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Experimental study on natural ventilation performance of one-sided wind catcher

H Montazeri*, R Azizian

Department of Mechanical Engineering, School of Engineering, Yazd University, Yazd, Iran

Abstract

Aerodynamic performance of a one-sided wind catcher was investigated by experimental wind tunnel and smoke visualization testing. Wind catchers or what is called Baud-Geers in Persian language was a main component of buildings in central region of Iran and the neighboring countries. A Baud-Geer is a tower used to capture wind from external air stream and induce it into the building in order to provide natural ventilation and passive cooling. Due to geographical coordinates of the region, wind power and the direction of blowing wind, wind catchers are employed in different heights, cross sections of the air passages and the places and the number of the openings. The one-sided wind catcher has only one channel as a passage of induced air and is often related to the areas where there is prevailing wind. These Baud-Geers are employed to catch the wind blowing at higher elevations and direct it to the building, causing it to leave through windows, doors or other exhausted segments. In this study a 1:40 scale model of Kharmani's School Baud-Geer was employed and the induced air flow rate into the test room and the pressure coefficients around all surfaces of its channel were measured for different values of approaching air incident angles. Using measured pressure coefficients, the theoretical values of ventilation air flow were estimated to evaluate ability of simplified models in natural ventilation studies. Due to placing of urban full-scale wind catchers in the boundary layer of atmospheric winds, the effect of this phenomenon was also examined. The experiments were conducted when the wind catcher model with adjoining house was placed in the wake of upstream objects, resembling neighboring buildings. It was found that for an isolated wind catcher model, the maximum efficiency is achieved at zero air incident angle. Also it was concluded that the angle of incidence of the wind, the presence of an upstream building around the structure and blowing of atmospheric wind influence the pressure coefficients, the rate and the direction of ventilation air flow.

Keywords: wind catcher (Baud-Geer), Ventilation, Pressure coefficient, Flow rate, Experiment

1. Introduction

Buildings in hot and humid climates have been traditionally cooled by ventilation. Wind catcher or what is called Baud-Geer in Persian language has been employed in arid central regions of Iran and the neighboring countries to provide natural ventilation and passive cooling. In these regions due to the hot summer time, the buildings used to have special architectural features and components in order to protect the occupants from the harsh outdoor environment. The function of the Baud-Geer in these regions is to capture wind from external air stream and induce it into the building and courtyard in order to cool the occupant directly by increasing the convective and evaporative heat transfer from body surface. It cools the occupant indirectly by removing heat stored in the building structure. When wind is blowing over the tower and the building it severs, a wind pressure develops on various apertures. Air enters from the windward openings, with positive wind pressure coefficient, and leaves the leeward openings, with negative or lower values of the pressure coefficients [1].

Shapes, heights and internal structures of Baud-Geers were not only influential to the volumetric air delivery and cooling capacity of the building, but were an indication of dignity, wealth and social position of the house

* **Corresponding author:** Hamid Montazeri
E-mail address: h.montazeri@tue.nl

owners. They can be beautiful objects, feasible architectural feature additions to buildings and are inherently durable [2, 3]. Nowadays due to geographical coordinates, wind power and the direction of blowing wind, wind catcher designs differ in the height, the cross section of the air passages, the placement and number of the openings and the placement of the wind catcher with respect to the structure it cools. The wind catcher systems come in various configurations to suit various building type and requirements such as the incorporation of solar panel and light pipes to boost stack effect [4, 5]. Wind catcher is normally a tall structure with the height from 5 to 33 m mounted over the building roof. With taller tower capturing winds at higher speeds and with less dust [1]. The number of directions in which Baud-Geers face is different; therefore these towers are often classified to the number of their openings. One-sided, two-sided, four-sided (triangular cross section) and six-sided (hexagonal cross section) Baud-Geers are more common in Yazd. From many old buildings and houses equipped with Baud-Geers, Mahmoodi's house, Lariha's house and Dowlat-Abad garden Baud-Geers are the most famous ones which are the favorite tourist attraction areas in Yazd. Figure 1 shows several old Baud-Geers with different number of openings.

In the modern design of wind catchers, the two ventilation principles of wind tower and passive stack are combined in one design around a stack that is divided into two halves or four quadrants with the division running the full height of the stack [6, 7]. As the wind direction changes so do the functions of each of the halves or the quadrants in the wind catcher. This causes the wind catcher to be operational which way the wind is blowing.

Several academic studies have been reported in the field of hydrodynamic analysis of Baud-Geers for natural ventilation. Bahadori [8] in his first study determined the pressure coefficients of a 1:100 scale model of a wind tower attached to a house by testing it in a wind tunnel, where the atmospheric wind was simulated by means of horizontal rods and a vertical screen. The effects of adjoining house and courtyard in the pressure coefficient distributions were also investigated. The tower corresponded to a full-scale height of 10 m with openings on all four sides. Karakatsanis et al. [9] improved earlier model studies carried out by Bahadori [8]. In that study a model of the same building, but of different model scale, was tested in the boundary layer wind tunnel laboratory. Pressure coefficients were determined and natural ventilation through the building was estimated. Elmualim et al [10] carried out experimental investigation and CFD simulations to evaluate the performance of square and circular section wind catchers. Results showed that the efficiency of four-sided wind catcher is much higher than that for the circular one for the same wind speed. They explained this is due to the fact that the sharp edges of the square one create a large region of flow separation and higher pressure difference across the device. The hydrodynamic analysis of flow in wind catchers was done by Montazeri et al [11] using CFD technique. That work was based on the numerical solution of the two-dimensional Navier-Stokes. They concluded that the separated flow and wake region near to the lower edge of wind catcher opening cause the induced capacity of wind catcher to be decreased considerably. Elmualim [12] analysed performance of a wind catcher natural ventilation system which was installed in a real room. The results showed the chosen ventilation design provided a substantially greater ventilation rate than an equivalent area of openable window.

Most of previous related studies [8-12] have looked at the ventilation performance of four-sided wind catchers. Short-circuiting (the air entering through supply openings and leaving through another without flowing inside the house) is a harmful phenomenon in these structures. In the present study, one-sided wind catcher with a single opening was investigated. In this type of wind catcher, there is no short-circuiting and entire air, which is passed through the channel, flows inside the room. Moreover, many attempts have been made to estimate ventilation air flow rate as a main parameter in the passive cooling systems [9-13]. In the present study, a scale model of Kharmani's School Baud-Geer was employed and using the accurate measurements, the induced air flow rate into the test room and the pressure coefficients around all surfaces of its channel were measured for different values of approaching air incident angles. Also using measured pressure coefficients, the theoretical values of ventilated air flow were estimated to evaluate ability of simplified models in natural ventilation studies.

Initially and prior to all testing, smoke visualization tests were carried out in order to recognize the flow pattern in and over the wind catcher model. Further, flow visualization tests helped to identify the supply and extract segments during all tests.

Wind catchers are traditionally used in places of high urban densities where surrounding buildings obstruct free stream air flow [14]. Due to placing of urban wind catchers in the boundary layer of atmospheric winds, in this study, the effect of this phenomenon was also examined. The experiments were also conducted when the wind catcher with its house model was placed in the wake of upstream objects, resembling neighboring buildings.

2 Experimental Procedure

In this study, a 1:40 scale model of an ancient one-sided wind catcher was employed. The experimental investigations were conducted in an open working section subsonic wind tunnel located in the thermodynamics laboratory of the school of mechanical engineering of Yazd University. This wind tunnel is designed for the experimental testing of natural ventilation devices and has a test section with height, width and length of 46, 46 and 360 cm, respectively. According to the dimensions of models and wind tunnel cross section, the scaled model produced a maximum wind tunnel blockage of 5%, then no corrections were made to the pressure measurements obtained with these configuration.

In aeronautical studies, it is normally required that the Reynolds number for the model and the full-scale body it represents be the same. This would require that the 1:40 scale model be tested at velocities about 40 times that of the prevailing winds, something not possible to accomplish. But, it has been found that the hydrodynamic behavior and the pattern of the air flow in buildings are independent of the Reynolds number which is due to the forced flow separation at the angular corners of these geometries. Such that, a wide variation in wind velocity does not affect the pressure distribution or the flow pattern, if the test velocity is maintained above a certain limit [8]. In this study and for the present model this value corresponds to 7 m/s.

The wind direction along with the geometry of wind catcher are the main parameters those influence the wind pressure distribution and air flow rate on a given building, thereby in this study, all test cases were also performed for approaching air angles of 0 to 180 in 15^o increments.

2.1 The Wind Catcher Model

One-sided wind catcher is often related to the areas where there is prevailing wind. In these regions, the air enters from its single opening and passes through the building and at last leaves window, door or other exhausted segments. In this study, one-sided wind catcher model is a scale model of Kharmani's School Baud-Geer in Ardakan. Figure 2 shows the Kharmani's School Baud-Geer, which is located at the back of a neighboring wind catcher.

The scale model was constructed from wood and 23 internal pressure taps were installed at three surfaces of its channel to measure static pressure at those points. These three surfaces are marked S (L), S (P) and S (R) as left, projected and right surfaces. In addition, in order to measure induced air flow rate, 20 pitot and 11 static tubes were installed at the bottom of channel. Because of different angles of wind catcher opening relative to the blowing wind, a reversal of the flow direction through the building appears and the wind catcher acts as a suction device. In these cases, 10 pitot and 5 static tubes were employed at the top of channel to allow the measurement of ventilation air flow rate. The model was so constructed that could be rotated in the test section in order to provide different approaching air directions. Figure 3 shows constructed model under investigation with the attached pressure taps, pitot and static tubes at the bottom of its channel. Figure 4 shows the isometric drawing of scale model and locations of pressure taps along with their dimensions. As it is shown, the opening and the underneath air channel area of the wind catcher are equal to 35 and 20 cm^2 respectively.

The wind catcher model was attached to a scale model of an actual house, which was installed under the wind tunnel floor. The house model had a single vertical window as an exhausted device, which was placed at the end of it. Note that the area of the window was equal to the area of the opening of wind catcher and the dimensions and position of this window were fixed in all experiments. Figure 5 shows the isometric drawing of house scale model along with their dimensions.

2.1 Measurements of Pressure Coefficients and Ventilation Air Flow

The most important factor influencing internal flows in a naturally ventilated structure is the external pressure field induced by the wind. The wind pressure coefficient C_P is defined using the following formula:

$$C_P = \frac{p - p_s}{\frac{1}{2}\rho V_{ref}^2} \tag{1}$$

In this equation, p is the surface pressure measured at each location, p_s the static pressure, V_{ref} the reference wind velocity and ρ is the air density. Upstream static and total pressures were measured using a pitot-static tube, which was placed 16.5 *cm* upstream of the test model and 12 *cm* above the wind tunnel floor. Several pressure taps were neatly placed at aperture of the model to measure static pressure at those points.

Several tiny and sensitive pitot and static tubes are used to measure the air flow rate passed through its single channel. For this purpose, the stainless steel tubes with an outside diameter of 1 mm were employed. Because of the different angles of openings relative to the direction of incoming air, its opening may acts as supply or extract; so it was required that these pitot and static tubes set at both top and bottom segments of channel. Furthermore, experimental and numerical [11,15] investigations show that at the entrance openings and near to the lower edge, there exists a separated flow and circulation zone due to the rotation of incoming air stream into the underneath air channel which causes a non-uniform flow inside the underneath air channel. Therefore, it was decided to use more pitot tubes at the bottom of windward channel. The cross section area of channel was divided to several portions and the air flow rate passed through it was calculated as follow:

$$Q = \sum_{i=1}^{n} A_i V_i \tag{2}$$

Where Q is the flow rate through the channel of wind catcher and A_i and V_i are the area and velocity of portion i , respectively.

2.2 Simulation of Atmospheric Wind

In the wind tunnel that used in this study, wind profile was nearly uniform. This simulates the wind high above the surface of the earth. At lower levels, the frictional drag of the surface produces a boundary layer in which there is a progressive reduction in speed toward the ground surface. Then there is considerable difference between the pressure distribution found in models tested in uniform flow wind tunnels and those from full scale studies on similar buildings [8]. Therefore, in this study, effect of this phenomenon was examined too.

Boundary layer simulation was carried out using a model law which formulated by Jensen [16]. He stated that the correct model test for phenomena in the wind must be carried out in a turbulent boundary layer and the model-law requires that this boundary layer be to scale as regards to velocity profiles.

The wind catchers usually have been used in the relatively small cities with low-rise buildings, therefore following velocity profile was employed in this study.

$$\frac{V_y}{V_\delta} = \left(\frac{y}{400}\right)^{0.28} \tag{3}$$

where V_y is the wind velocity at elevation y. Also in this profile, V_δ the wind velocity at boundary layer thickness, δ =400 m, is assumed to be constant. To create this atmospheric wind with a velocity profile given by equation (3), horizontal rods with an outside diameter of 8 mm were employed which placed close together near the floor and further apart near the roof. The wind velocity profile was measured with a hot wire anemometer located 16.5 cm upstream of the model. This velocity profile and the one with no rods are shown in Fig. 6.

All tests with uniform flow were performed for nominal wind velocity of 20 m/s. This velocity was used as the wind velocity at boundary layer thickness and then simulation of atmospheric wind was carried out according to this value.

Figure 7 shows the whole experimental test rig employed in this investigation.

2.3 Wind Shadowing Effects of Adjacent Buildings

As it is shown in figure 2-b, in urban environments, buildings are often located quite close to each other and the natural ventilation devices will be strongly influenced by the surrounding structures. In this study, the effect of a single adjacent upwind building on the ventilation performance of one-sided wind catcher was investigated. For this purpose several upstream object models with different heights were used which were located at different spacing. The width and the depth of these neighboring building models were held at fixed values equal to the dimension of wind catcher model. For each of the four height ratios, h/H=0.75, 1, 1.25, 1.5, the tests were investigated for ten spacing ratios of L/H=0.5 to 5 in 0.5 increments. It note that in order to study of wind shadowing effects of adjacent buildings, in all experiments, wind catcher was exposed under zero air incident angle.

3 Theoretical Analysis

3.1 Natural Ventilation Efficiency

Natural ventilation efficiency of one-sided wind catcher can be defined as follow:

$$\textit{Natural Ventilation Efficiency} = \frac{Q}{Q_0} \times 100 \tag{4}$$

where Q_0 is the air flow rate through the channel of wind catcher for the wind angle of 0° and Q will be the flow rate in various conditions which both were determined experimentally. In the one-sided wind catcher, entire ventilation air is passed through the occupant zone, so neglecting the extract/supply segments; natural ventilation efficiency could describe its performance effectively.

3.2 Estimation of Ventilation Rates from the Pressure Coefficients

Given a set of pressure distribution data for a building, simplified model can be used to estimate the amount of ventilation airflow through inlet and outlet. The equation for calculating the air flow through a building with one effective inlet and one effective outlet is given below [12, 17-18].

$$Q_t = C_d A_e V_{ref} (\Delta C_p)^{1/2} \tag{5}$$

where Q_t is the theoretical air flow rate (in m^3/s), C_d the discharge coefficient, A_e effective area of inlet and outlet (in m^2) and ΔC_P is the pressure coefficient difference across the inlet and outlet. These coefficients are determined through experimental studies of the wind catcher model in a wind tunnel. Combination of equations (4) to (5) gives:

$$Natural\ Ventilation\ Efficiency)_t = (\frac{\Delta C_P}{|\Delta C_{P,0}|})^{1/2} \times 100 \tag{6}$$

where $\Delta C_{P,0}$ is the pressure coefficients difference across the inlet and outlet for the zero air incident angle. Note that due to exposing the window of the house model to the atmospheric environment, the pressure coefficient of this segment will be constant for all calculations. For the wind catcher, a representative average pressure could be obtained from the pressure taps, which are located in the wind catcher opening (Pressure taps 1 and 2, in all surfaces).

Neglecting the dependence of discharge coefficient on the direction of flow, equation (6) may be used for all operating conditions of one-sided wind catcher.

4 Results and Discussions

Analysis of one-sided wind catcher can be very useful to evaluate performance of wind catchers with different configurations; Therefore in this study, various tests were carried out on its model.

In order to recognize the flow pattern in and over the wind catcher model, smoke was used. To flow visualization, both roof and one side of a one-sided wind catcher model were built of glass and the model was exposed under zero incident angle. Figure 8 shows the flow field in front face and underneath air channel of this wind catcher model. In this case, upstream velocity was equal to 7 m/s and smoke was injected to the air flow as a vertical line. The separated flow and wake region can be seen near to the lower edge of its opening which cause the pressure coefficient varies sharply in this region. Furthermore, due to existence of these phenomena wind catcher could not achieve its maximum efficiency. In addition, the presence of wake region in the air passage strongly influences the induced air velocity distribution through the channel.

Figure 9 shows the top view of the passing flow through the wind catcher for various air incident angles. As it is shown in figure (9a), situating wind catcher on the route of prevailing wind streams (zero angle), will cause the maximum entrance flow rate into the isolated wind catcher. With increasing the air incident angle, the vortices that appear into the channel and perpendicular to the air passage, decrease the induced air flow rate (9b). Also with increasing the wind angle and hence developing the region of influences of vortices, the induced operation of wind catcher will reduce continuously (9c) to its minimum value at the "transition angle". At this angle that is equal to 68 degrees for Kharmani's School Baud-Geer model, the vortices surround the whole opening of the wind catcher and won't let the flow to enter wind catcher indeed.

Exceeding the wind angle over the transition angle, will cause a change in air flow direction into the wind catcher. In this situation, wind catcher acts as a suction device, so the air enters from the window, passes the whole internal spaces, and finally leaves there from the wind catcher opening. This is due to the fact that exposing the body of wind catcher on the route of air stream, causes a low-pressure wake region behind it and posing its opening there in that region with the pressure lower than the environment pressure, will result in an air flow from window to the wind catcher opening.

Figure 10 shows the variations of C_P with the distance y in all three surfaces of opening and its conduit for different values of approaching air incident angles. As it is shown, under zero incident angle, for all surfaces and for points 1and 2, the pressure coefficients are positive while for points 3 to 8, they become negative. It should be mentioned that points 1 and 2 are exposed to the incoming air stream while points 3 to 8 are positioned inside the underneath air channel. Incoming air impinges on point 1 and hence their pressure coefficients exhibit their maximum values. In this case, as the air bends 90 degrees to proceed its way downward through the underneath channel, it accelerates and therefore its pressure coefficient starts decreasing and finally in point 3, it becomes negative. Variation of the pressure coefficients indicates an initial acceleration of the air inside the channel and deceleration of it afterward. Figure 10 also shows considerable reduction in the pressure coefficients at points 3 and 4. The reason for this variation is that, at the entrance opening and next to the lower edge (in the vicinity of point 3), there exists a separated flow due to the rotation of incoming air stream into the underneath air channel. Thereby, after the flow separation and in the region of air vortices, the air pressure decreases sharply.

According to the figure 10, for low values of air incident angles, pressures on the windward side of model exhibit large differences between individual surfaces. This is due to flow separation at exterior segment of surface, which is exposed to the incoming air stream. In these wind directions, the average pressure coefficient of the wind catcher opening will be larger than the one for window and then wind catcher captures wind from external air stream and induces it into the building. The induced air leaves house from the window.

By increasing the air incident angles and near a wind angle of 70, pressure coefficients around the all surfaces will be almost identical and equal to the environment pressure coefficient. In this angle, which is named transition angle in the present study, the flow pattern will be very complicated. When the wind angles exceed transition angle the wind catcher acts as a suction device. In these cases, the pressure coefficients are nearly constant at all tap locations for a given wind angle. This clearly demonstrates how the wake region encompasses the entire leeward side of the model.

Figure 11 shows natural ventilation efficiency of one-sided wind catcher versus wind angle for uniform and atmospheric wind simulating flows. It is seen that the results follow similar trends for both cases. As it is shown for an isolated wind catcher maximum efficiency is achieved at zero air incident angle. In this case, the induced air flow rate was equal to 0.016 m^3/s. For wind direction angles lower than transition angle, the natural ventilation efficiency decreases by increasing the wind direction. Maximum reduction in this efficiency is achieved at the transition angle. In this case, there is no flow rate through the wind catcher and its house and then the value of natural ventilation efficiency tends to the zero. With the increase of wind direction and by placing of wind catcher opening under the wake of the upstream air, one-sided wind catcher acts as a suction device and its performance considerably is improved. As described in Figure 10, at large wind angles, opening of the one-sided wind catcher experiences large negative pressure coefficients and then pressure difference across the inlet and outlet increases. This causes for wind angle of 180°, wind catcher has largest ventilation efficiency as a suction device.

The performance of the wind catcher decreases for atmospheric wind simulating by 50% at zero air incident angle. This ratio is approximately constant for all air incident angles.

Table 1 gives the experimental and theoretical values of natural ventilation efficiency for different values of approaching air incident angles. According to these results, the general agreement of the theoretical result with the present experimental data is relatively satisfactory. This comparison reveals that the theoretical method can accurately evaluate the ventilation performance of one-sided wind catcher. It can be concluded that although the specific values of the discharge coefficient, inlet and outlet areas and reference velocity will directly influence the obtained air flow volume, an analysis of $(\Delta C_P)^{1/2}$ helps to clarify the characteristic performance of the ventilation configuration.

Figure 12 shows the variation of natural ventilation efficiency of one-sided wind catcher with spacing ratio for different values of height ratio of a single upstream building. For the taller upstream object and at small spacing, opening of the model lies in the wake region of the upwind model. In these cases, this segment experiences lowers pressures than the window of the building and acts as a ventilation flow outlet. In this conditions and at the fixed spacing, natural ventilation efficiency of wind catcher increases with increasing height of upstream building. By more increasing the building spacing, wind catcher enters the transition region, where the ventilated airflow and hence its efficiency decrease to their minimum values. Hence, it can be concluded that the one-sided wind catcher, which is located at the transition spacing of a tall upstream building is incapable of doing its duty as a passive air ventilation devices. In the transition region where the flow pattern is very complicated, there are no certain inlet and outlet and the direction of ventilation airflow reverses continuously.

Getting farther from the neighboring building and leaving back the transition region, wind catcher will do its induced operation again. In this condition ventilation efficiency is improved with increasing spacing for the all height values. In these cases and at a fixed spacing a reduction in induced flow can be seen for taller building which is due to the fact that the model and specially a portion of opening are under the wake of that upstream building. By increasing the height of upstream object model, the position where the flow field is separated remains fixed, therefore approximately entire area of wind catcher place in the wake region and passive air ventilation is reduced.

From Fig 12 also it can be seen, placing of an upstream building with a shorter height in compare with wind catcher increases its efficiency especially in small spacing ratios. In this situation the effects of flow separation at several locations of wind catcher especially in the vicinity of lower edge of its opening are reduced and cause the induced capacity of wind catcher to be increased considerably. In other words for an isolated wind catcher and at zero incident angle, the separated flow and wake region near to the lower edge of its opening cause the wind catcher not to achieve its maximum ventilation efficiency. By increasing the spacing ratio the wind catcher tends to act as an isolated wind catcher and then its performance is reduced.

Smoke visualization tests were carried out to demonstrate the effect of a short upstream object on the ventilation performance of one-sided wind catcher. The results are shown in figure 13. It is seen that in compare with isolated wind catcher, Fig. 13(a), placing of one-sided wind catcher model under the wake of a short upstream object leads to decrease of the circulation region at the entrance opening and next to the lower edge. This causes the effective inlet area of the wind catcher increases and its ventilation efficiency improves considerably, Fig. 13(b).

5 Conclusions

In central or arid regions of Iran and the neighboring countries, wind catchers which are named Baud-Geers in Persian literature, were one of the main components of the old buildings. In the absence of modern air conditioning systems or mechanical driven air ventilation equipments, they were responsible to capture wind from any direction and guide it to the house or occupants zones. In this study, a 1:40 scale model of Kharmani's School Baud-Geer was employed and the induced air flow rate into the test room and the pressure coefficients around all surfaces of its channel were measured for different values of approaching air incident angles. Using these pressure coefficients, the theoretical values of ventilation air flow were estimated to evaluate ability of simplified models in natural ventilation studies. In this study, the effect of placing of urban wind catchers in the boundary layer of atmospheric winds was also examined. The experiments were conducted when the wind catcher model with adjoining house was placed in the wake of upstream objects, resembling neighboring buildings.

Results showed that the one-sided wind catcher has the potential to be an effective ventilation design for urban settings.

The separated flow and wake region near to the lower edge of wind catcher opening cause the pressure coefficient varies sharply in this region and the induced capacity of wind catcher to be decreased considerably.

The air flow rate from the wind catcher to the house strongly depends on the pressure coefficients at the wind catcher opening. These coefficients vary sharply with the air incident angle. Depending on the wind angle, the air may flow from the house to the wind catcher. In this case wind catcher acts as a suction device, so the air enters from the window, passes the whole internal spaces and finally leaves there from the wind catcher opening.

The performance of the wind catcher decreases for atmospheric wind simulating by 50% at zero air incident angle. This ratio is approximately constant for all air incident angles.

By using the simplified models to estimation of natural ventilation efficiency of one-sided wind catcher, the general agreement of the theoretical result with the present experimental data is relatively satisfactory.

Reducing the effects of separation at several locations of wind catcher especially in the vicinity of lower edge of its opening will cause the induced capacity of wind catcher to be increased considerably.

Placing of an upstream building with a shorter height in compare with wind catcher increases the efficiency of wind catcher especially in small spacing ratios. For the taller upstream object and at small spacing, opening of the model lies in the wake region of the upwind model and wind catcher acts as a suction device. Getting farther from the neighboring building and leaving back the transition region, wind catcher will do its induced operation again.

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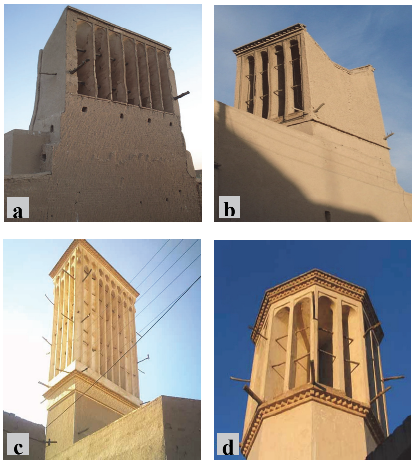

Fig. 1 several old Baud-Geers with different number of openings, one-sided (a) two-sided (b) four-sided (c) and six-sided (d) wind catchers.

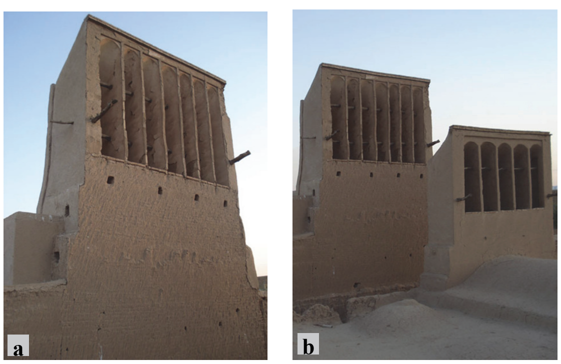

Fig. 2 Kharmani's School Baud-Geer (a) which is placed at the back of a neighboring wind catcher (b).

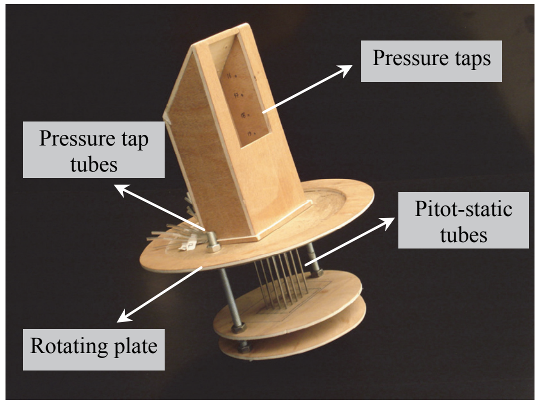

Fig. 3 One-sided wind catcher model with the attached pressure tabs, pitot and static tubes.

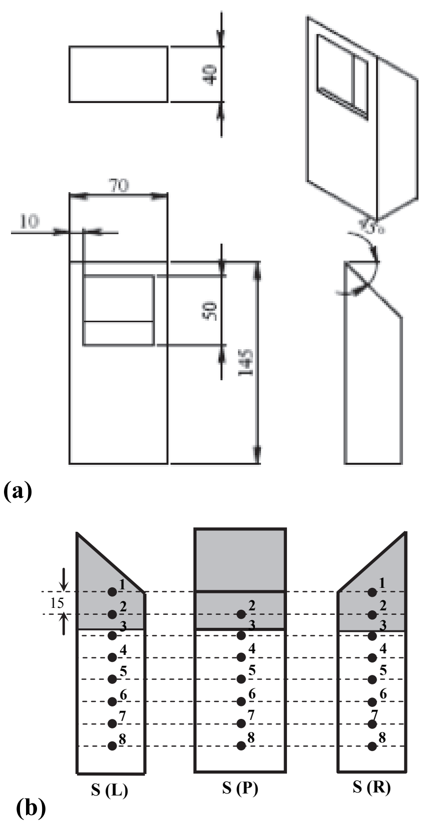

Fig. 4 Isometric view of the one-sided wind catcher model (a) and locations of pressure taps (b). Dimensions are in millimeter

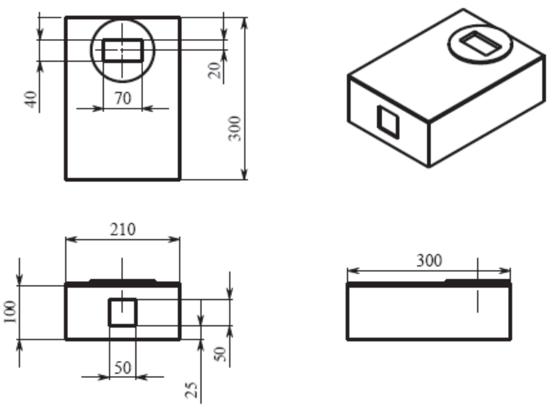

Fig. 5 Isometric drawing of house scale model along with their dimensions

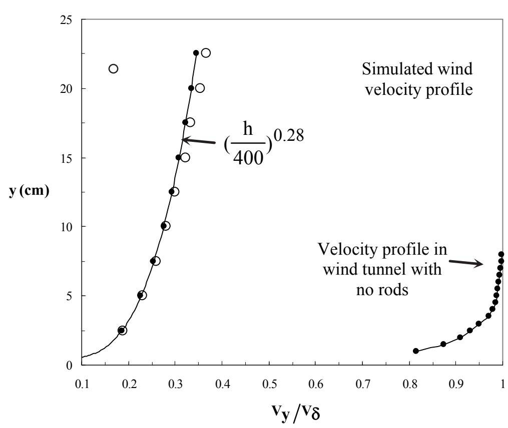

Fig. 6 Atmospheric wind velocity profile simulated in wind tunnel

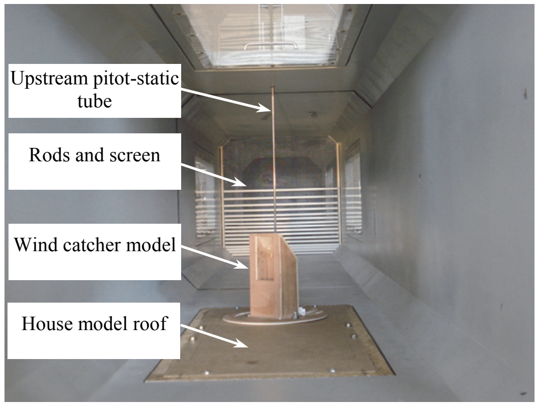

Fig. 7 The wind tunnel and experimental test rig

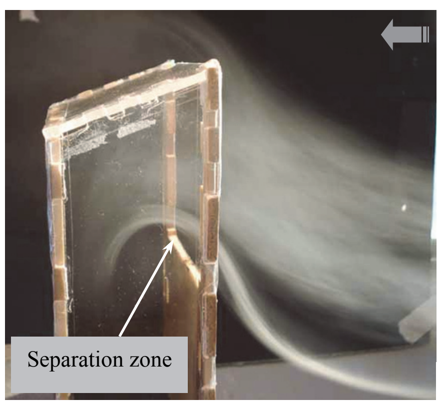

Fig. 8 Flow visualization with smoke, for one-sided wind catcher model under zero incident angle.

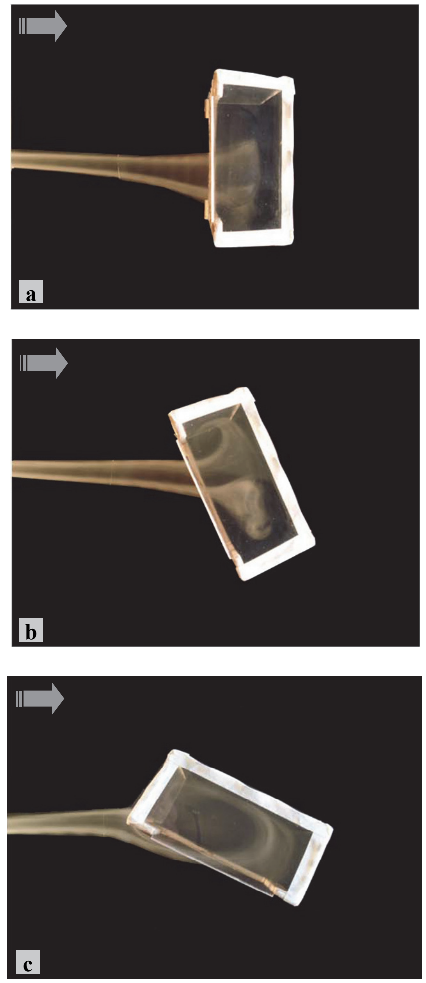

Fig. 9 Flow visualization with smoke, for one-sided wind catcher model under 0º (a) 30º (b) 60º (c) incident angles

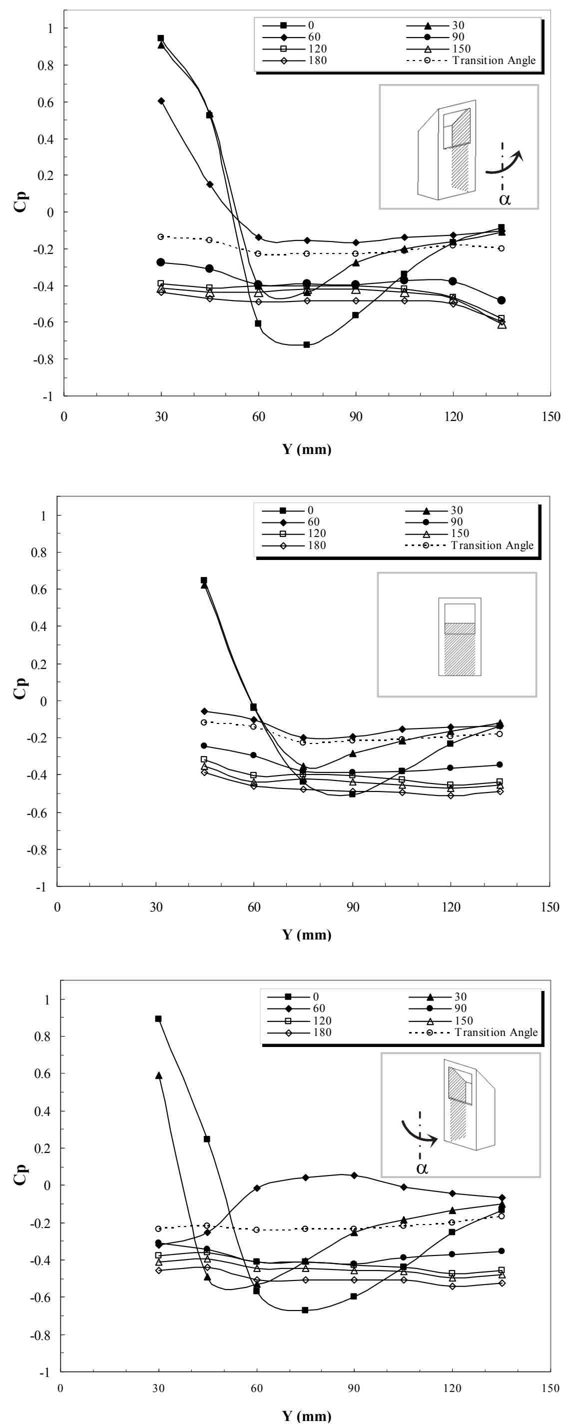

Fig. 10 Variation of the pressure coefficient in all surfaces (a) left surface (b) middle surface (c) right surface

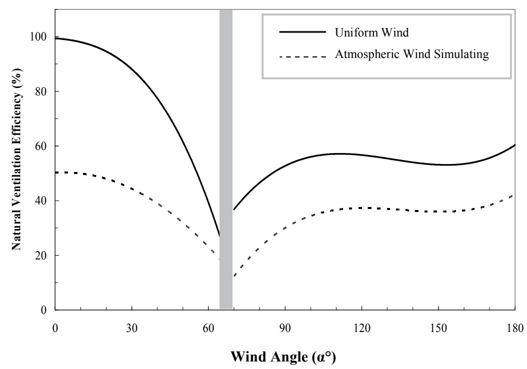

Fig. 11 Natural ventilation efficiency versus wind angle for one-sided wind catcher

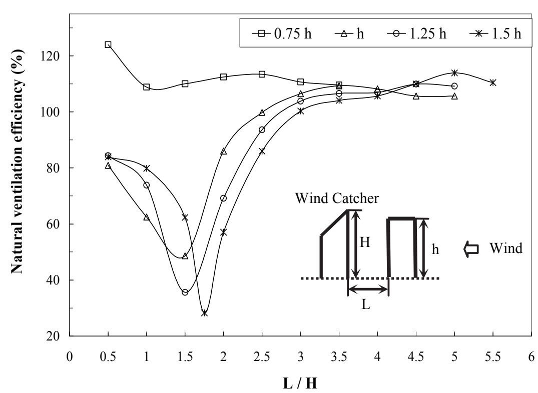

Fig. 12 Variation of Natural ventilation efficiency with spacing ratio for different values of height ratio of upstream object

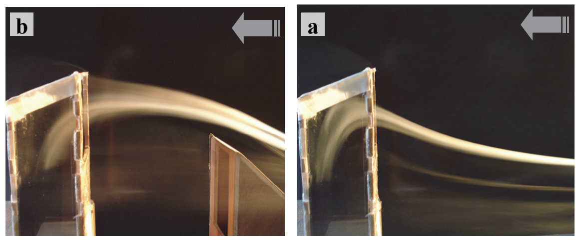

Fig. 13 Flow visualization with smoke, for isolated wind catcher model (a) and placing under the short upstream object.

	Natural Ventilation Efficiency (%)	
Wind Angle	Experimental	Theoretical
0	100	100
30	91	93
60	39	40
90	54	48
120	55	56
150	53	60
180	59	63

Table 1 experimental and theoretical values of natural ventilation efficiency for different values of approaching air incident angles.