to turbulent occurs at Ra~10^9. The flow characteristic is defined as follows:

$10^4 < Ra < 10^9$ laminar flow, $10^9 < Ra < 10^{12}$ turbulent flow.

The Rayleigh number is about $6x10^8$ in the present study. Therefore, the flow is considered as laminar.

A coupled implicit solution model is used for the flow model. In this model, the continuity, momentum and energy equations are solved simultaneously, using the pseudo-time-marching approach [18]. The analysis is carried out in two stages, at 3600 and 5400 seconds. Therefore, the distribution of the temperature is analyzed another half hour after an hour.

4. RESULTS AND DISCUSSIONS

Figure 4 shows the temperature distributions of the inner surfaces of the wall at the end of 3600 and 5400 seconds. The temperature range is adjusted between 15 °C and 16 °C so that the temperature distributions can be seen in detail. Therefore, a higher temperature than 16 °C appears as red, and there is also no temperature below 15 °C. As the windows are fixed at 15 °C, their surfaces remain at 15 °C for both cases. The air rises with the increase in temperature due to contact with the radiator surface, which is set at 60 °C. Therefore, there is a dense high temperature distribution above the radiators. In particular, the rising warm air is concentrated in the small domes, as can be seen in Figure 4.

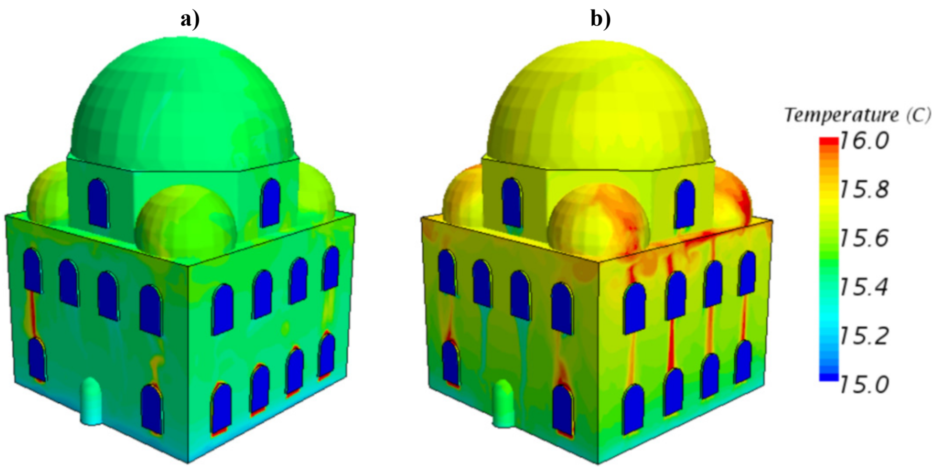

Figure 4. The temperature distributions at the inner surface of the walls at the end of **a)** 3600 s and **b)** 5400 s.

Figure 5 shows the temperature distribution in the first and mid-planes with respect to height. The occupied zone for comfort conditions is generally considered to be the volume between the floor and 1.8 m above the floor according to ASHRAE handbook [2]. Considering the environmental parameters, the most important parameters for the thermal comfort conditions are; air temperature, air velocity, air relative humidity and mean radiant temperature. As indicated in Equation (1), the air temperature surrounding the human body is important for the convective heat transfer. Furthermore, there is a great distance between the upper walls (domes etc.) and worshippers. When the radiation heat transfer is considered, it would be a little effect on worshippers. Because, the intensity of radiation is inversely proportional to the square of the distance [20]. The temperature above 2 m has no direct effect on a human being in the environment under consideration.

Worshippers spend most of the time sitting on the floor in places of worship such as a mosque. This height is less than about 1 m. As can be seen in Figure 5, the temperature distribution takes place firstly in the small domes and then secondly in the big dome. This increase in temperature is even more intense in the small domes at 5400 seconds. The temperature is at the lowest level below the 2 m height for both planes. Even though the temperature gradient is very low from 0 to 2 m, the slope increases after 2 m. The lowest temperature when the worshippers are sitting which is how most time is spent in mosques, that is at 1 m and below.

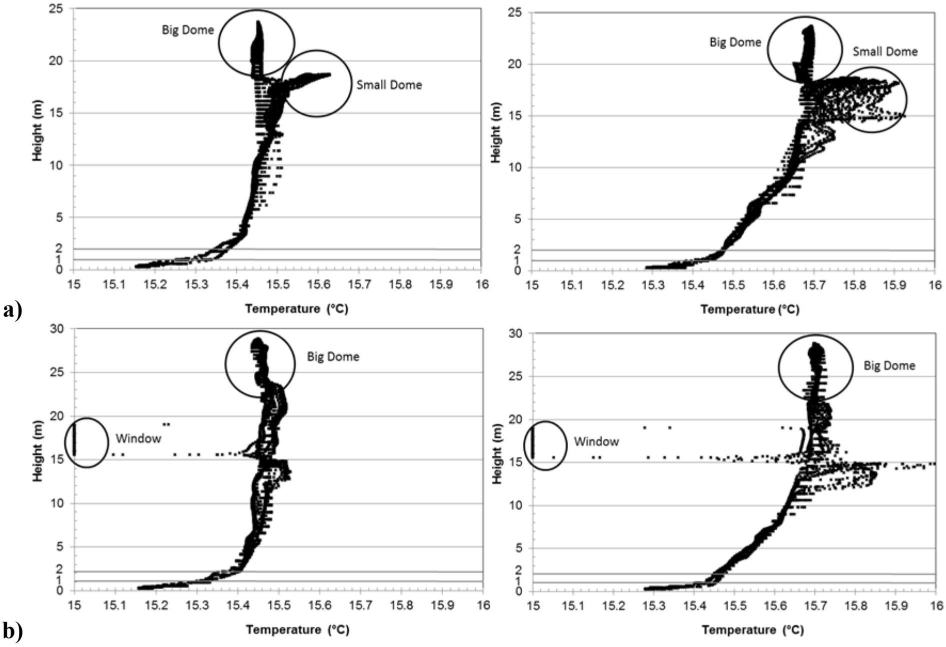

Figure 5. The temperature distribution at the end of the 3600 s and 5400 s in the a) first plane and b) mid-plane.

Figure 6 shows the temperature distributions with regard to the first plane. The highest temperatures are found around the small domes at the end of 3600 seconds, and then these higher temperatures concentrate around the big dome at the end of 5400 seconds. The hot air moves towards the floor after warming both the small dome and the big dome, as shown in Figure 6b. The mosque has a large volume and height. Therefore, the living volume is heated after the unused volume such as in the big dome and in the small domes are warmed up. Namely, the temperature of the living area starts to increase after this unused volume reaches a certain temperature. This takes a long time because of the large volume and height. In addition, this unused volume will remain at higher temperatures than the living area throughout the entire heating process.

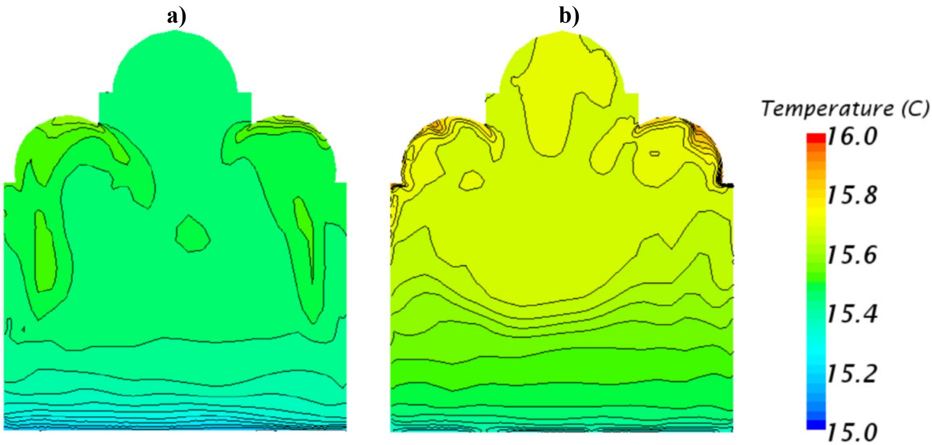

Figure 6. The temperature distribution at the end of the **a)** 3600 s and **b)** 5400 s on the first plane.

Figure 7 shows the velocity gradients on ISO surfaces at 15.5 °C. The velocity vectors in the vertical direction are only shown in this figure. As the windows are at 15 °C, the air moves down the sides of the mihrab and doors because there is no heating source (radiator). The air in contact with the radiator rises rapidly. Then, the temperature reaches 15.5 °C above the windows cavities. The air velocity in a vertical direction is high near the wall, and very slow in the middle of the mosque. This means that the warmed air rises rapidly towards the domes. This warmed air then goes down towards the floor slowly.

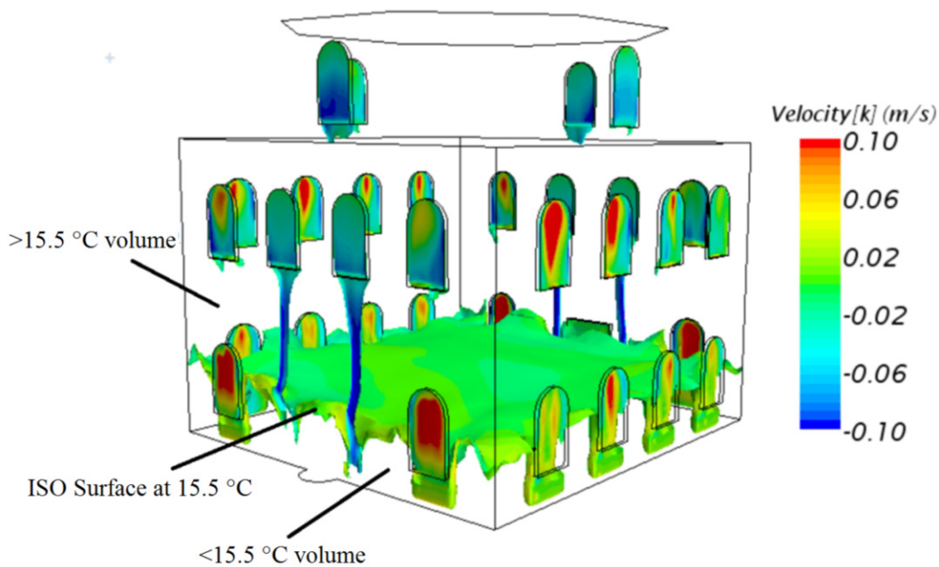

Figure 7. Velocity gradients on the ISO surface in a vertical direction at 15.5 °C after 5400 seconds. Positive and negative values indicate that the velocity vectors are up and down, respectively.

5. CONCLUSIONS

In this study, the heating of a 3D mosque model by panel radiators is examined numerically using the Star CCM+ software. There is a large unused part of in the mosque because the interior of the mosque has a very large volume and height. It takes a great deal of time to warm up this large volume. Furthermore, the heating of the living space, which is below 2 m, takes place after all these unused volumes have been heated. In this case, the heating time is extended too much to warm up the living space. Moreover, there are large temperature differences between the living space and the unused volumes. Thus, the majority of the time and the energy consumption are used for heating the unused volume.

Mosques are generally used for about half an hour a day at 5 different times of day. For this reason, they must be heated quickly to make the living environment comfortable. According to the results obtained, the use of panel radiators does not satisfy both conditions.

This study proves that heating systems using panel radiator should never be used for building with a high internal volume such as mosques.

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