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Visualized Flow Patterns around and inside a Two-Sided Wind-Catcher in the Presence of Upstream Structures

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***Abstract*—**In this paper, the influence of upstream structures on the flow pattern around and inside the wind-catcher is experimentally investigated by smoke flow visualization techniques. Wind-catchers are an important part of natural ventilation in residential buildings or public places such as shopping centers, libraries, etc. Wind-catchers might be also used in places of high urban densities; hence their potential to provide natural ventilation is dependent on the presence of upstream structures. In this study, the two-sided wind-catcher model was based on a real wind-catcher observed in the city of Yazd, Iran. The present study focuses on the flow patterns around and inside the isolated two-sided wind-catcher, and on a two-sided wind-catcher in the presence of an upstream structure. The results show that the presence of an upstream structure influences the airflow pattern force and direction. Placing a high upstream structure reverses the airflow direction inside the wind-catcher.

***Keywords*—**Natural Ventilation, Smoke Flow Visualization, Two-Sided Wind-Catcher.

I. INTRODUCTION

NOWADAYS, due to increasing concerns about environmental pollution and the human need for efficient energy sources, natural ventilation has become important and has been reconsidered by many researchers and building designers. Ventilation that acts by using renewable energies, and without mechanical ventilation systems, has been named natural ventilation. Natural ventilation is generated by the buoyancy force induced by the temperature differences between inside and outside air temperatures or wind pressure force generated by outside wind. Wind-catchers, which for centuries have been used in hot and arid regions of Iran and neighboring countries, were an example of using natural ventilation and passive cooling method in these climates (Fig. 1). In addition to reducing environmental pollution induced by burning the fossil fuels, wind-catchers can reduce the cost of building ventilation and create a healthy and favorable environment for residents compared to “modern” power-consuming methods such as air conditioners and chillers. Wind-catchers can guide fresh and high speed air flows, at high altitude with less pollution, through the channels of the windward openings to the residential area. A wind-catcher is normally a tall structure with a height between 5 and 33 m, mounted on the roof of the building. Design of these systems has been traditionally based on the personal experience of architects as well as the dignity, wealth and social position of the house owners. Each differed in the height of tower, cross-section of the air passages, placement and number of openings as well as placement of the tower with respect to the structure it cools. In arid central regions of Iran, the warm and dry air induced by the wind-catcher, may pass over a water pool equipped with a fountain to create evaporative cooling (Fig. 2).

Fig. 1 Several wind-catchers with different shapes as used in Iran

When wind is blowing over a building, a positive pressure field forms on the windward face of the building and negative pressure forms on the leeward side. Wind enters into the wind-catcher from the area with the positive pressure and tends to move to the lower pressure zones (Fig. 3). When there is no wind, the wind-catcher operates with buoyancy driven force. During the day time, because of the wind-catcher structure warming and decreasing air density in the wind-catcher’s channels, the wind-catcher operates as a chimney. This action continues until midnight. However, after midnight, when the air temperature decreases in clear sky with desert sky radiation, the wind-catcher and air become cool. At this time, the air density increases and fresh air come to the residential

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areas from openings. Traditional wind-catchers have been used for centuries in hot and arid regions of Iran and neighboring countries, helping to maintain comfort for the residents of these areas on hot summer days. Nevertheless, these designs also had disadvantages and limitations. For example, dust, insects and small birds can enter the building through the openings. As part of that air is induced, without circulation in the building it leaves the building from other openings of the wind-catcher. This phenomenon, named short-circuiting, occurs in multi-opening wind-catchers. During a fire, wind-catchers could also provide the necessary oxygen for a fire's progress.

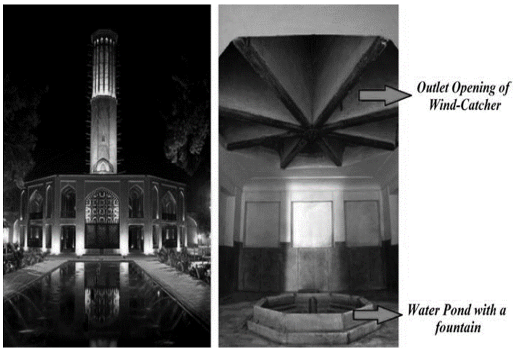


Fig. 2 Use of evaporative technique in Iranian Vernacular Architecture (Dolat-Abad garden in Yazd)

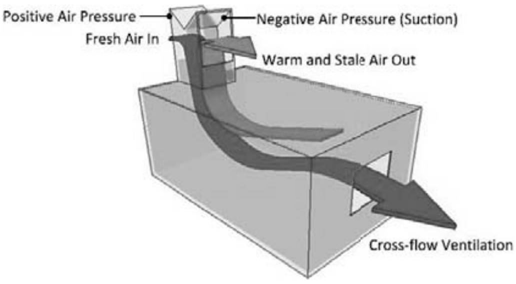
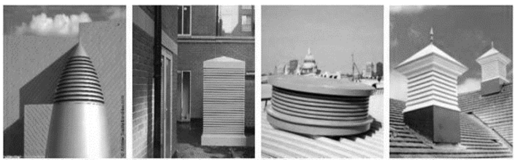


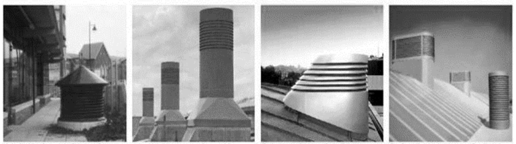
Fig. 3 Performance of two-sided wind-catcher when wind is blowing

In this age, new wind-catchers are equipped with systems that can close the wind-catcher's openings when air is polluted or a fire is diagnosed. This wind-catcher's openings are programmable according to the season and can be opened or closed. In the new wind-catchers, steel openings are installed in residential spaces to overcome the traditional venting security problem [1]. According to the various tastes of inhabitants, these new wind-catchers are made differently than traditional vents. Fig. 4 shows an example of wind-catchers which are used in England.

Several academic studies investigated the cooling performance of wind-catchers. The results show that wind-catchers can play an important role in creating natural ventilation and adjusting the thermal comfort of interior living spaces. Kalantar [2] carried out experimental investigation and numerical simulation to evaluate the cooling performance of wind-catchers in hot and dry regions of Yazd. The results show that by using a logical amount of water in the evaporating system of a wind-catcher, the inside temperature decreases and the relative humidity increases; both of which are suitable for proper ventilation of hot and dry regions.



Bluewater Retail Park, Dartford, Kent. Restaurant, Lisson Grove, London. The Oxo Tower Restaurant. Old Hill Primary School, West Midlands.



Chingford Hall Community Buildings, Essex. University of Hertfordshire, Faculty of Art and Design. Collier House, Brompton Road, Chelsea. The Press Association, Howden, East Yorks.

Fig. 4 Modern wind-catchers used in a European country

Bahadori et al. [3] compared the thermal performance of two new designs of wind-catchers with a conventional wind-catcher in the city of Yazd. The two new designs of wind-catchers were one with wetted column and the other one with wetted surfaces. The achieved results show that both new designs performed better than the conventional one. The results also showed that the air leaves these towers at a much lower temperature and a higher relative humidity than the ambient air. Karakatsanis et al. [4] measured the wind pressure coefficients at various openings of a wind-catcher by testing a scale model of a building in a boundary layer wind tunnel. Tests were conducted on an isolated wind-catcher, the wind-catcher and adjoining house and also the wind-catcher and house surrounded by a courtyard. It was concluded that the presence of a courtyard around the structure and the wind incidence angle influence the rate and the direction of the air flowing from the tower to the house. Su et al. [5] carried out experimental investigation and CFD simulation to evaluate the net flow rate of a circular-section wind-catcher for various wind speeds and directions. They stated that the wind direction has a small effect on the flow rate. However, the induced air capacity of this unconventional type is less than the rectangular cross-section versions. Elmualim and Awbi [6] compared the performances of two square and circular cross-section wind-catchers. The obtained results of experimental and CFD simulations showed that the efficiency of the four-sided wind-catcher is much higher than that of the circular one for the same outdoor wind velocity. They explained that this is due to the fact that the sharp edges of the square one create a large region of flow separation and higher pressure differences across the windward and leeward faces. Montazeri et al. [7] analyzed the natural ventilation performance of a two-sided wind-catcher. They concluded that for an isolated two-sided wind-catcher model, the maximum efficiency is achieved at the angle of 90°. Montazeri and Azizian [8] examined the performance of a one-sided wind-catcher model with experimental wind tunnel testing. In order to recognize the flow pattern around and inside the wind-catcher model, a few smoke visualization experiments were also carried out. These visualized flow structures showed the separation of incoming flow from the lower edge of windward opening of wind-catcher. Montazeri [9] used several cylindrical wind-catcher models with various opening and same cross section and heights. He observed that by increasing the number of openings the induced airflow rate decreases and sensitivity of cylindrical wind-catchers with the wind angle decreases. Kazemi et al. [10] carried out smoke visualization tests on wind-catcher models with, flat, inclined and curved roofs. Investigation of visualized flow structure inside the wind-catchers with the inclined and curved roofs showed that the size of separation zone and vortices become smaller than that of the wind-catcher with a flat roof. Dehghan et al. [11] conducted wind tunnel and flow visualization experiments concluding that the flow pattern, the internal pressure field and induced airflow rate inside the wind-catchers, are strongly influenced by the geometry of a wind-catcher's roof and the approaching wind direction. Dehghan Kamaragi [12] introduced heat transfer and turbulence model for a quad-directional wind-catcher based on a real one in Siraf city. This model is based on CFD numerical solutions. In this study, wind speeds, temperatures, angles, humidity, building materials (clay soil), wall thickness, and openings, doors and windows locations are investigated. Results showed that a CFD numerical model is effective for diversified and optimized Iranians wind-catchers across the country.

II. EXPERIMENTAL PROCEDURE

In hot and arid regions of Iran with wind-catchers, the buildings were usually in group of high density. This group of high density buildings decreased the amount of solar radiation on the buildings. Thus the amount of heat absorption decreased. Fig. 5 (a) shows the height of nearby buildings can affect the performance of wind-catchers. In this region, reservoirs - a combination of wind-catchers and domed roofs - were used for cooling water in the warm seasons. In this case, dome height and the distance to the wind-catcher, can affect the amount of air entering or leaving the reservoir (Fig. 5 (b)). In modern buildings with wind-catchers, those wind-catchers were usually in consecutive arrangement such that their distance from each other can influence the rate induced flow and the flow field around each of the wind-catchers (Fig. 6).

Realizing the importance of upstream structures effect on performance of these wind-catchers, in this study, the effects of upstream structures on the performance of a sample two-sided wind-catcher was investigated by using smoke visualization. The tested models, of transparent Plexiglas, were two-sided wind-catchers based on a real one in Yazd city. This two-sided wind-catcher has two separate channels for the air entry and exit.

Fig. 7 shows a sample of the two-sided wind-catcher of the Iranian desert regions. A low speed smoke tunnel is used to visualize flow patterns around and inside the wind-catcher models for different upstream structures. The movement of the smoke-lines was captured with a high-speed camera at a rate of 2500 frames/s.

Fig. 5 (a) High density of construction in hot and arid region of Iran, (b) The two-sided wind-catcher and domed roof as reservoir

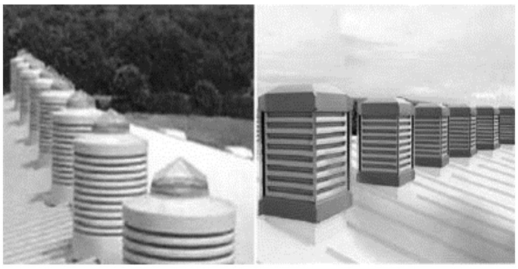


Fig. 6 Using wind-catchers in modern buildings ventilation at consecutive arrangement

Fig. 7 A sample of two-sided wind-catchers of the Iranian desert

Fig. 8 Experimental setup and wind-catcher model

The instrumentation and techniques used to illuminate the smoke filaments in the test section are important for photography. It should be noted that for obtaining the best result, the light should not illuminate the background or the wind tunnel walls in the test section. It is necessary to use lighting equipment to generate a sheet of light normal to the camera lens direction. The camera shutter was synchronized with two flash bulbs. To properly photograph smoke lines, the camera shutter speed must be fast enough to avoid blurring of the smoke. As the flow velocity gets higher, a faster shutter speed is needed and a larger amount of light is needed to have properly exposed photographs. Fig. 8 shows experimental setup and wind-catcher model which was used in this study.

III. RESULTS AND DISCUSSION

To evaluate the effect of upstream structures on flow pattern around and inside the two-sided wind-catcher, structures with different heights were used. Fig. 9 shows flow patterns around and inside of an isolated wind-catcher. In this state, air enters from the windward opening of the wind-catcher and then circulates in a room. Some portion of this air exits the room from a window and some portion exits the room from the leeward side of the wind-catcher. Flow in the leeward channel has a high intensity of turbulence, so disarray flow patterns exist in this channel. Nimbus of flow in front of the leeward opening shows flow driven out from the leeward channel. This action confirm that a leeward wind-catcher operate as a chimney. The flow separation from lower edge of the wind-catcher opening considerably decreases the effective area of passing flow. In other word, a separation zone in the wind-catcher's channel is a disadvantageous phenomenon. It is thus postulated that reducing the effects of separation at the entrance zone will increase the ventilation capacity of the wind-catcher. It was seen in Fig. 9 that the approaching free-stream to the wind-catcher directed toward the upper half of the opening and the flow separation from lower edge of the opening stimulates this phenomenon. It is also seen in Fig. 9 that even one of the smoke lines sticks to the inner side of wind-catcher roof. In summary, factors that reduce wind-catcher ventilation capacity are:

1. Separation of flow from the lower edge of the wind-catcher opening (that reduce the effective flow passage area),
2. Formation of large vortices in the separation zone and deviation of entering flow towards the upper half of the wind-catcher opening (which scales the recirculation zone size).

Controlling these factors enhances the wind-catcher ventilation performance. Flow separation from the upper edge of the windward face of the wind-catcher leads to shear layer formation, which ultimately leads to KH (Kelvin–Helmholtz [13]) structure formation.

In Fig. 10, the flow patterns around and inside the wind-catcher in the presence of an upstream structure with height 0.5H at the distance of 0.75H is located, is shown (H is the height of the wind-catcher). Smoke lines in Fig. 10 show that the presence of the upstream structure with height 0.5H, at the vicinity of wind-catcher decreases the affected area by flow separation from the lower edge of the windward opening. In other words, in this case, the air flow induced by wind must be increased. A shear layer, which separated from the upstream structure, has high velocity. It is expected that airflow rate became more than seen in an isolated wind-catcher because the windward opening is located at the path of shear layer. At this state, similar to isolated wind-catcher, air enters the room from the windward opening, and after circulation in the room it exits from the leeward opening and a room's window. In the presence of this upstream structure, the vortices formed in the windward channel of isolated wind-catcher vanished. Flow separation from the upper edge of the windward face of the wind-catcher leads to shear layer formation, which ultimately leads to KH structure formation, similar to an isolated wind-catcher.

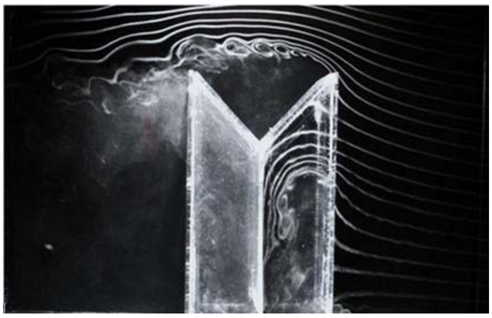


Fig. 9 Visualized flow pattern around and inside the isolated two-sided wind-catcher

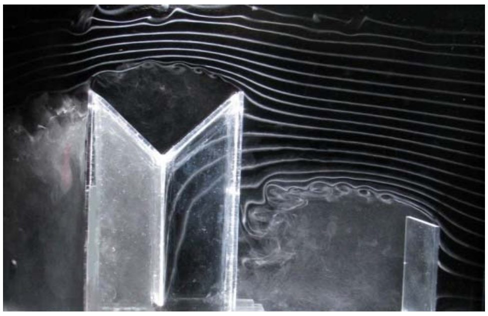


Fig. 10 Visualized flow pattern around and inside the two-sided wind-catcher with upstream structure (h=0.5H & X=0.75H)

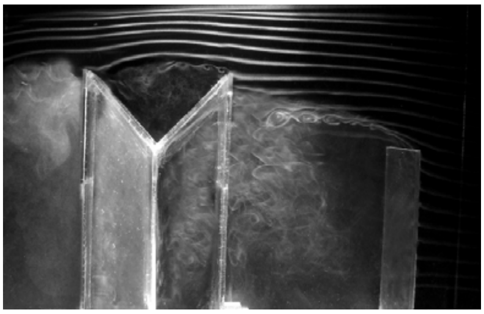


Fig. 11 Visualized flow pattern around and inside the two-sided wind-catcher with upstream structure (h=0.75H & X=0.75H)

When structure with a height of 0.75H and distance relative to wind-catcher of 0.75H (h=0.75H & X=0.75H), is placed at the front of the windward face of a wind-catcher, the performance of windward wind-catcher was reversed. As shown in Fig. 11, the windward wind-catcher acts as a chimney, hence air enters the building from a room window and leaves through both the windward and leeward wind-catchers. A windward opening was located in the nether of shear layer, in other words windward opening placed in the wake of upstream structure. Wake zone has low pressure so the windward opening's pressure is lower than building pressure; for this reason air direction in the windward channel is reversing. As clearly seen in Fig. 11, two wind-catchers operate similarly. In this state no airflow enters the room from the wind-catchers. KH structures which formed in this state are very unstable so very soon disappear.

Fig. 12 shows a two-sided wind-catcher in the presence of an upstream structure with height equal to the wind-catcher's height and at a distance of 0.75H relative to wind-catcher. Two-sided wind-catcher was perfectly located in the wake of an upstream structure. According to Fig. 12, two wind-catcher's openings operate as a chimney similar to Fig. 11. Ventilation performance of a two-sided wind-catcher in this state was such that air enters the building through a room window, and after circulation in the room space, it leaves through two channels of the wind-catcher. It is predicted that stack efficiency of a windward wind-catcher will be increased when height of the upstream structure increases. In this case we observe KH vortices which formed at the upper edge of the wind-ward face disappeared. Because the shear layer that separated from the upstream structure contacts the upper edge of the windward face it did not allow the creation of a KH structure.

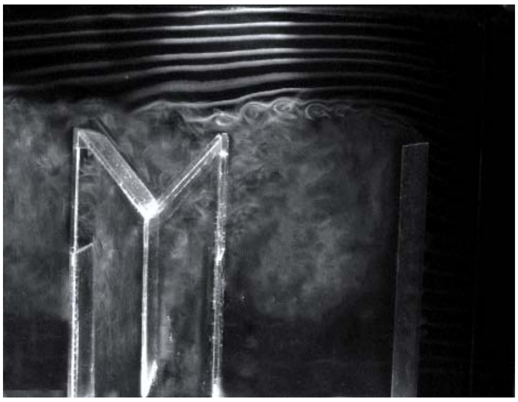


Fig. 12 Visualized flow pattern around and inside the two-sided wind-catcher with upstream structure (h=H & X=0.75H)

Fig. 13 Visualized flow pattern around and inside the two-sided wind-catcher with upstream structure (h=1.25H & X=0.75H)

In this study, the effect of an upstream structure with the height higher than the wind-catcher height on the flow pattern was also carried out. Fig. 13 shows the flow pattern around and inside a wind-catcher in the presence structure with 1.25H height, placed at 0.75H from wind-catcher. Flow exit through both openings of the wind-catcher confirm that two openings have similar operation so a two-sided wind-catcher operates as a chimney. Fig. 13 indicates that a tall building located in front of wind-catcher influences ventilation performance. Because of the wake of the upstream structure, a low pressure zone is created around a wind-catcher's openings. This low pressure zone causes airflow to enter the building through room windows and leave that building through both wind-catcher openings.

IV. CONCLUSION

In order to determine the airflow characteristics around and inside isolated two-sided wind-catchers and a wind-catcher in the presence of upstream structures, smoke visualization tests were carried out. The wind-catcher model tested was the two-sided wind-catcher, constructed from two similar one-sided wind-catcher models attached together back to back. The visualized flow structures showed the separation of incoming flow from the lower edge of the wind-catcher windward opening resulting in a large recirculating vortex in the separation zone, and reduction of airflow passage effective area. It was also observed that the approaching air stream tends to move towards the upper part of the wind-catcher opening. In this paper, the influence of the upstream structure height on the flow structure around and inside the wind-catcher is experimentally investigated by smoke flow visualization techniques. The results show that the performance of the wind-catcher in the high-density urban areas is dependent on the upstream structure height and its distance from the wind-catcher. The results show that exposure to low upstream structure with height 0.5H at distance 0.75H from the wind-catcher, will increase the airflow to the building (In this case the wind-catcher acts as a blower device). Placing upstream structures with height greater than half the height of the wind-catcher at a distance 0.75H causes the wind-catcher to be placed in the wake of upstream structures and airflow to be moved from the building to the wind-catcher (In this case the wind-catcher acts as a suction device).

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