Windcatcher design for natural cooling of domed mosque buildings

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Abstract

Increasing the energy efficiency of buildings such as mosques contributes to building sustainability. Windcatchers can reduce the cooling loads of the mosque space. This study aims to investigate various windcatcher designs for cooling mosque spaces in the climate conditions of Laghouat City, Algeria. Ansys-Fluent software is used to solve the governing equations consisting of mass, momentum, and energy conservation. A comparison of the numerical results with experimental and numerical results in the literature is performed for validation purposes. Various geometries are proposed for the main components of the windcatcher: windcatcher block, windcatcher inlet, and windcatcher outlet. The findings show that the windcatcher geometry significantly impacts the space cooling. The study enables us to figure out the best design (case 6) which provides optimal thermal performance. The best windcatcher design shows a significant improvement in heat transfer rate up to 28%.

Keywords: Cooling, Design, Mosque building, Windcatcher, Thermal comfort.

1- Introduction

The world has recently witnessed a great demand for energy. According to statistics, by 2050, it could rise by as much as 50% [1]. Buildings consume 40% of the total energy and contribute to almost 40% of greenhouse gas emissions worldwide [2]. Conventional heating, ventilation, and air conditioning (HVAC) systems are behind the huge energy consumption and pollution [3]. Researchers have investigated solutions for energy-efficient buildings, including natural ventilation and passive cooling systems [4].

Using windcatchers for ventilation and space cooling in arid climate zones was considered an architectural invention in the pre-mechanical air-conditioning era [5]. It was common in the Abbasid era when all hospitals were equipped with windcatchers. The windcatcher is a natural solution to thermal comfort in hot climates. It operates on the principle of suctioning cold air from elevated altitudes into structures or via subterranean ducts to facilitate heat exchange with the cooler earth [6].

Experimental and numerical studies have been dedicated to building ventilation using windcatchers. Gage and Graham [7] conducted an experimental study to evaluate the ventilation performance of two modern windcatcher designs with square (four-sided) and hexagonal cross-sections in response to various wind velocities and directions. A test chamber beneath the wind tunnel was equipped with a 1:10 scale model of two windcatcher models. The results indicated that the hexagonal cross-section windcatcher offered more consistent and dependable ventilation performance in locations with varying wind angles. Nevertheless, given the available wind conditions, the four-sided windcatcher operated efficiently at an air incidence angle of 45°. Satwiko and Tuhari [8] employed theoretical and experimental approaches to investigate a contemporary windcatcher's thermal and ventilation efficacy with a longitudinal shape specifically designed for basements in warm and humid areas. The findings indicated that the interior air circulation in the occupant's area was uniformly dispersed as a result of the longitudinal layout. Despite the absence of significant external wind, the system effectively enhanced ventilation and prevented heat accumulation inside the building. A modern windcatcher's ventilation effectiveness was examined by Farouk [9] in three alternative cross-sectional shapes: square (four-sided), circular, and hexagon. It was found that the hexagon windcatcher's ventilation was barely affected by variations in wind direction. The circular windcatcher also showed the lowest indoor air velocity and change rate. Liu et al. [10] evaluated the ventilation effectiveness of windcatchers with two alternative window positions: leeward (case 2) and windward (case 1). They determined that the ventilation rates in case 1 and case 2 were 5570 m^3/h and 2310 m^3/h, respectively. The airflow rate in case 1 was higher; however, the distribution was affected due to the short circuit caused by the wind blowing directly into the window. The windcatcher exhibited enhanced ventilation rates when a window was positioned on the leeward side, attributable to the negative pressure. The aerodynamic performance of a rectangular windcatcher with six sub-sections at various wind incidence angles was addressed by Mohamadabadi et al. [11]. CFD models and wind tunnel model experiments were employed in the study to assess the towers' performance. The findings indicated that the interconnected towers, without wind-responsive regulation, may experience a short circuit phenomenon at the base. This occurs when the incoming fresh air rapidly exits the interior without effectively mixing with the exhaust air. Balabel et al. [12] examined the impact of inlet opening angles on the geometry of a partial-cylinder windcatcher and the various tower placements within a particular building. According to their findings, the windcatcher performs better between 20.55 and 37.5% when it is behind the building because of the oncoming wind, as opposed to the other types. Higher opening angles can also yield better results. By examining the thirty-three variants of six parameters, Alsailani et al. [13] conducted an extensive parametric CFD analysis of the windcatcher topology. Out of the scenarios, there was about a 23% variation in the findings; this increased to 29% upon implementing guide vanes in the model.

An analysis of windcatcher shapes was conducted by Varela-Boydo and Moya [14]. CFD simulations were used to solve 174 cases across 28 versions. In another study, Varela-Boydo et al. [15] simulated 204 scenarios using a scale windcatcher model with 33 distinct outlet opening modifications to obtain traps that enhance the airflow and make the wind towers more effective. Abdo et al. [16] examined the impact of inlet design on airflow enhancement and the efficiency of windcatchers in a two-dimensional room setting. They revealed that, with a difference of about 3% from the uniform inlet and 8% from the bulging-convergent inlet, the divergent inlet has collected the most airflow. The same results are obtained in a three-dimensional room [17]. Bekleyen and Meli̇koğlu [18] examined the thermal impacts of windcatchers on the comfort conditions of a traditional house in Sanliurfa, Turkey. It was found that windcatchers with scoop shapes work well for capturing wind. Obeidat et al. [19] examined the association between wind velocity (V_{Tw}), fin angle (θ), and actual ventilation rate. They found a formula that quantifies the relationship between V_{Tw}, θ, and the performance of the window-windcatcher. Mohamed and El-Amin [20] performed a parametric analysis to assess different windcatcher designs regarding their dimensions, proportions, and aperture ratios. They discovered that the windcatcher reduced the air temperature on the various floors. Sangdeh and Nasrollahi [21] reviewed contemporary advancements and utilizations of windcatchers in modern architecture, emphasizing their efficacy and functionality. It highlights that height, configuration, and cross-section significantly impact the windcatcher's performance. Regions with favorable wind directions benefit more from one-sided windcatchers, whilst areas with varied wind directions benefit more from other types. They also explored the windcatchers' potential in contemporary architecture and urban planning. Zhang et al. [22] examined the impact of the dense construction of high-rise buildings in central Hong Kong on pedestrian-level airflows, resulting in stagnant airflows, reduced wind speed, and impacted thermal comfort and wind. A novel system called smart urban windcatchers employs motion-controlled billboards overseen by a deep reinforcement learning agent. The system can alter street flow direction and provide accurate instructions under different weather conditions, achieving near-optimal wind environment scores. Taufan et al. [23] reviewed various retrofitting strategies for improving the mosque building performance. The research indicated that the mosque's energy usage may be diminished by 50% via the enhancement of its design and operational procedures. Also, significant annual energy reductions were attained by implementing a zoning method that restricted the air conditioning system to a confined partitioned area. Advanced air-conditioning design and efficient cooling systems, combined with intermittent operating system management, can save energy and meet thermal comfort standards. The mosque building's performance can be substantially enhanced by integrating these strategies with appropriate operational management. Katona et al. [24] investigated the feasibility of additional enhancements in ventilation efficiency as a result of the aerodynamic design of the roof-integrated inlet structures by testing various windcatcher geometries. Heidari and Eskandari [25] demonstrated that the quality of ventilation within a building is influenced by the height of the windcatcher. They demonstrated that the airflow rate and velocity increase as the height of the windcatcher in the inlet facade increases. Kubota et al. [26] revealed that a cross-windcatcher is an appropriate solution for enhancing ventilation in mid-to-high-rise inexpensive flats in tropical regions where natural ventilation is crucial. Alwetaishi and Gadi [27] conducted a study using CFD and an actual model experiment. They found that curved designs exhibit the highest wind speed patterns, particularly those with multiple inlets. Takuwa et al. [28] utilized CFD analysis and field measurements to quantify the enhancement in the ventilation rate achieved by windcatchers. These windcatchers can augment the ventilation ratio without generating carbon dioxide (CO_2) emissions. Sakhri et al. [29] investigated the impact of a windcatcher device's one-sided position on the design of a ventilated space or structure, as well as natural ventilation performance, in the arid region of southwestern Algeria.

The literature review shows that the natural cooling of domed mosques in the presence of a windcatcher has received less attention, namely in arid zones. This study aims to investigate the thermal performance of a windcatcher for a domed mosque in the climate conditions of Laghouat City, Algeria. Various windcatcher designs are examined, including the windcatcher block, inlet, and outlet, specifically tailored for a domed mosque to enhance passive thermal comfort through natural ventilation. The thermal performance of 19 configurations is investigated. Velocity and temperature profiles are examined along with Nusselt number, airflow velocity contours, and flow streamlines.

2- Physical model and mathematical formulation

A domed mosque with a windcatcher is considered (Figure 1) for the natural cooling of indoor space. The windcatcher has two openings with the same dimension of 1.5 m at the top and bottom to enable airflow inside the mosque building. To facilitate the airflow outlet from the mosque space, two lower and upper windows were placed on the right wall of the mosque, with dimensions of Ho_1 = 1.5m and Ho_2 = 0.4m, respectively. The dimensions and boundary conditions are chosen based on a mosque in Laghouat City, Algeria. The studied cases are shown in Figure 2.

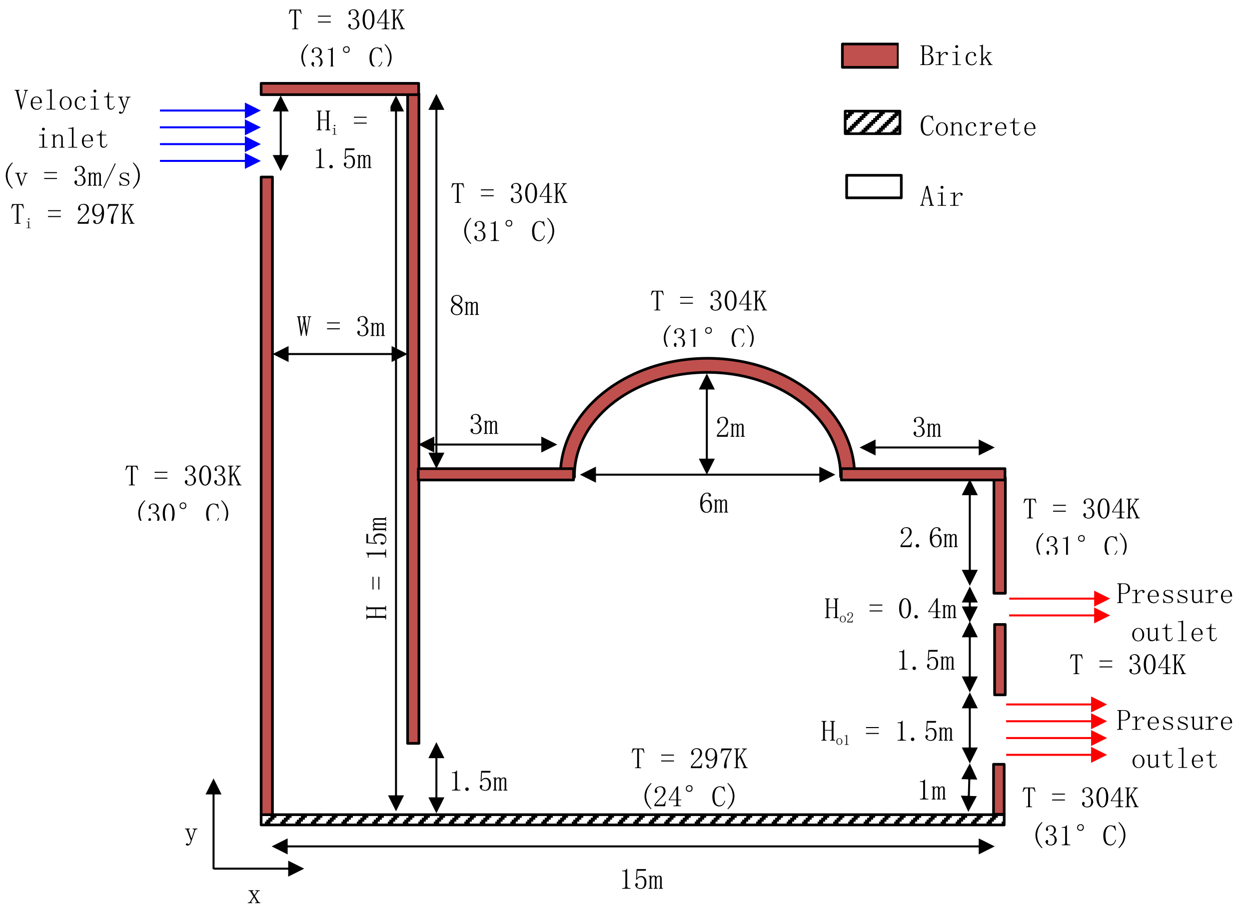
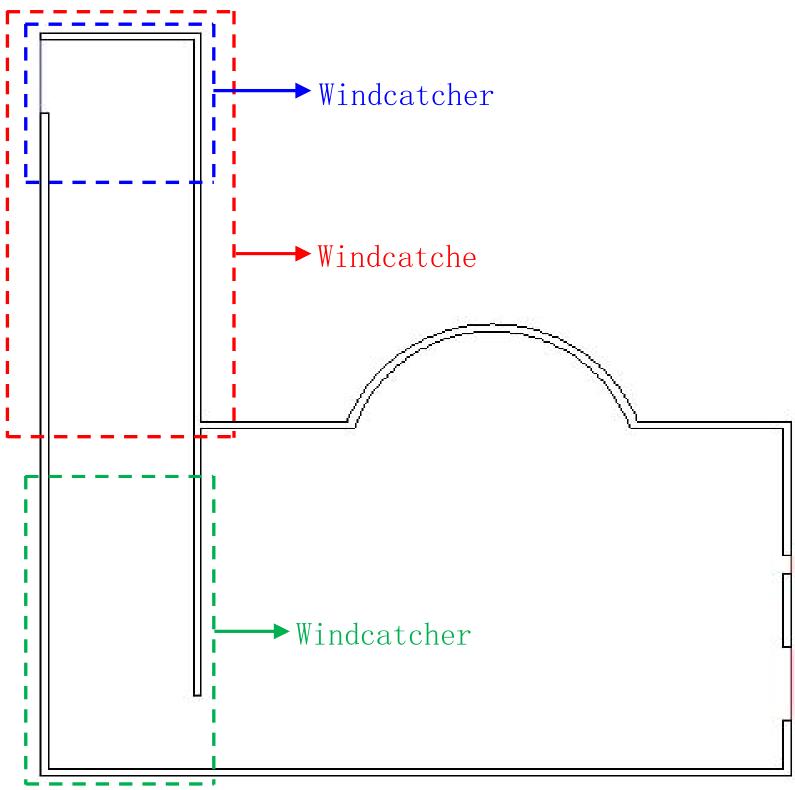
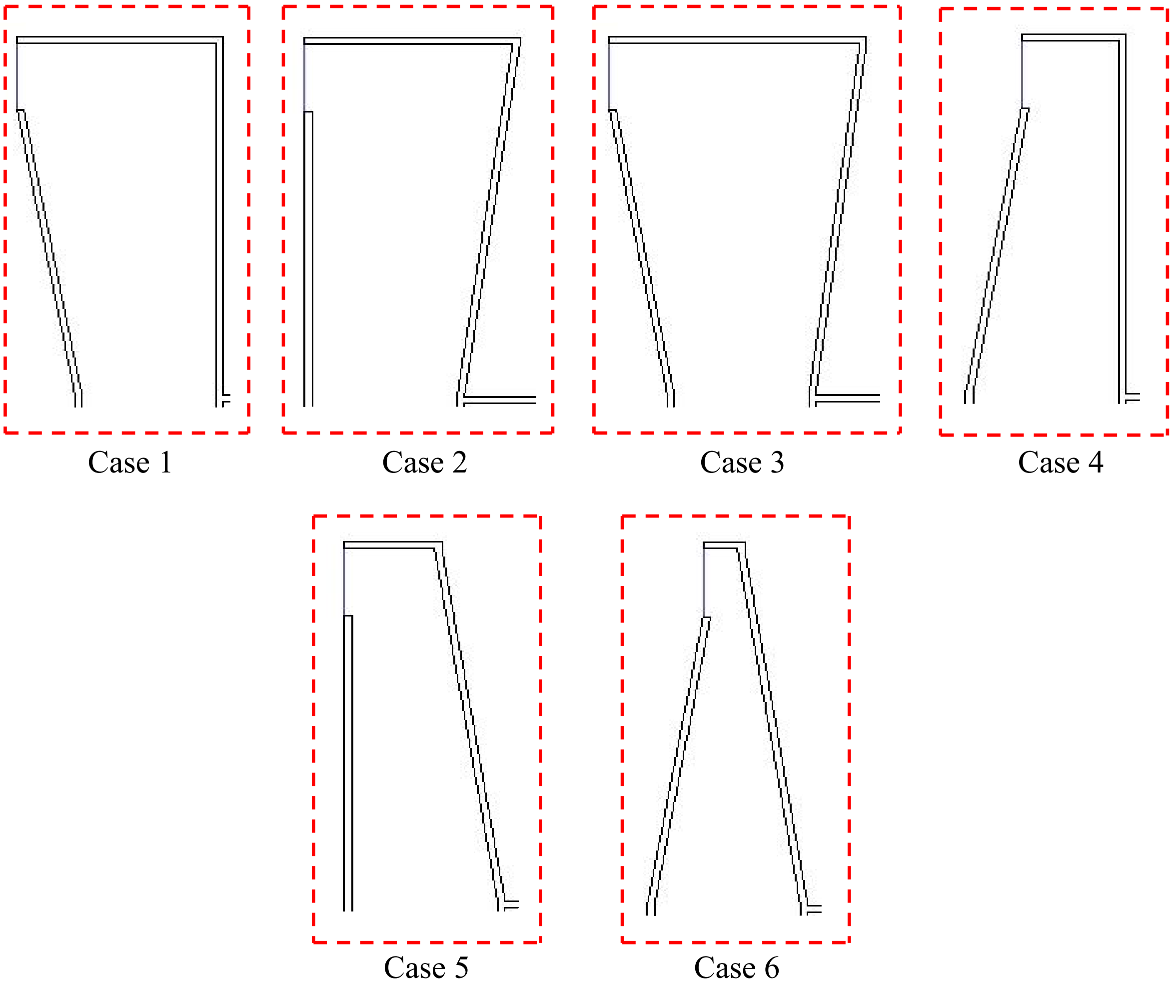


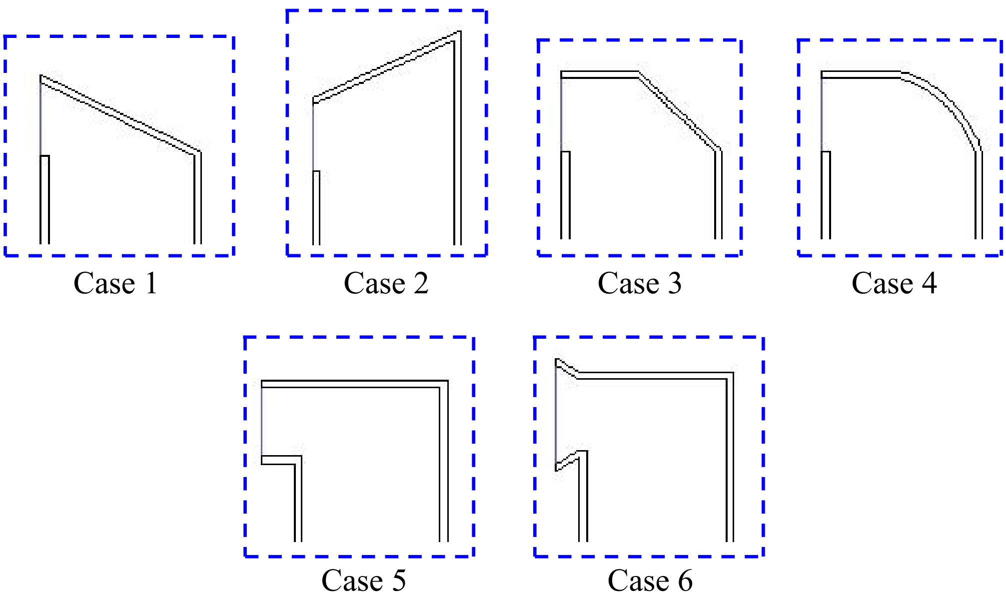
Figure 1. Computational domain with boundary conditions.



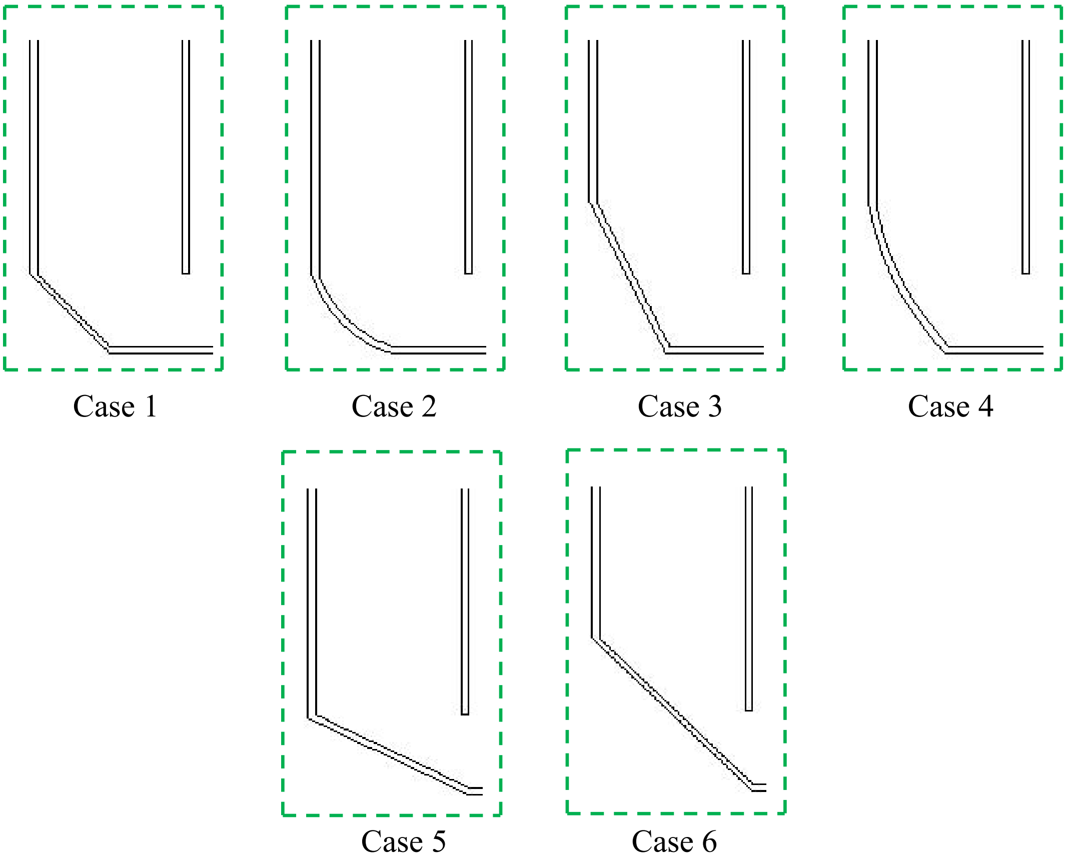
(a) Modified zones



(b) Proposed windcatcher block shapes



(c) Proposed windcatcher inlet shapes



(d) Proposed windcatcher outlet shapes

Figure 2. Physical model with proposed configurations.

The governing equations are shown below [30]:

- Equation of mass conservation:

$$\frac{\partial \rho}{\partial t}+\nabla.(\rho \vec{V})=0 \tag{1}$$

- Equation of momentum conservation:

$$\frac{\partial \vec{V}}{\partial t}+(\vec{V}.\nabla)\vec{V}=-\frac{1}{\rho}\nabla P+\nu\nabla^2\vec{V}+\vec{g}-\frac{1}{\rho}\nabla\tau_t \tag{2}$$

- Equation of energy conservation:

$$\rho C_P\left[\frac{\partial T}{\partial t}+(\vec{V}.\nabla)T\right]=k\nabla^2 T+\phi \tag{3}$$

where $\vec{g}$ is the gravitational acceleration, ν is the constant kinematic viscosity, and τ_t is the divergence of the turbulence stresses. T, k, ϕ, and C_P are the temperature, thermal conductivity, dissipation rate, and specific heat at constant pressure, respectively.

- Equation of turbulent kinetic energy [31]:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\varepsilon-Y_M+S_k \tag{4}$$

- Equation of energy dissipation rate [31]:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon \qquad (5)$$

Where G_b and G_k represent the generation of turbulence kinetic energy due to buoyancy and mean velocity gradients. Y_M stands for the overall dissipation rate. α_k and α_ε are the inverse effective Prandtl numbers for k and ε. S_k and S_ε are source terms [32].

The thermo-physical properties of the typical materials used in the studied windcatcher are shown in Table 1.

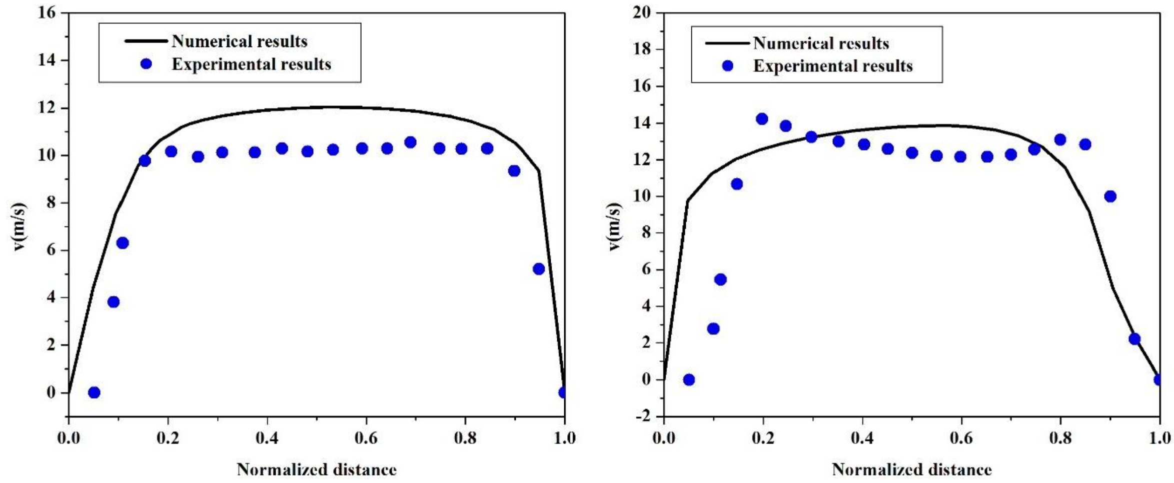
Table 1. Thermo-physical properties of materials [30].

Materials/ proprieties	$\rho(kg/m^3)$	$C_P(J/kg.K)$	$k(W/m.K)$	$\nu(kg/m.s)$	$\alpha(1/K)$
Air	1.225	1006.43	0.0242	1.7894×10^{-5}	0.001
Brick	1920	840	0.72	-	-
Concrete	2300	1000	1.13	-	-

3- Numerical procedure

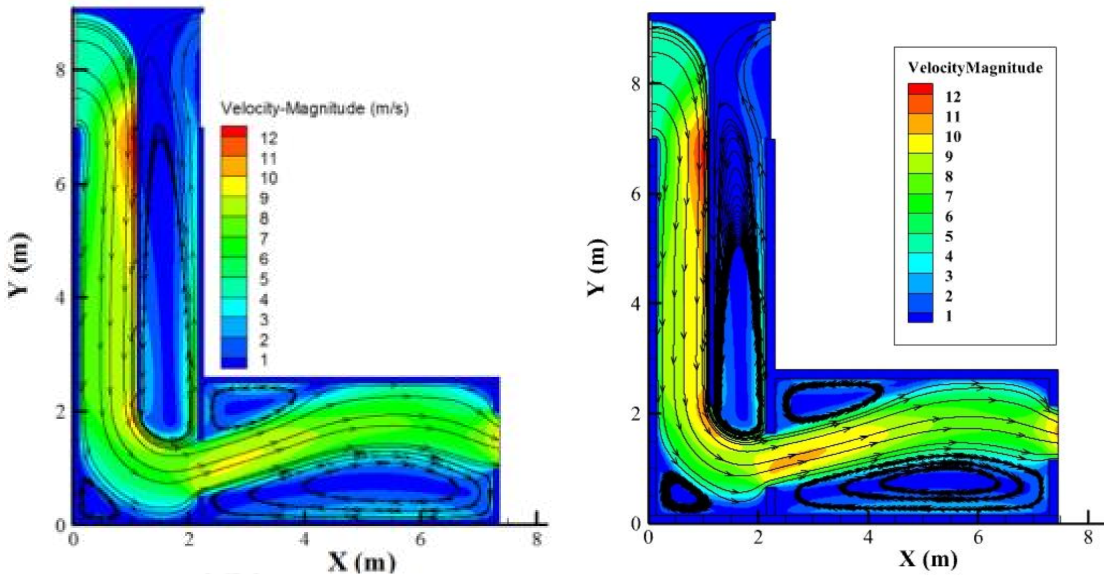
Numerical simulations for solving the above equations are performed using the Fluent CFD Software tool based on the finite volume method [33]. The studied problem is 2D in Cartesian coordinates; the flow is compressible, steady, and turbulent. The PRESTO scheme and second-order upwind approach are selected for pressure spatial discretization and spatial estimation of the momentum and energy equations, respectively. The SIMPLE method proposed by Patankar and Spalding [34] is considered to solve coupling pressure and velocity. Finally, the convergence criteria are set at 10^{-6} and 10^{-5} for energy and other equations, respectively [35]. The computer employed for simulations has an Intel Core i7, a 2.4 GHz processor, and 8 GB of RAM. The mesh size is selected to minimize the CPU time and to achieve the desired accuracy [36]. After conducting a study of grid independence, 59621 grid cells are chosen in the present simulation, which corresponds to the stability of the results.

A comparison is conducted with the experimental and numerical data from the literature to confirm the accuracy and validation of the numerical findings. The same conditions of the studied model are considered, including dimensions, boundary conditions, flow rate, wind speed, and temperature. The first comparison is made with the experimental results of Reyes et al. [37]. The authors tracked the airflow inside a windcatcher using particle image velocimetry (PIV) technology [38]. Figures. 3a and 3b display the magnitude velocity profiles at the main room entrance and outlet through the window (The normalized distance Y = y/6.2). It is noted that the numerical results have the same behavior as the experimental data of PIV measurements, with some minor differences due to the boundary conditions used in the numerical simulation. The second comparison is performed with the numerical results of Hosseini et al. [30]. The results in the form of magnitude of velocity contours are shown in Figures 3c and 3d. Excellent agreement was observed among the outcomes.



(a) Main room entrance (b) Outlet through the window

Experimental results [37].



(c) Numerical results of Hosseini et al. [30] (d) Present results

Figure 3. Comparison with previous results: experimental results of Reyes et al. [37] (a, b), numerical results of Hosseini et al. [30] (c, d).

4- Results and discussion

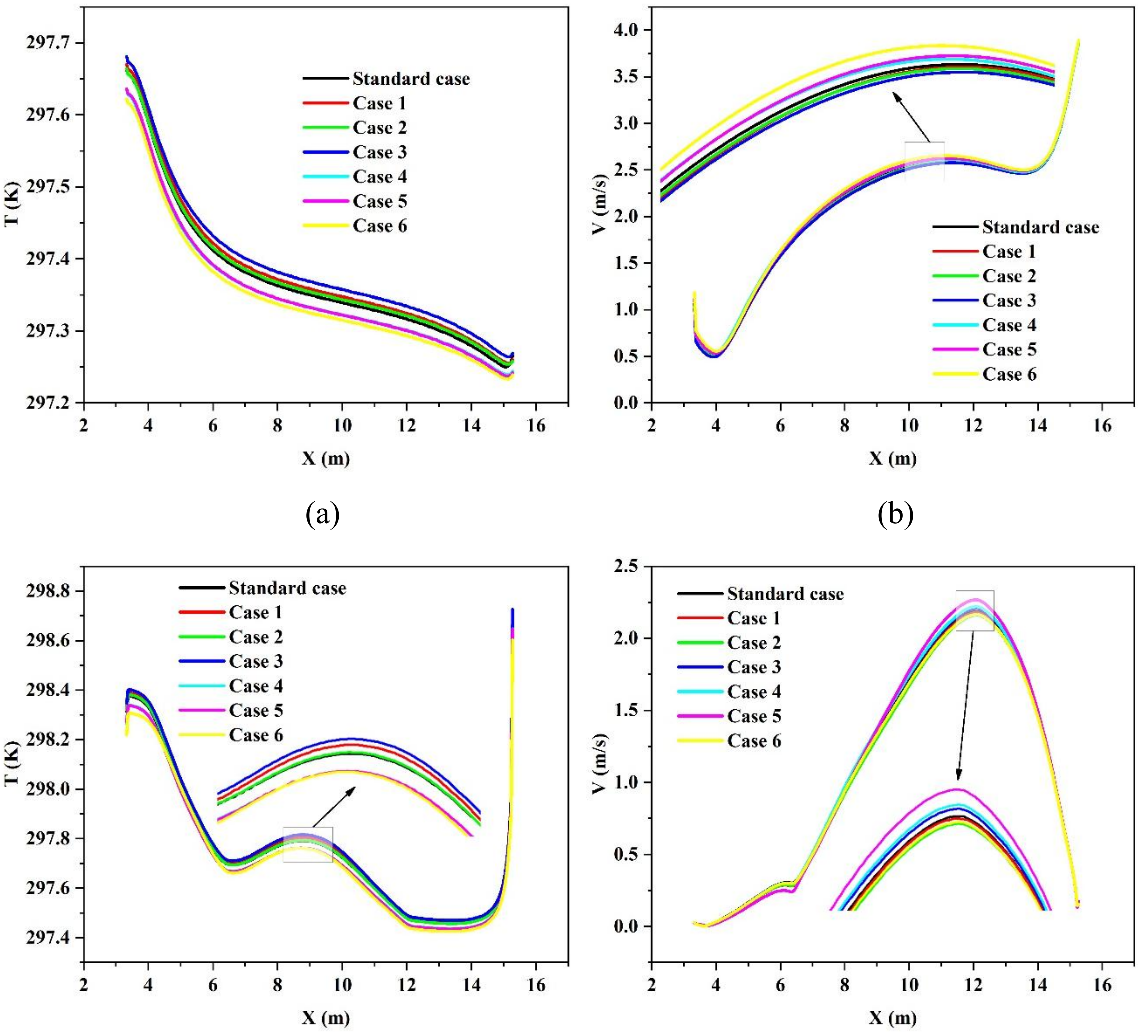
4.1- Effect of windcatcher shape

Direct ventilation is one of the most crucial methods to increase human comfort. Opening the windows allows airflow, which increases air velocity and enhances the sensation of coolness for humans [30]. In this section, six cases of windcatcher shapes are investigated and compared with the thermal performance of the baseline configuration, as shown in Figure 2b.

Figure 4b (y = 1.5 m) reveals that the velocity reaches its lowest point at the mosque's entrance, gradually increasing along its length as the right windows draw in the airflow current. At y = 6.85 m (Figure 4d), the velocity reaches its maximum in the middle of the mosque due to the dome (semi-circle shape), which extends the airflow. For the temperature profiles (Figures 4a and 4c), we have noticed an adverse behavior to the velocity profiles in the two vertical distances, and this is an indication that increasing the airflow velocity inside the mosque reduces the temperature in the area and thus achieves thermal comfort. Among the studied shapes, we have noticed that shape 6 achieves the highest levels of airflow velocity inside the mosque, but on the contrary, it achieves the lowest levels of indoor temperature.

Figure 5 depicts the average Nusselt number variation in the mosque roof for different windcatcher shapes. It is observed that the windcatcher shapes have a significant impact on the heat transfer rate. Moreover, all studied shapes are better than the standard windcatcher, where the optimal heat transfer corresponds to case 6.

Figure 6 shows the airflow velocity contours and flow streamlines for various windcatcher shapes. This figure demonstrates that the windcatcher shape affects the airflow lines and recirculation zones. The important airflow velocity noticed corresponds to case 6 i.e., the airflow velocity in this case is more significant than in the other studied cases due to the divergent shape of the windcatcher, which works to push the air very quickly from the entrance of the windcatcher toward the mosque space.



(a) (b)

(c) (d)

Figure 4. Temperature and magnitude velocity profiles in the mosque space for various windcatcher shapes: (a,b) at y = 1.5m, (c,d) at y = 6.85m.

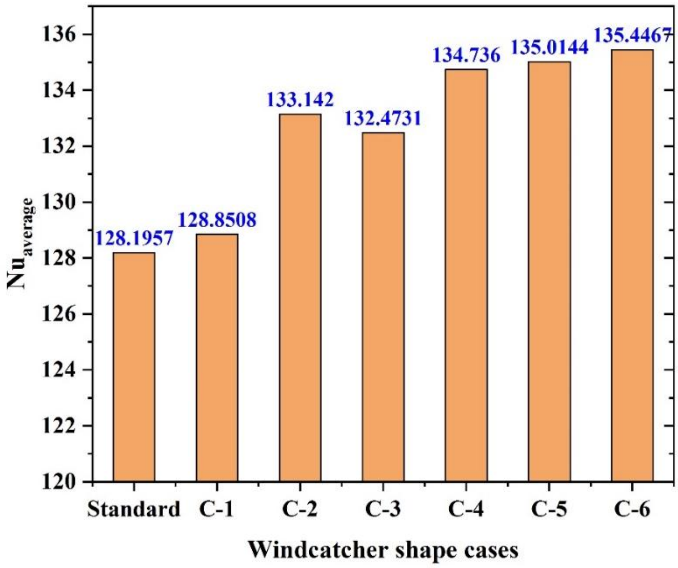
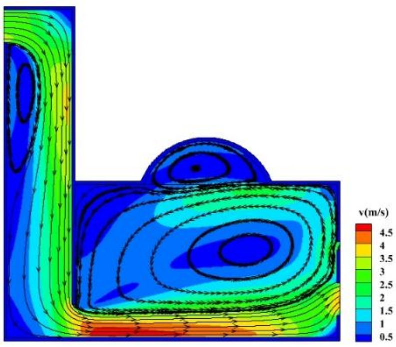
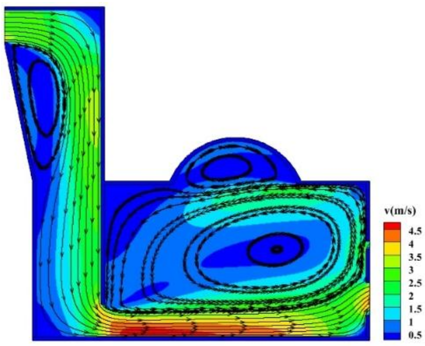


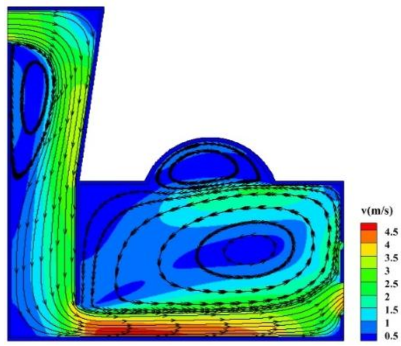
Figure 5. Average Nusselt number for various windcatcher shapes.



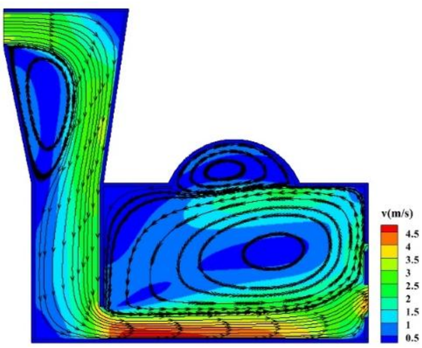
(a) Standard case



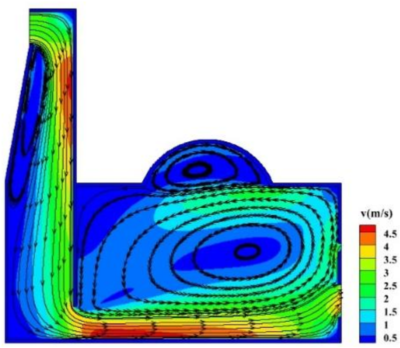
(b) Case 1



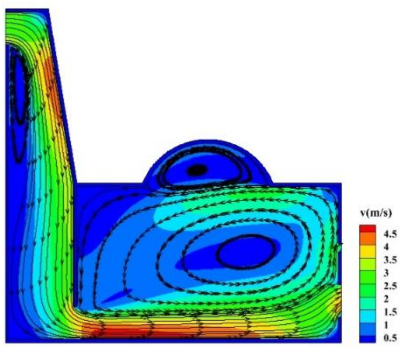
(c) Case 2



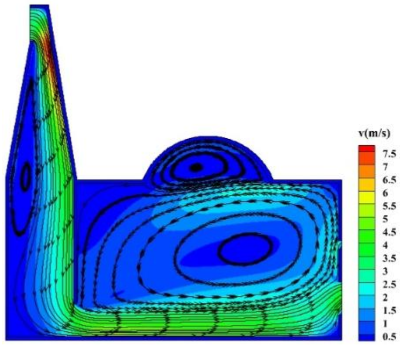
(d) Case 3



(e) Case 4



(f) Case 5



(g) Case 6

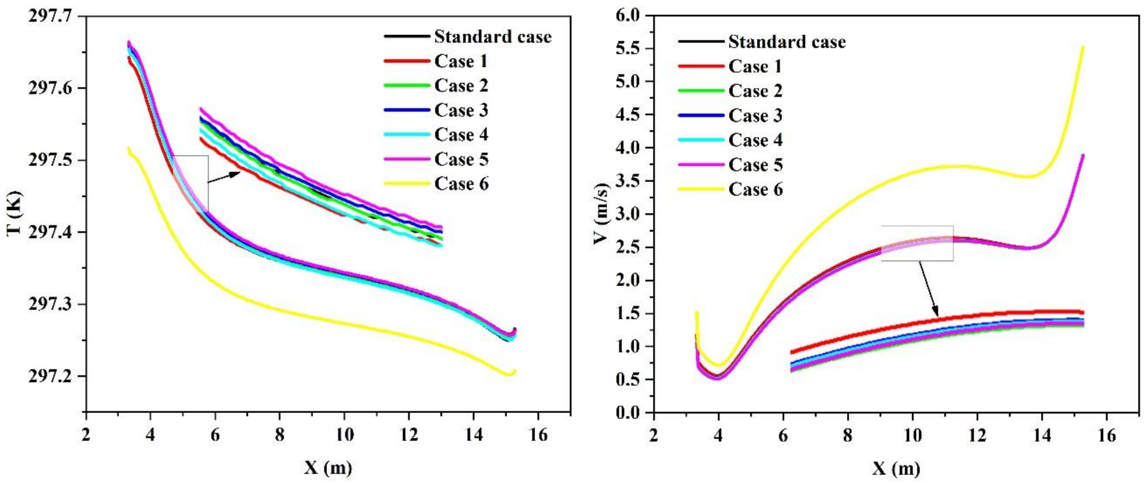
Figure 6. Contours of airflow velocity and flow streamlines for various windcatcher configurations.

4.2- Effect of windcatcher inlet shape

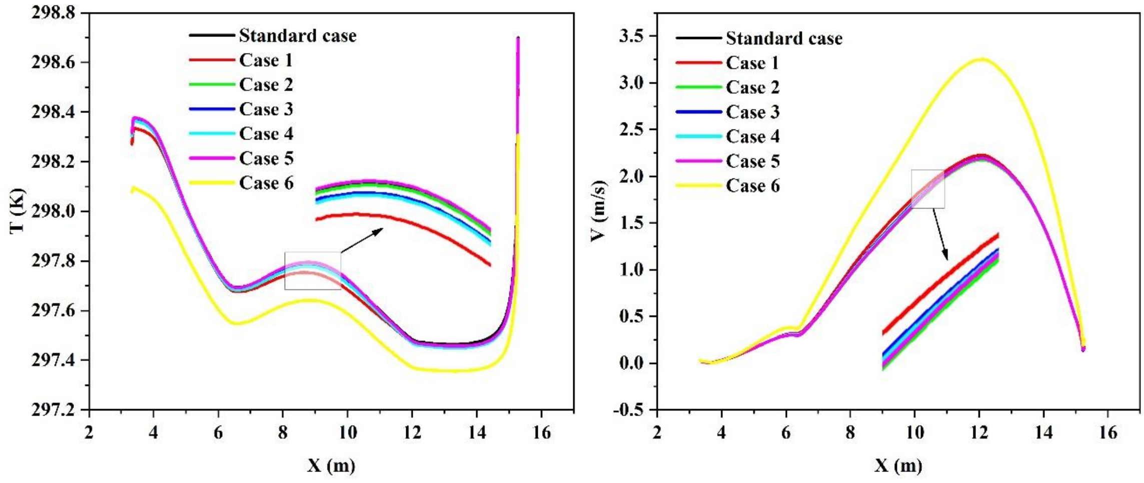
The performance of the windcatcher is also influenced by other factors, and one of the most important factors is the geometry of the inlet, as the inlet is the part where the wind is collected and is necessary to be used effectively. This section investigates the performance of six windcatcher configurations featuring varying inlet geometries while maintaining consistent mosque plan dimensions (see Figure 2c).

Figure 7 presents the velocity magnitude and temperature profiles for different windcatcher inlet shapes at different vertical distances (y = 1.5 m and y = 6.85 m). It is found that these inlet shapes have a remarkable effect on the fluid flow and indoor temperature, which vary from one shape to another. Also, we can see (Figure 7) clearly that increasing the airflow velocity decreases the indoor temperature along the mosque space, thus achieving thermal comfort. Furthermore, case 6 demonstrates the optimal enhancement of airflow characteristics.

Figure 8 illustrates the variation in the average Nusselt number at the mosque roof for different windcatcher inlet shapes. The figure demonstrates that the proposed inlet shapes significantly improve the heat transfer rate within the mosque space compared to the standard case, with case 6 showing an excellent enhancement. Airflow velocity contours and flow streamlines (Figure 9) confirm this case due to the divergent inlet shape, which works to collect the largest amount of air from the highest height to the windcatcher.



(a) (b)



(c) (d)

Figure 7. Temperature and magnitude velocity profiles in the mosque space for various windcatcher inlet shapes: (a,b) at y = 1.5m, (c,d) in the mosque space at y = 6.85m.

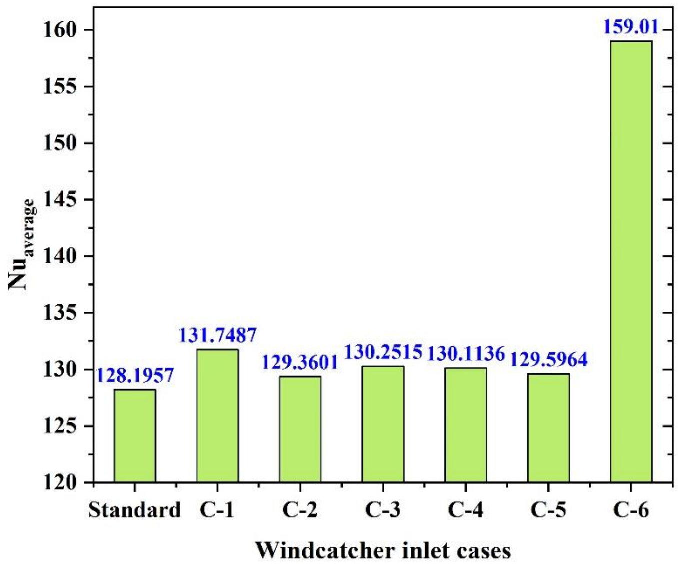
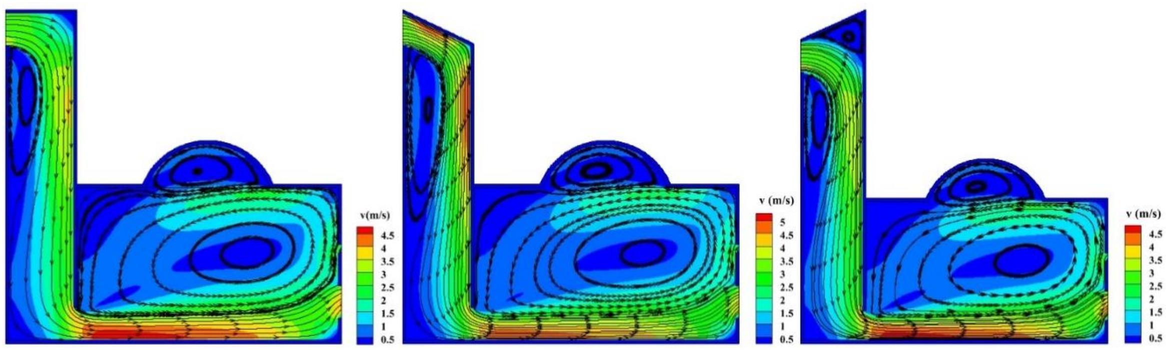
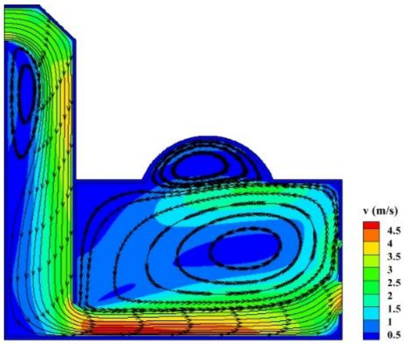


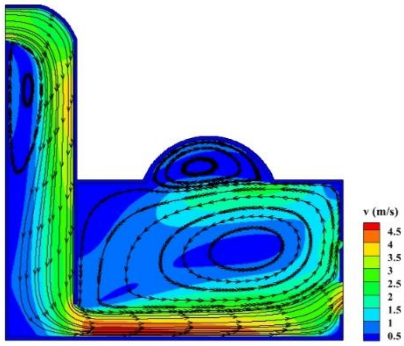
Figure 8. Average Nusselt number for various windcatcher inlet shapes.



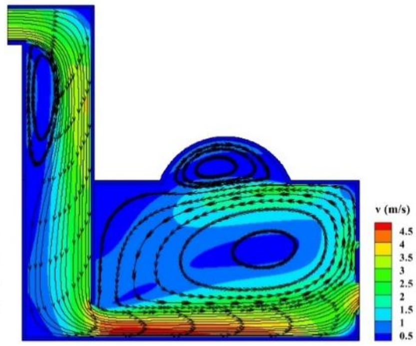
(a) Standard case (b) Case 1 (c) Case 2



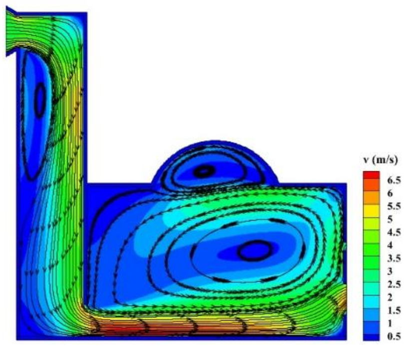
(d) Case 3



(e) Case 4



(f) Case 5

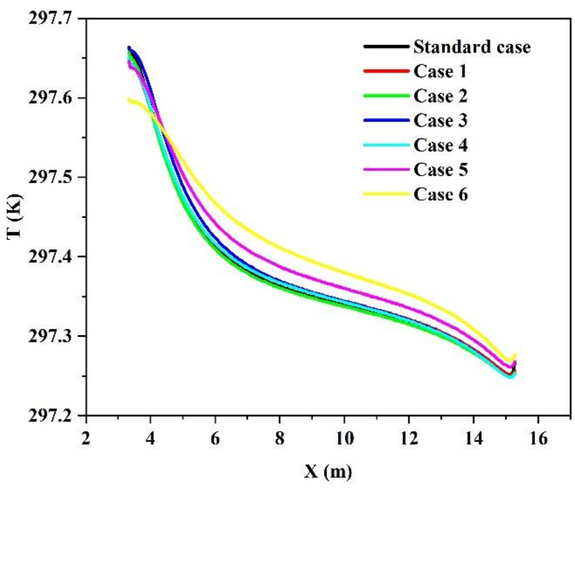


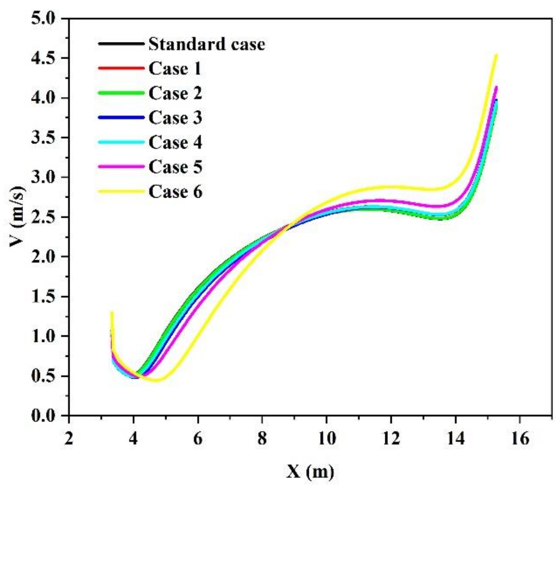
(g) Case 6

Figure 9. Contours of airflow velocity and flow streamlines for various windcatcher inlet shapes.

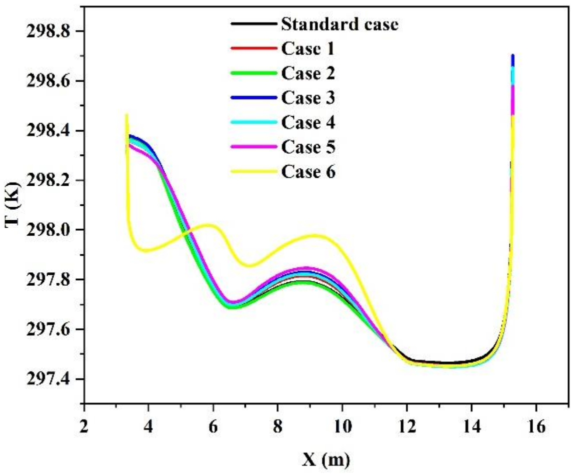
4.3- Effect of windcatcher outlet shape

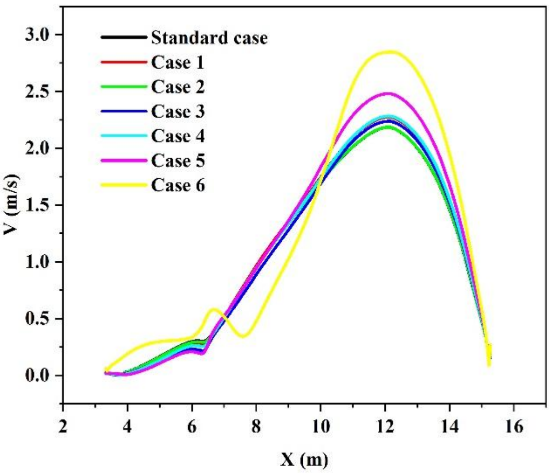
This section aims to determine the most suitable wind outlet shape based on the windcatcher's utilization. Six windcatcher outlet shapes are examined (see Figure 2d). Figure 10 shows the magnitude velocity and temperature profiles for different windcatcher outlet shapes at y = 1.5 m and y = 6.85 m. The same behavior is observed with the previous cases, and the important magnitude velocity values appear in case 6 for all vertical heights, which in turn works to reduce the indoor temperature. In addition, the heat transfer rate is enhanced for all proposed cases compared to the standard case, as shown in Figure 11, and enhancement is shown for case 6. The airflow and streamlines, in this case, appear to have a different behavior than other cases, where multi-recirculation zones are shown due to the high acceleration of airflow in mosque space (Figure 12).





(a) (b)





(c) (d)

Figure 10. Temperature and magnitude velocity profiles in the mosque space for various windcatcher outlet shapes: (a,b) at y = 1.5m, (c,d) at y = 6.85m.

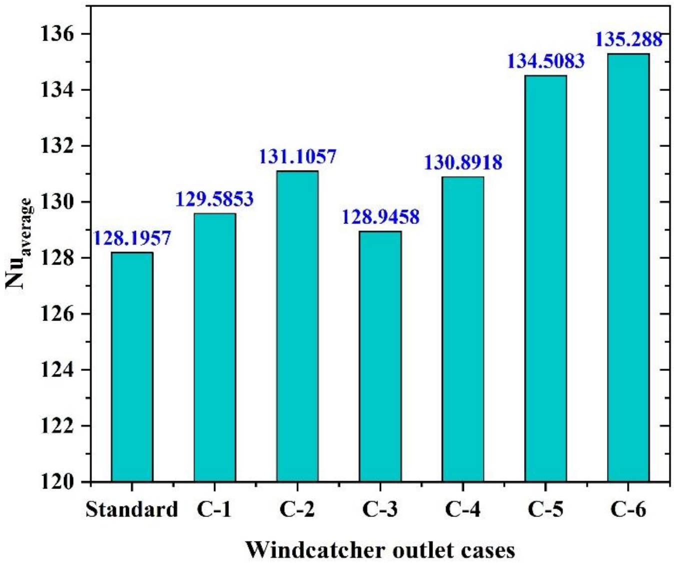
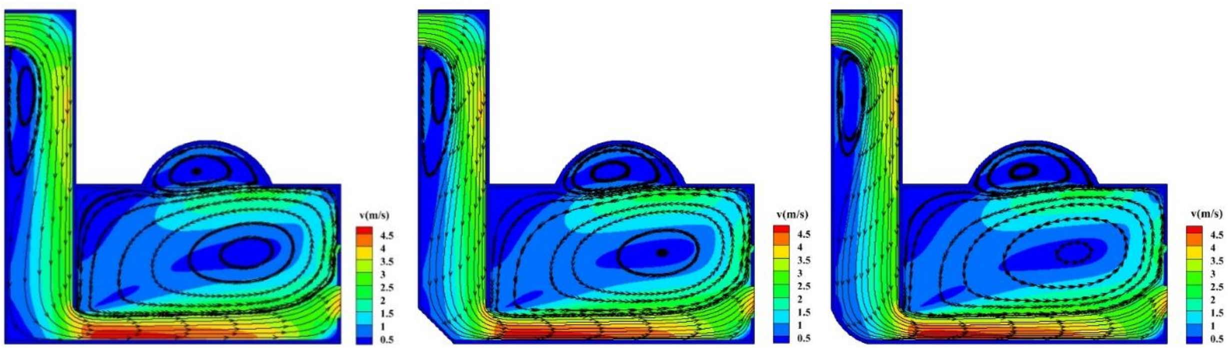
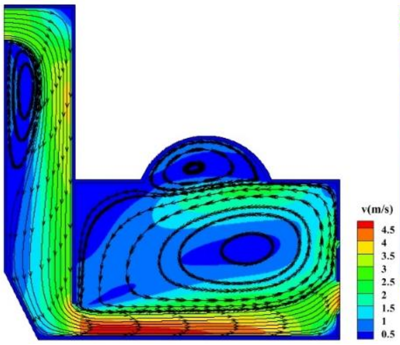


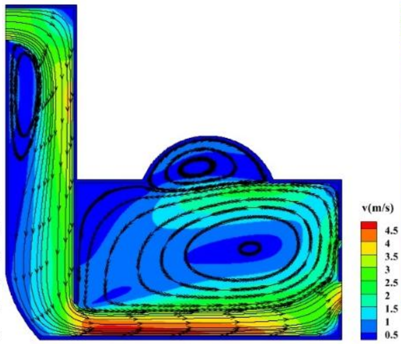
Figure 11. Average Nusselt number for various windcatcher outlet shapes.



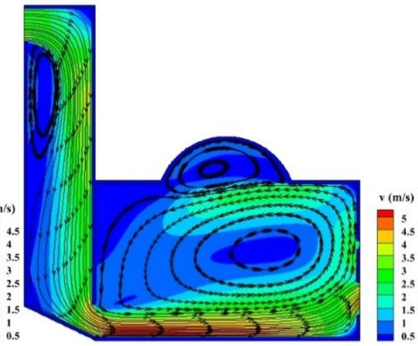
(a) Standard case (b) Case 1 (c) Case 2



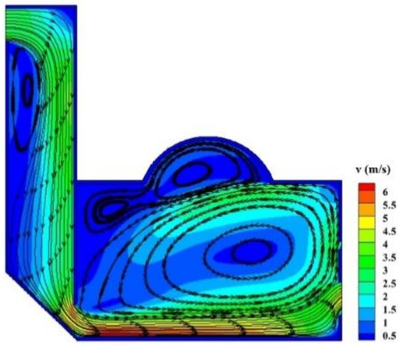
(d) Case 3



(e) Case 4



(f) Case 5



(g) Case 6

Figure 12. Contours of airflow velocity and flow streamlines for various windcatcher outlet shapes.

4.4- Optimized case

In this section, the proposed mosque design is simulated based on the best cases studied previously, which include the block (case 6 in Figure 2b), inlet (case 6 in Figure 2c), and outlet (case 6 in Figure 2d) of the windcatcher. The latter gives a new design called the optimized case, as illustrated in Figure 13a. The velocity contours with flow streamlines and pressure contours within the optimized case have been presented in Figures 13b and 13c, respectively. The airflow is multicellular inside the mosque space due to the highest velocities created by the high-pressure difference between the windcatcher and the mosque space (see Figure 13b). In addition, the magnitude velocity values of the optimized case are higher compared to all studied cases. As a result, it improves thermal comfort. Comparisons between the optimized and standard cases are shown in Figure 14 in terms of maximum temperature, maximum velocity, and average Nusselt number variation. It is shown that the optimized case is the appropriate condition for the comfort of the prayers, as it works to improve the air velocity inside the mosque, thus reducing the temperature and providing thermal comfort better than the traditional design.

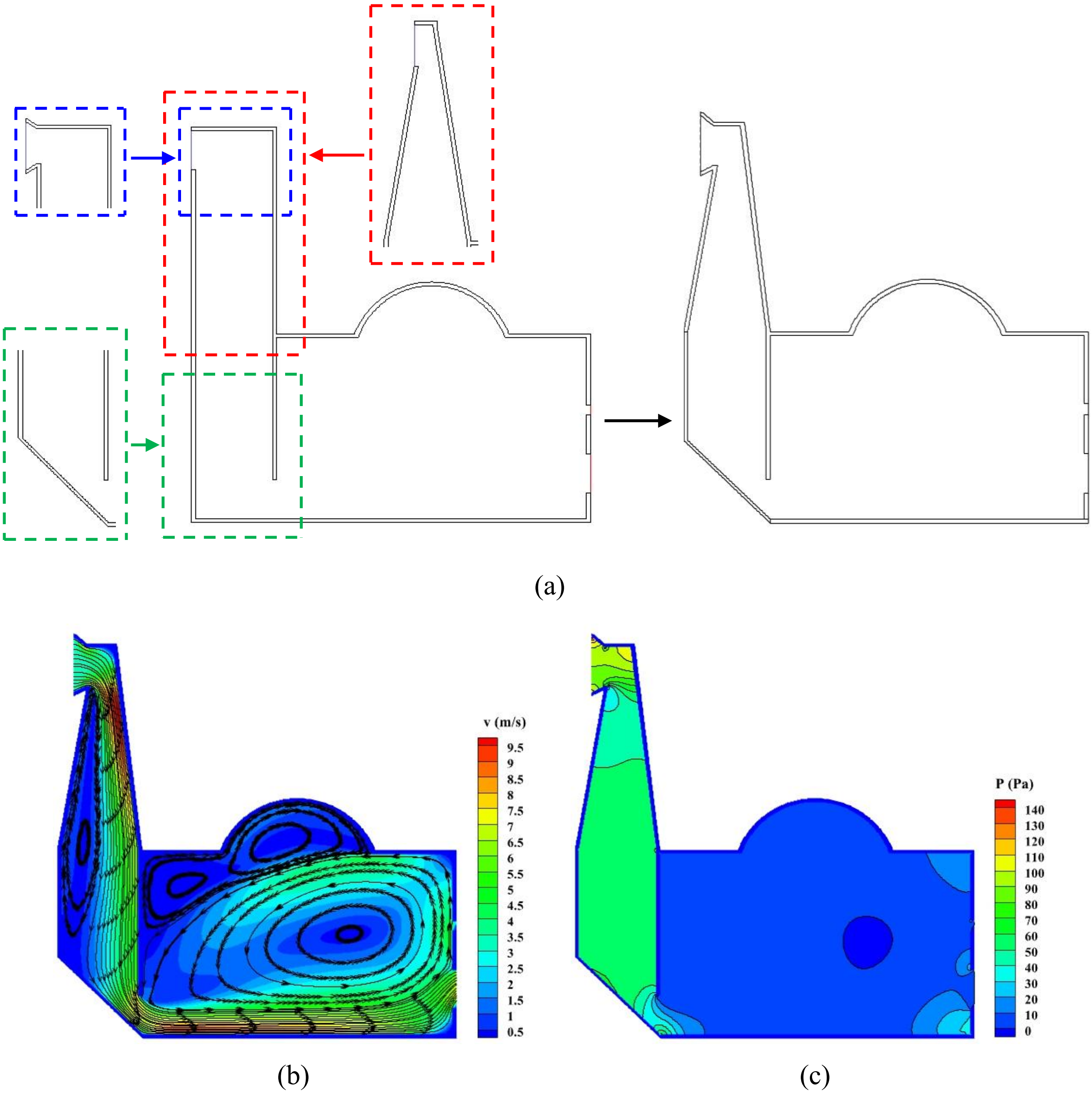
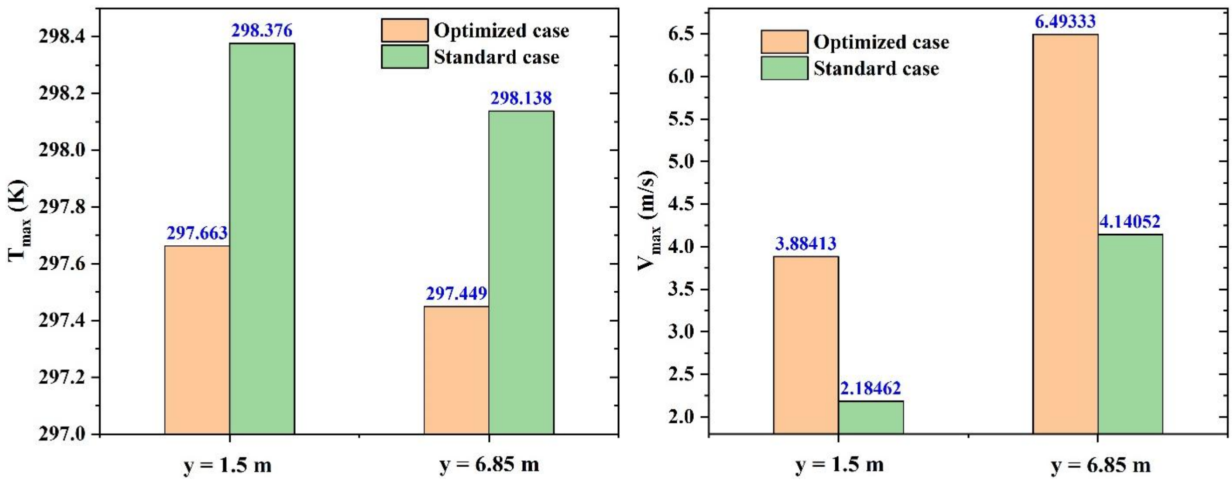
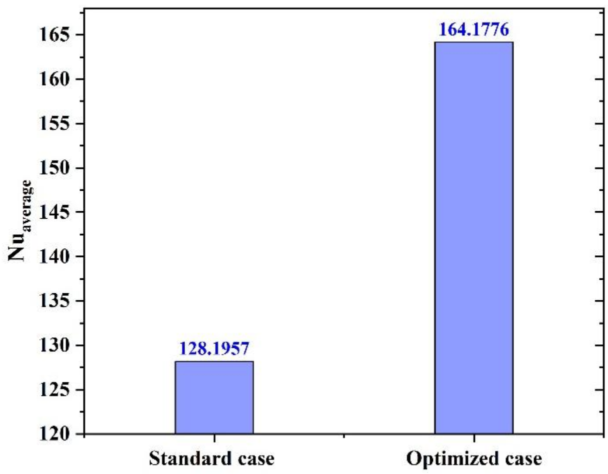


Figure 13. Designing of the optimized case (a), airflow velocity contours with flow streamlines (b), and pressure contours (c) within the optimized case.



(a) (b)



(c)

Figure 14. Comparison between optimized and standard cases: (a) maximum temperature, (b) maximum velocity, and (c) average Nusselt number.

5- Conclusions

Various windcatcher designs are investigated to improve the natural cooling of a domed mosque under the climate conditions of Laghouat City, Algeria. Various windcatcher shapes, including the windcatcher block, inlet, and outlet, are compared for thermal comfort improvement in the mosque's indoor space. The conclusions drawn are summarized as follows:

- Windcatcher geometry can potentially enhance thermal comfort for prayers in the mosque space.
- A windcatcher with a divergent shape, which corresponds to case 6, significantly impacts the fluid flow and heat transfer inside the mosque space compared to other cases.
- Modifying the windcatcher inlet to a divergent shape enables the collecting of the largest amount of air and thus enhances thermal comfort.
- The optimal case of the windcatcher outlet shape corresponds to the highest improvement of airflow velocity inside the mosque space.
- The windcatcher configurations tested in this study demonstrate significant improvement in airflow velocity from 1.69951 m/s to 2.35278 m/s and reduction in indoor temperature by 0.689K-0.713K, with an average Nusselt number 35.9819, highlighting their potential for improving passive ventilation.
- The results of this study help design environmentally friendly mosques that use natural airflow to cool down the interior space and thus reduce energy consumption as well as emissions.

Future research could consider the effect of occupants (prayers) to accurately assess thermal comfort.

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