Modeling and Simulation of Parametric Wind-Catcher Designs for Natural Ventilation in Sustainable Building Skin Architecture

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Abstract

In this paper, we model and simulate the performance of different advanced building skins that integrate wind-catcher tower designs, designed parametrically, into a building façade. We use a computational fluid dynamics (CFD) model to simulate the effects of tower height, tower position, wind-catcher architecture, wind velocity, temperature on ventilation rates, and performance. This CFD modelling and simulation shows the benefits of integrating a breathable tower into building skin design for the purpose of natural ventilation. We include a case study that compares the new building designs with an existing design to enhance better natural ventilation efficiency.

Keywords: Natural Ventilation, Wind-Catcher, CFD, Efficiency, Sustainable Design, Architecture

1. Introduction

Mechanical heating, ventilation, and air conditioning (HVAC) systems of buildings are enormously energy-intensive. Cooling alone, on average, accounts for 15% of the electricity used in commercial buildings [1]. Additionally, mechanical systems waste almost 30% of the energy powering them [2]. Natural ventilation [3] is an energy-efficient alternative that can reduce wasted HVAC energy and improve sustainability, in some cases by up to 60% [4]. Natural ventilation is limited to certain climates [5]. Although natural ventilation is a current trend in modern architecture to reduce energy costs, the technique dates back thousands of years, pre-dating mechanical systems.

Natural ventilation (NV), also called passive ventilation, uses outside air movement and pressure differences to both passively cool and ventilate a building. NV moves fresh air without mechanical fans to ensure both good indoor quality and acceptable comfort conditions. For NV to be successful, high thermal comfort and adequate fresh air must be present while little to no energy is used by the HVAC system. NV can be further described as the flow of outdoor air to an indoor space as the result of pressure differences arising from natural forces [6]. Two such natural forces drive air through a building: wind and buoyancy, which can be harnessed, respectively, by two primary NV strategies: cross ventilation and stack ventilation. As wind hits the windward façade, it creates positive pressure, and as wind flows away from the leeward façade, it creates lower pressure. If windows are open to both the windward and leeward façades of a building, the resulting pressure difference forces air through the building [7]. Traditionally, NV systems were difficult to design due to such complex physical processes. Presently, Computational Fluid Dynamics (CFD) is successful in simulating NV behavior in buildings [8].

A wind-catcher (wind-tower) is a tower-like architectural feature mounted on the roof of a building to capture fresh air from outside. These wind-catchers were designed specifically with natural ventilation in mind [9], and date back to ancient Persian and Egyptian architecture [10]. They work extremely well in arid climates with large diurnal temperature changes. Both the buildings and the wind-catchers were often built from thick, high insulating materials, such as stone or ceramic.

This paper simulates eight different wind-catchers air flow designs with a CFD model in order to predict changes in total temperature and airflow velocity (ventilation). We validate our approach with a case study by simulating the Kolar ab-Anbar (water reservoir) and compare the results with the seven other designs. We also highlight entrance and exit locations of air flow and their effects on the moving air and total temperature of the indoor air, in order to find the best natural ventilation design.

2. Architectural Concept

Wind-catchers are towers that are used to capture and direct wind from an outdoor stream into a building, in order to provide natural ventilation and passive cooling. Natural features such as geographical location, wind power, and wind direction, influence the design of wind-catchers. Building skin architecture variations include height of wind-catcher, number of air passage cross sections, number of side openings and their placement, etc. Some variations of ancient wind-catchers are shown in Figure 1.

Figure 1: Sample of variations of wind-catcher designs: (A) single sided; (B) four-sided; (C) eight sided.

A single-sided wind-catcher has only one channel as a passage of induced air and is often placed in the direction of a prevailing wind. In this study, we focus on single-sided wind-catchers and the effects of the blowing wind direction (direction of entrance and existence of air flow) on the ventilation. The first and primary design is taken from a real-world example – an ancient architecture in the heart of Persia, a hot and arid climate. Kolar Ab-Anbar (water reservoir), shown in Figure 2, is a historic building with four single-sided wind-catchers to provide natural ventilation to store water and keep indoor air cool and fresh.

Figure 2: Here we show different views of Kolar water reservoir as a real case study model: (A) shows two of the side towers and faced single sided one; (B) shows a top view of site location with symmetry of building and locations of towers; (C) shows all four wind-catchers in lower view and structure of main walls.

Due to the symmetry of this building, only half of it will be studied for this paper. Figures 3 shows three views of the parametric design of the Kolar water reservoir and its wind-catchers; this will be primary reference design of this study. In this architecture, two of the wind-catchers are designed to catch the outdoor blowing wind in higher elevations and direct it into the building. Two others are used to exhaust the indoor airflow to complete the natural ventilation process. Also, the results of different physical properties such as temperature, pressure, and indoor airflow velocity will be evaluated on the plane in the middle of the parametric design in the z-direction. All new design concepts will occur on this 2D-plane. This plane is shown in a yellow color in Figure 3.

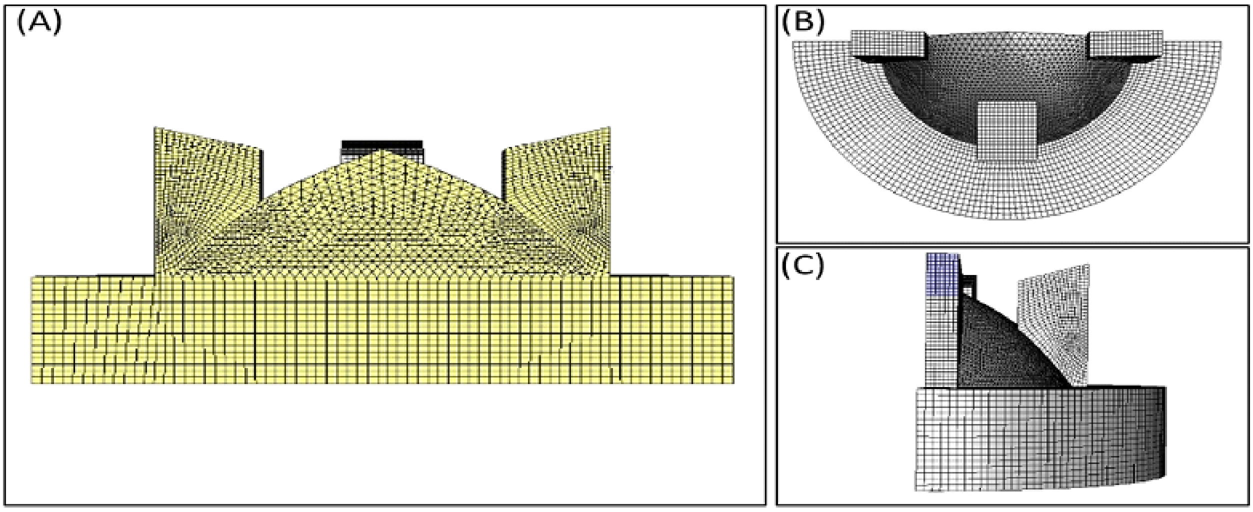

Figure 3: Shows different views of a parametric design of Kolar Ab-Anbar. (A) Show the front view plus yellow plane which will be used for CFD analysis; (B) show the top view of parametric view and symmetry of design; (C) show the side view of design

Seven more parametric designs employed to show the effects of the air flow direction and circulation inside the building. Then, all eight designs will be compared to find an optimum one which provides the best natural ventilation in the results section. For this purpose, the mentioned eight designs are shown in Figure 4. Different designs are based on the location, shape, and the counts of the entrance and existence of airflow.

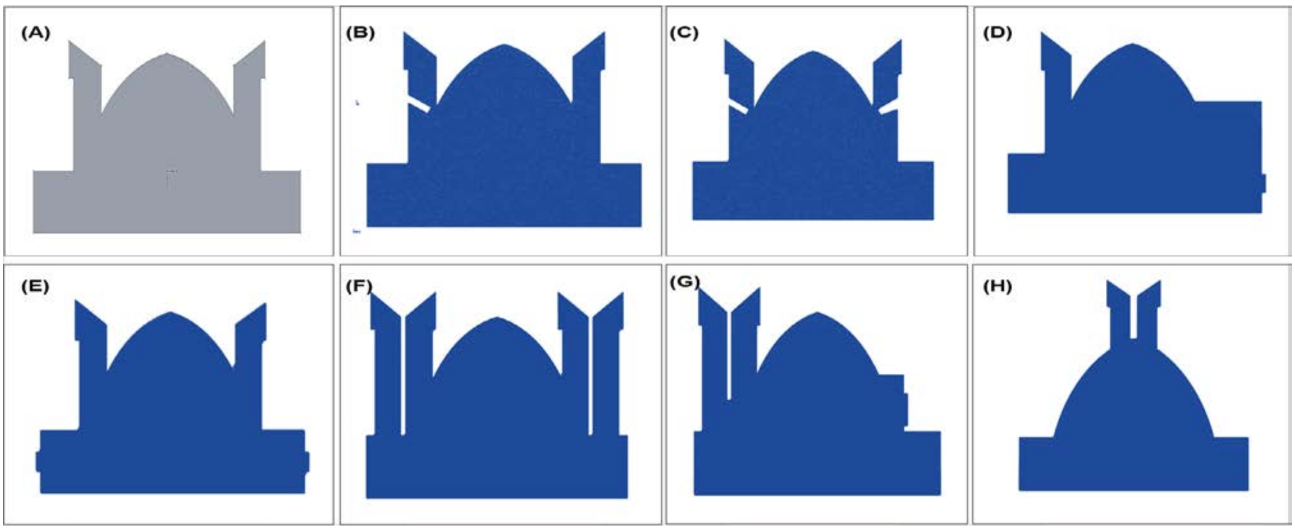

Figure 4: Shows a parametric variation of the eight different test designs. (A) show the original site design; (B) cuts the flow of the intake; (C) cuts the intake and outtake flows on the towers; (D) replaced the exhaust wind-catcher with lower level window; (E) Two higher level wind-catcher as entrance of airflow and two lower level of windows as an airflow exhaust; (F) two couple of opposite sided wind-catcher; (G) one couple of opposite sided as an entrance and lower level window as exhaust; (H) one couple of opposite sided wind-catcher in the highest elevation of building.

"Design A" is the main which has one wind-catcher as entrance and another as exhaust. "Design B" is the same as A with the difference in the left wind-catcher which is for the entrance of the outdoor airflow. "Design B" is narrowing the airflow channel right before the entrance to the main indoor area. "Design C" has narrowing nuzzle in the entrance and exhaust of air flow. "Design D" uses wind-catcher as an entrance for the outdoor air and windows in the lower place as exhaust. “Design E” processed natural ventilation by two wind-catchers to for entering airflow and two windows in two opposite side of building as exhaust ones. “Design F” worked by two opposite face wind-catchers as entrance and another couple for the exhaust. “Design H” has a couple of opposite face as entrance and middle-level windows as exhaust. Finally, “Design H” wanted to proceed with the natural ventilation by using two wind-catchers in the highest level of the indoor area. One for entering the airflow and one for exhaust.

3. CFD Implementation (Numerical Analysis) and Results

The driving forces for natural ventilation are wind and buoyancy. Differences in wind pressure along the façade and difference between indoor and outdoor temperature create a natural air flow. The strength and direction of these forces and the resistance of the flow path determine the ventilation rate. It is challenging to control natural ventilation in order to obtain the required indoor air quality condition because of complexity and difficulties in predicting ventilation rate. This research used the numerical technique, called computational fluid dynamics (CFD). CFD numerically solves the mass, momentum, and energy of flow conservation equations. Because the most indoor and outdoor airflows are turbulent, large eddy simulation and Reynolds averaged Navier-Stokes (RANS) turbulence modeling will be used. Several CFD studies have been done for single-sided ventilation. Such as Schaelin et al. [11] simulated the bi-directional wind and stack flow through a door opening by coupling the indoor airflow to the outdoor flow. They found that the airflow rate increased with the power of the heat source and height of the window. Gan [12] evaluated the effective depth of fresh air in a particular space for buoyancy-driven flow through a large opening. With CFD results, we can decide optimum layouts and opening for the best natural ventilation. In this paper, eight different design for wind-catcher entrance and exhaust of airflow has shown. Then, these designs analyzed by the CFD in the same initial and boundary conditions to find optimum ventilation for the wind-catcher as a building skin structure.

3.1 Set up CFD boundary and initial conditions

The building studied is a Kolar water reservoir in the Yazd Province of Persia (Iran). The outdoor air temperature based on the local weather agency for a hot summer day (July) is about 100 ^{o}F and wind velocity is about 9 *mph* and humidity is about 0%. With these initial condition and defined boundary conditions for internal walls of building as 78 ^{o}F, simulation and analysis were done. Also, a viscous model of K-epsilon for turbulence flow is employed.

3.2 Results

CFD is a reliable tool to obtain accurate results for NV simulations. ANSYS-FLUENT is used in this case study to simulate the airflow in the proposed parametric design that utilizes a single-sided wind-catcher connected to a main room. The analysis is conducted at steady state and two-dimensional model (the symmetry plane in the middle of the three-dimensional model). The SIMPLE pressure-velocity-coupling algorithm with a quick scheme as the finite difference scheme is used. K-ε is the turbulence model which is investigated for determining the pressure distribution and airflow. In order to achieve an optimum configuration for designing a wind-catcher system, it is necessary to compare the all the different designs in the case study. Comparison factors are lower total temperature and higher velocity airflow circulation in the main indoor area.

Figure 5 and 6 shows the filled and linear distribution of total pressure (in units Pascal) of all designs. The highest pressure is design B and C. These two designs contain a narrowing throat channel in the entrance of the tower and it is about 718 Pa. It is better to have lower pressure in the main living area. Also, higher pressure in analysis shows we need different and stronger material to construct and deploy the design in the built-environment.

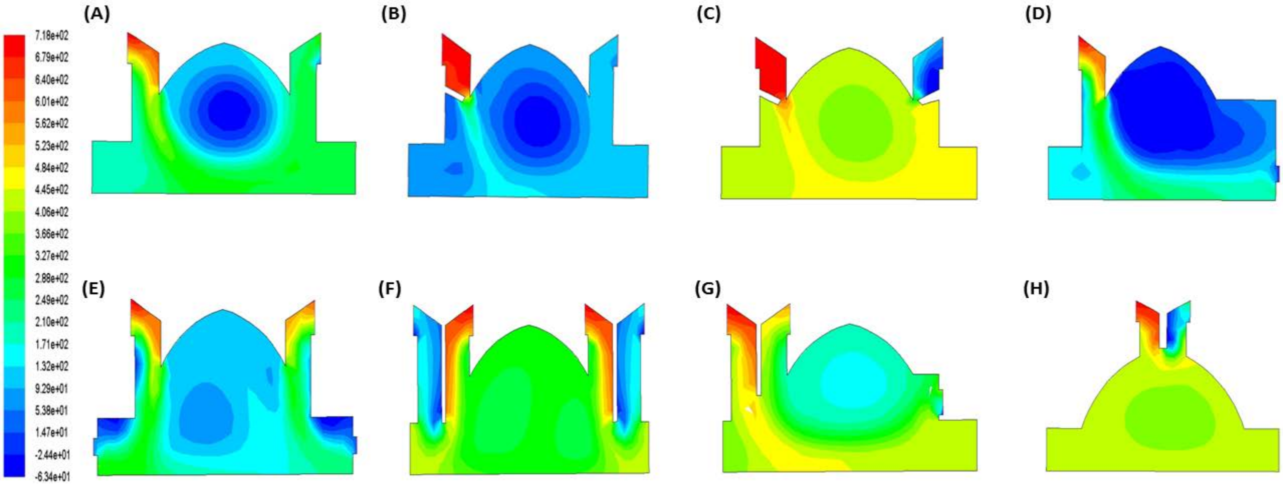

Figure 5: Show the filled total pressure distribution, Pascal; (B) And (C) show the highest pressure stress hitting the entrance wind-catcher walls.

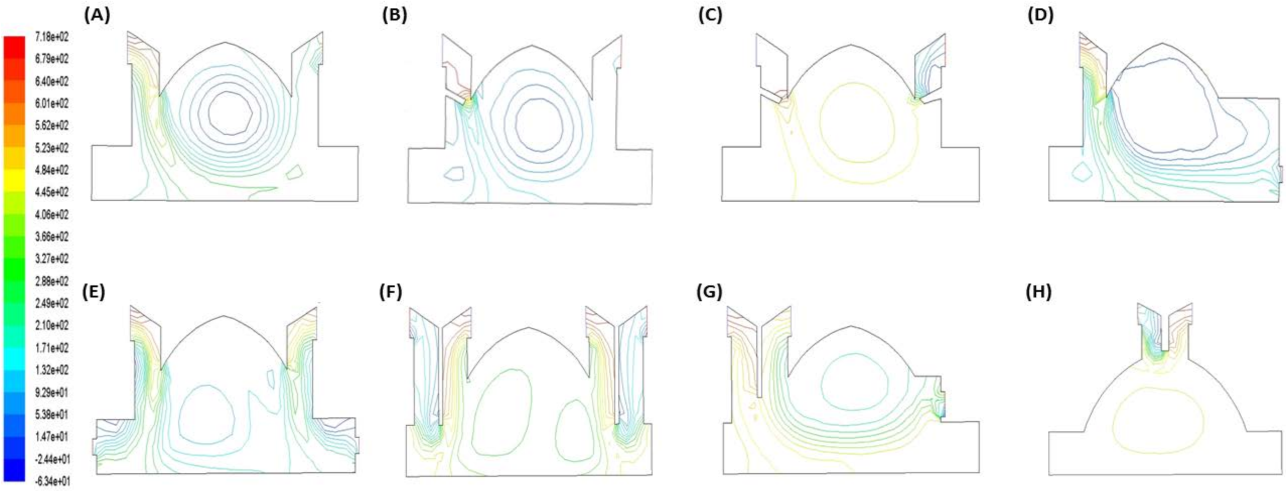

Figure 6: Show the linear total pressure distribution, Pascal; (B) And (C) show the highest pressure stress hitting the entrance wind-catcher walls.

One of the comparison factors for this case study is total temperature. Total temperature is important because temperature is one of the convenience factors for ventilation and air-conditioning. Thermal comfort is important to humans in the space. A rough estimate of human comfort in a space is around 68 ^{o}F to 72 ^{o}F. Using NV in this manner allows the building itself to regulate total temperature to a thermal comfort zone without utilizing an HVAC system. This allows for a more energy efficient design of a building skin design. In Figure 7 and 8 total temperature distribution is shown to find the best design. A lower total temperature in the main living area (is under round ceiling) is one important factor but is not enough to be chosen for the best design. Design E, F, and H have the lowest total temperature in the living area. This result is shown with the green color which is between 87 and 92 ^{o}F. Design B has another low-temperature profile around 90 ^{o}F.

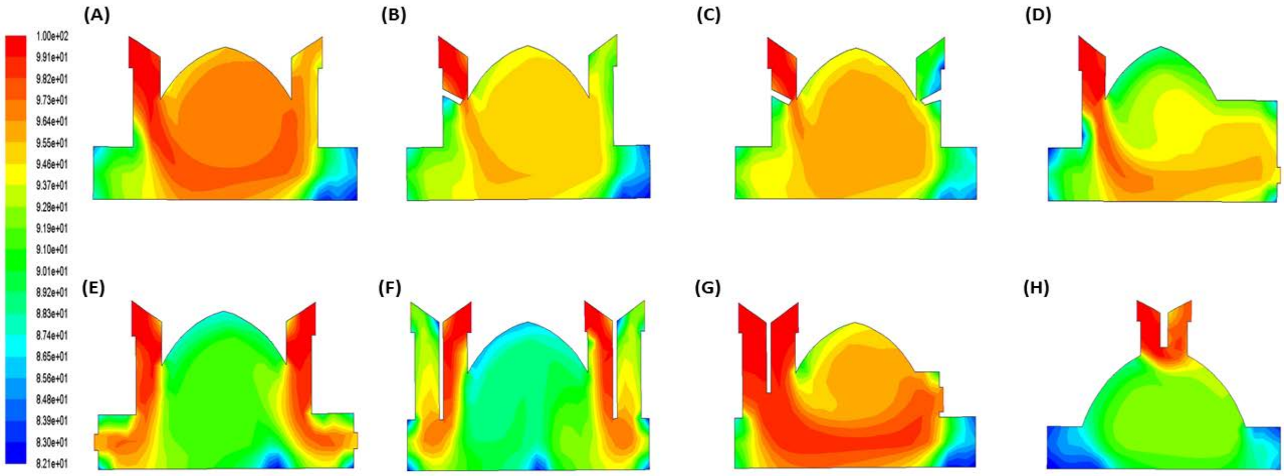

Figure 7: Show variations of filled total temperature (ºF) distribution; Designs (E), (F), and (H) have the lowest temperature profile; Design (A) and (G) entering a hot airflow directly to the main living area.

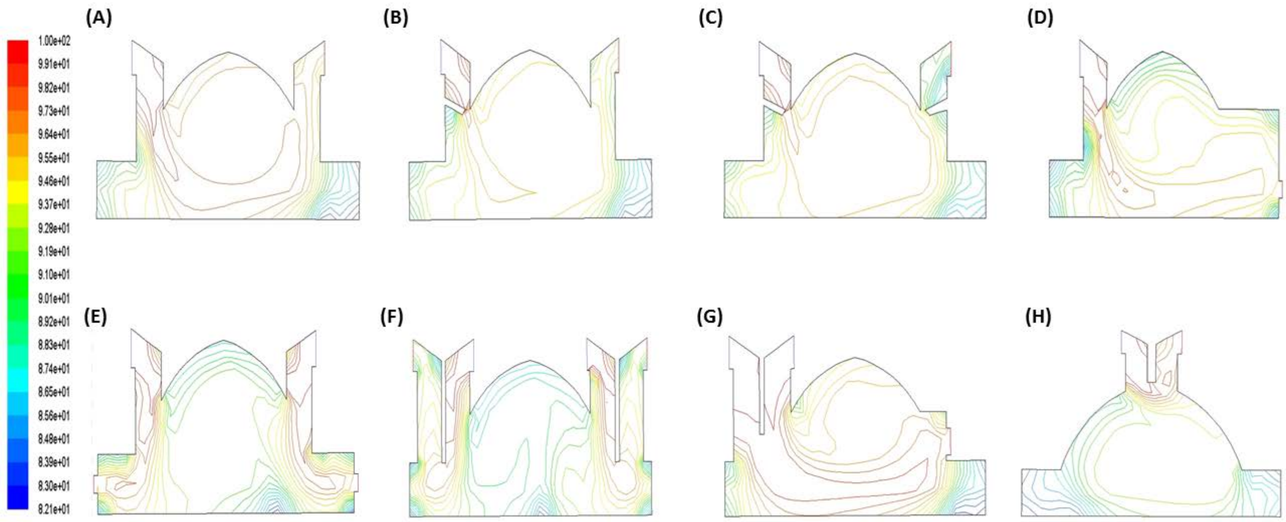

Figure 8: Show variations of linear total temperature (ºF) distribution; Designs (E), (F), and (H) have the lowest temperature profile; Design (A) and (G) entering a hot airflow directly to the main living area.

The second comparison factor is the airflow velocity inside the building. Airflow in a building reduces moisture damage and helps provide thermal comfort to the building's occupants. For airflow to occur naturally in this space the towers provide a continuous flow path between the entrance and exhaust. The two points should also have a pressure difference. This circulation works like a natural fan due to win and buoyancy. The airflow increases the heat transfer coefficient and general heat transfer. Thus, it plays a very important role in this study to investigate the optimum design. This reduces energy by naturally producing airflow and reducing the need to rely on mechanical equipment through fans and blowers. Figure 9 and 10 contains the value of velocity magnitude of airflow from the entrance to the exhaust of the airflow inside the building. Designs A, B, C, and D give the highest circulation velocity. In this study, air velocity at the entrance of the wind-catcher assumed 9 mph. However, results show velocity in the main area in few designs increases to 25 mph.

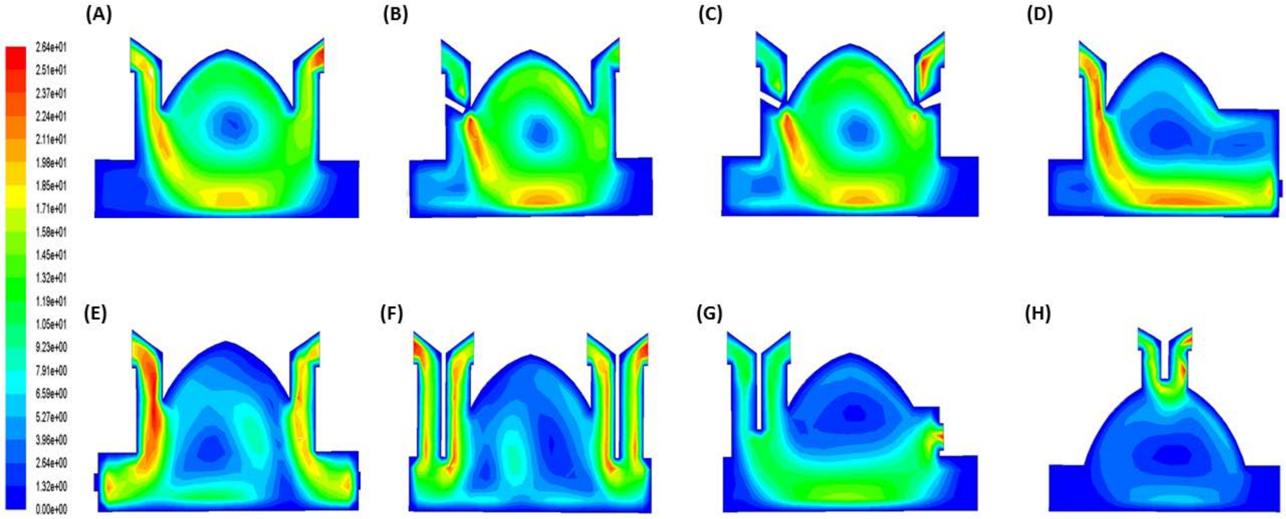

Figure 9: Show filled velocity magnitude profile for all designs; Designs A, B, C, and D has the best and highest airflow circulation. It reaches to 25 mph.

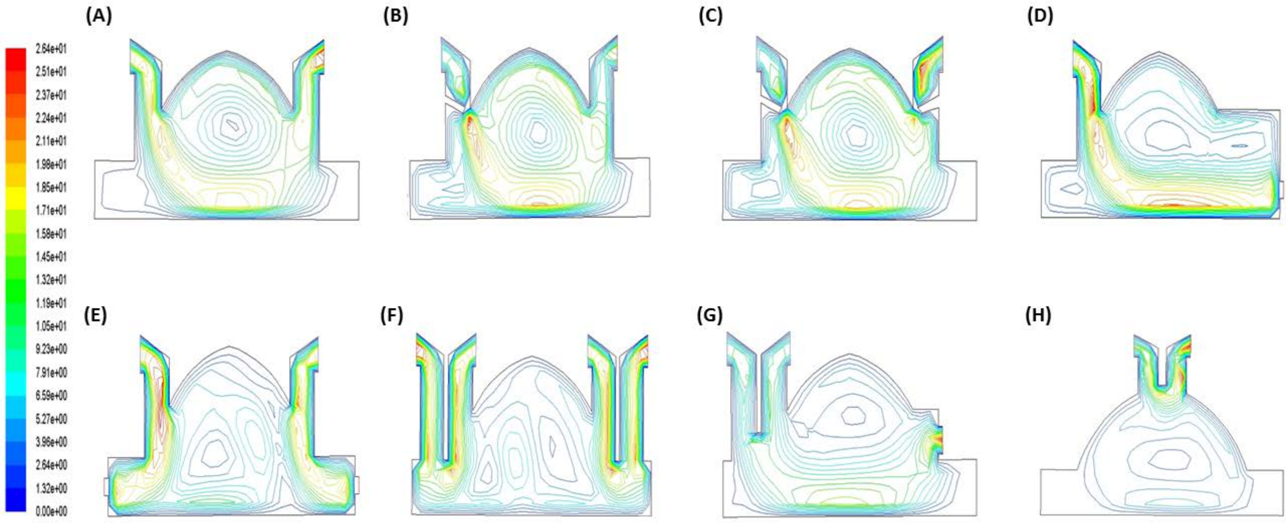

Figure 10: Show filled velocity magnitude profile for all designs; Designs A, B, C, and D has the best and highest airflow circulation. It reaches to 25 mph.

The optimum design needs the combination of the best comparison factors result (lower total temperature and higher air circulation). For this purpose, Figure 11, 12, and 13 provide this combination of the comparison factos in one picture to make it more clear and comparable. In Figure 11 vectors of moving air colored by the total temperature clearly, show the temperature of flow in each point.

Figure 12 and 13 show the simulation results of the path-lines of the airflow colored by the velocity and temperature respectively. With comparing these two figures, design B has the best comparison factors which are the combination of the lowest living area temperature and highest flow velocity.

Finally, the air stream function in the eight different suggested design for single-sided wind-catchers studied. Case study (Design A) is the model of Kolar water reservoir in the Yazd province of Iran and structured thousands of years ago. This study shows, after reviewing eight possible designs, case study model could be better with narrowing the entrance air channel right before pushing hot air into the living area. Design (B) can increase the natural ventilation efficiency in the Kolar water reservoir.

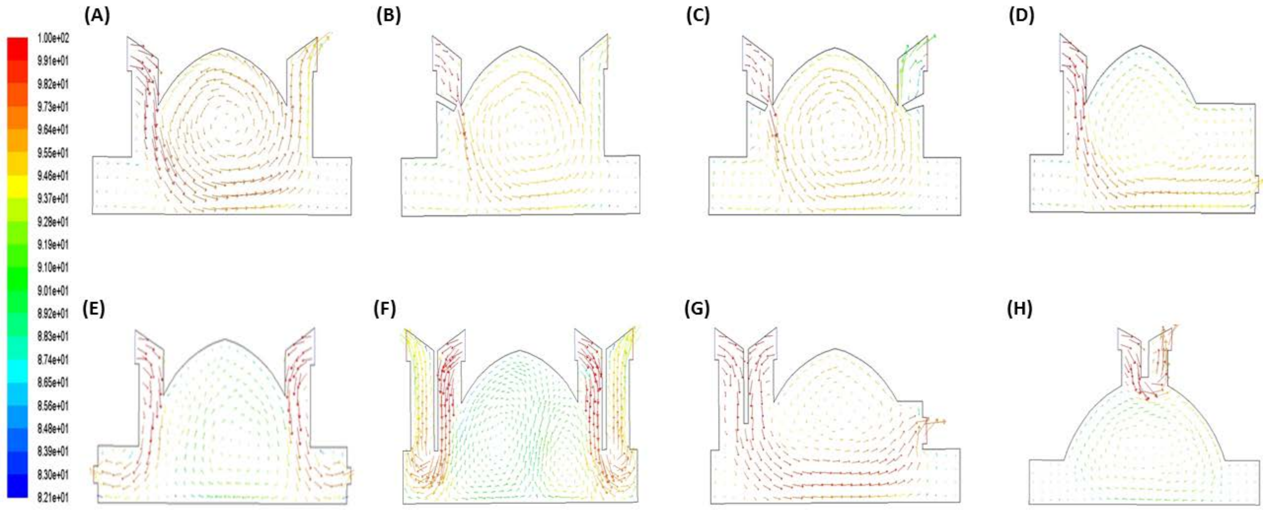

Figure 11: Show vectors of airflow colored by the total temperature; Designs (A), (B), and (C) has the best comparison factors

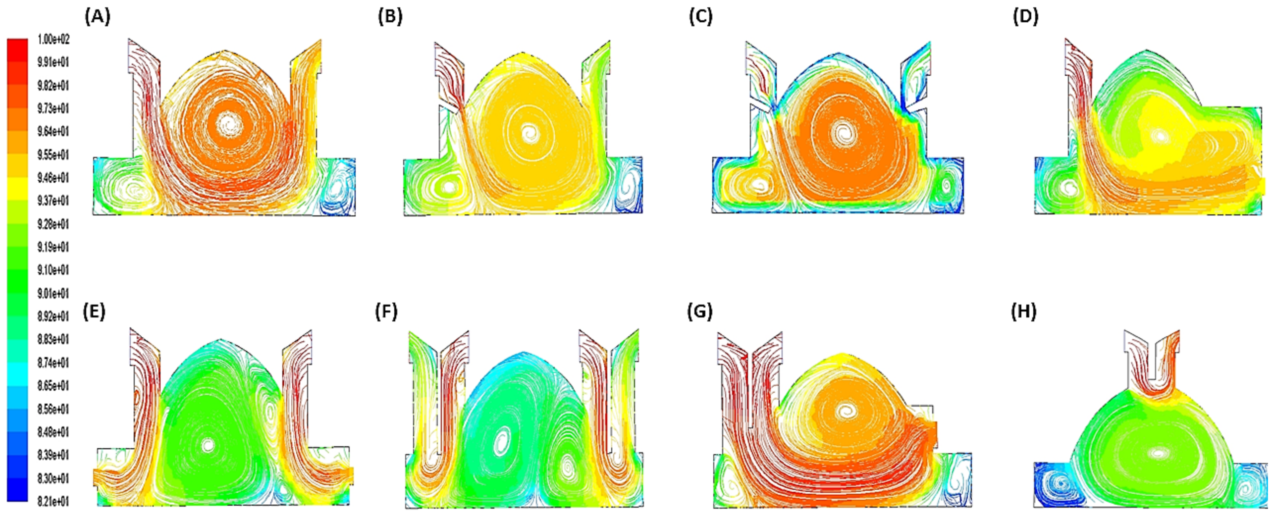

Figure 12: Simulation results of the path lines colored by the temperature; Design (B) has the best air circulation and moderate temperature around 92 which is around 8-degree air temperature decrease compare to the entrance flow.

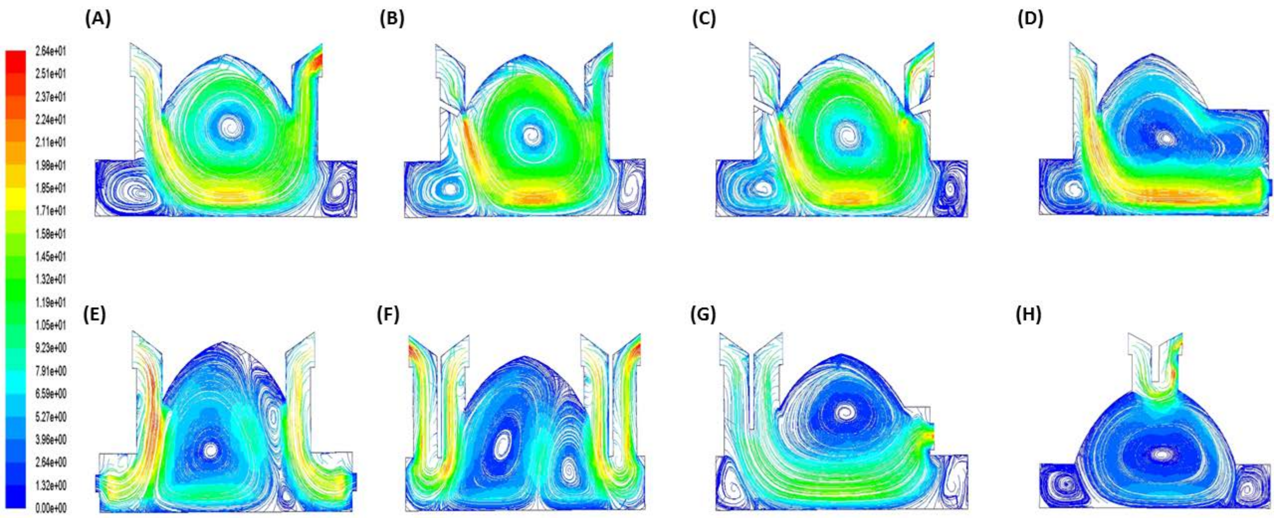

Figure 13: Simulation results of the path lines colored by the velocity; Design (B) has the best air circulation velocity in the living area. It increases to 25 mph in some points.

4. Conclusions

Various designs of single-sided wind-catcher natural ventilation systems were applied and analysed in this case study experiment. This paper explored and simulated these designs in order to gain a better natural ventilation efficiency for a building skin. Based on results from numerical solution and CFD models, trends were revealed and validated looking at simulated pressure and temperature. Upon validation with numerical simulation and CFD analysis, design B with cutting the intake flow has the best comparison factor. Specifically this study compared two factors: the lower indoor total temperature specifically in the living area and higher air flow velocity which cause flow circulation. Design B demonstrated the best results to the natural ventilation based on the two comparison metrics. This design is similar to the main case study design inspiration, except it is cutting the intake air flow in the entrance to the living area and existence from the wind-catcher channel. The CFD results show total temperature decrease about eight degrees and flow velocity increased by 16 *mph* compared to the intake airflow. The investigation also revealed that all other changes to the main design, which made six more designs, such as location, numbers, and directions of wind-catcher had no better results than main one. Design B's windward façade should be integrated into future NV building skin façades for better energy efficiency. In the future, we plan to integrate this design into designs for built-environment by using insights from this case study to produce a skin for large high-rise and residential buildings.

5. References

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