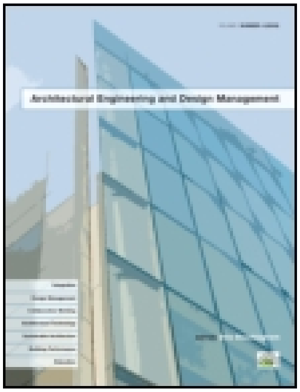

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Effect of Integrating Wind Catchers with Curved Roofs on Natural Ventilation Performance in Buildings

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ARTICLE

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Abstract

In an investigation into wind-induced natural ventilation performance in buildings, this study uses Computational Fluid Dynamics to examine the effect of integrating wind catchers with curved roofs, implementing three-dimensional modelling. It is intended to give more value to the symbolic role of the dome, vault and tower in architectural design. The early findings of this study revealed that curved roofs induce natural ventilation in buildings by suction. This is generally true for the central and upstream zones of deep-plan buildings, but not for the downstream zone. Thus, wind catchers can be used to overcome this problem. This has been investigated by considering different geometrical and climatic parameters. The results show that the proposed ventilation system increases airflow rates and improves internal airflow distribution.

■ *Keywords* – Natural ventilation; CFD; vault; dome; wind catcher

INTRODUCTION

Domed and vaulted roofs have been used separately or together in many types of buildings for centuries. In many cases, towers have been used with these curved roofs in a unique architectural cluster. For example, Escring (1998) has highlighted the role of domes and towers in the architecture of the Mediterranean region. He stated that in almost every city, with either modern or ancient architecture, there were many instances of the use of this architectural couple. This is also true for the vault, as can be observed in numerous examples in vernacular and contemporary architecture. The architectural elements of dome, vault and tower can be found in many types of buildings – residential, religious and cultural – in addition to other types of public buildings. From an environmental point of view, the important architectural role of these three elements can also be utilized to serve the need of sustainability in contemporary architecture.

In the early stages of this study, it was concluded that the use of domed and vaulted roofs for natural ventilation induced more inflow rate through the building. They also caused some of the outflow to leave through the roof openings instead of the wall openings. This improved natural ventilation performance in the upstream and central zones of the tested deep-plan buildings, but did not guarantee a significant improvement in the downstream zone. Thus, it was concluded that there is a need for a wind-inducement element in this zone of the building. This study suggests that this element can be the wind catcher, in order to reintroduce the architectural relationship between towers and curved roofs.

Wind catchers are designed to capture and drive airflow through their top opening, which usually faces the prevailing wind. During daytime, the operation mechanism of the catcher is dependent on the wind effect due to the air pressure difference across the inlet and the outlet. The catcher traps and channels down air at a higher velocity and lower pressure than the ambient air. This is known as the Venturi effect. It is also possible to use evaporative cooling to cool the air. During night-time, the relatively lower outdoor air temperature helps to cool the building, so that it can absorb some of the heat gains it will make the next day. If there is no wind, then the heat released by the catcher heats up the air inside it and drives it outside the building. This is effective when the diurnal variation in ambient temperature is high.

Wind catchers have attracted the attention of many researchers and architects for performance analysis, improvement and reuse. This is well reviewed in many works including Bahadori (1985, 1994), Yaghobi *et al* (1991), Fariga (1997), Al-Qahtani (2000) and Al-Koheji (2003). These studies have focused on many factors that affect the use of wind catchers for wind-induced natural ventilation. For example, Al-Qahtani (2000) has evaluated the performance of a wind tower building in Saudi Arabia. The study involved full-scale measurements of airflow rate in an existing tower. After that, different parameters were varied in a wind tunnel study to find out their effect. Many improvements have been recommended such as the use of a pitched roof on the tower to increase the suction effect, the use of automatic shutters for airflow rate control, and the use of a wing wall to protect the outlet from the incoming air. The improved design was constructed and mounted. Then the full-scale measurements for both designs were compared. Al-Qahtani claimed that the new design appears to provide an increase of 80% in the flow rate.

Bahadori (1985) has implemented a fluid flow analysis through a tower in order to achieve the required pressure difference between the tower inlet and outlet. This has been done systematically and for different sites and climatic conditions of hot, arid areas. It was possible to determine the dimensions of the tower, including its height, and to calculate air velocity at different points along the tower and at the occupied level of the building.

Priolo (1998) has claimed that integrating the dome with other natural ventilation devices such as windows, wind towers and wind catchers could increase the effectiveness of its suction ventilation. The same assumption can be made in the case of vaulted roofs, and many examples of this application can be found in vernacular and contemporary architecture. However, the author could not find any detailed study of the potential of integrating vaulted roofs to improve natural ventilation in buildings.

An early study on the combination of wind catchers and roof vents was carried out for the house of Othman Katkhuda in Cairo (Fathy, 1986). In this traditional house, a wind catcher has been built on the roof of a northern room. Air enters the catcher and passes through the room slowly, before it accelerates towards the main living hall. The hall is covered by a pitched roof, with many roof vents incorporated at its base. Thus, air rises in this hall from the high-pressure zone to the lower-pressure zone, until it leaves through these roof vents. In spite of the interesting findings of this study, the data are limited to the case that has been tested, and it lacks a systematic approach from which a variety of design guidelines could be concluded. However, it does open the door for further investigation of the integration of the curved roofs and wind catchers for natural ventilation in buildings.

STUDY PARAMETERS

This study is presented in two main parts: the first one investigates the integration of the catcher with the dome and will be referred to as the ‘tower and dome’ study. The second one investigates the same idea but in the case of the vault, and will be referred to as the ‘tower and vault’ study. Airflow rate and internal airflow distribution are compared before and after the integration of the catcher. The CFD software used is Fluent 5.5, given that:

- solver: segregates
- viscous model: standard k-ε model
- boundary conditions: velocity-inlet and outlet
- turbulence intensity: 5% in normal wind, and 10% in an oblique one (as a result of increasing solution domain size)
- residual sum for convergence: 10^{-6}.

Solution domain at both normal and oblique wind directions has been divided into many volumes to allow for the use of a hierarchy in mesh size. This is intended to keep the resulting file sizes within the available computer abilities. It is worth mentioning here that the total file size of the 48 cases involved in this modelling study is 4.5 GB.

The wind velocity profile simulated here is the ‘city’ profile, which assumes that the building is exposed to a wind speed that is modified by a city-like terrain. This profile is commonly defined using the following equation (CIBSE, 1988):

$$V = V_r * cH^a \qquad (1)$$

Where V is wind speed at datum level (the sub-inlet here, as explained below) (m/s), V_r is reference wind speed, H is the height above the ground, c is the parameter relating wind speed to terrain nature (0.21 in the city terrain), and a is an exponent relating wind speed to the height above the ground (0.33 in the city terrain).

This profile has been simulated using an approximation method, with an acceptable level of accuracy. The large velocity inlet of the solution domain has been divided into many sub-inlets. Air velocity magnitude has been defined for each sub-inlet according to Equation 1.

Ventilation performance of wind catchers is dependent on many geometrical parameters including catcher height, form and its relationship with the building. However, the intention here is not to assess the detailed design of wind catchers, but the effect of integrating them with curved roofs as a ventilation strategy. Thus, three operation systems of the catcher are suggested and are illustrated in Figure 1. Many similarities have been observed in the behaviour of domed and vaulted roofs tested in terms of inducing ventilation through the roof by suction. Thus, the parameters considered in the 'tower and vault' study have been reduced in order to cope with the study limitation. Thus, the second wind-catcher system, T2, is only considered in the 'tower and vault' study. Wind directions of 0°, 45° and 90° and reference wind speeds of 1 and 3 m/s are examined here.

The wind catcher's form is assumed to be square, which is commonly used in both vernacular and contemporary architecture. Relative cross-sectional area is assumed to be small, only 1.2% of the building floor area. Although this area represents an acceptable architectural proportion between the different elements of the modelled prototype, it has the advantage of reducing the construction cost as well. Building area is assumed to be 400 m^2. This corresponds to square plan geometry and rectangular building geometry given that the aspect ratio of the rectangular form is 1:1.5.

The tested roof geometry is domed or vaulted. The tested dome here is hemispherical, raised on a cylindrical base in which eight openings are placed. Its

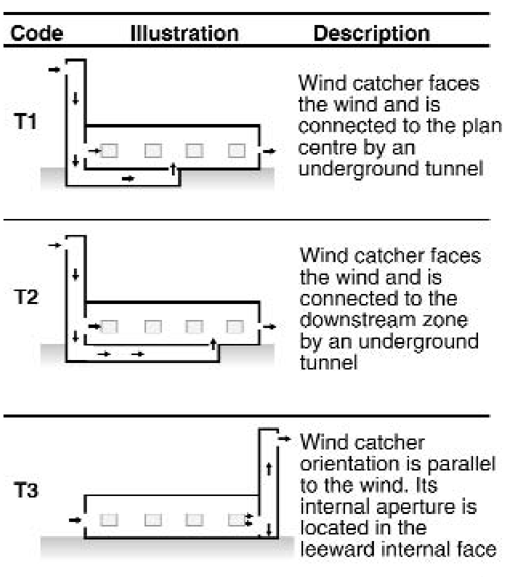

FIGURE 1 The three wind-catcher systems examined in the study

diameter is 7.5% of the building area, and its porosity is 13% of its plan area. The tested vault is semicircular, raised on a cubical base in which four openings are located. Its porosity is the same as that of the dome. Its base has a length equal to double that of the dome diameter, and a width that equals it. The catcher relative height is assumed to be 2.5 H, where H is the height of the main building, which is 5 m. Catcher porosity is assumed to be 0.5% of the plan area. In the case of 0° and 90° wind directions, this is equivalent to two square openings (inlet and outlet), having a length of 1.4 m and an area of about 2 m^2. In the case of 45°, the top opening is equally divided into two openings located at both windward faces of the catcher.

The different cases modelled in this study are designated with a 'T' to refer to the tower. This letter is followed by a serial number, from 1 to 3, to indicate the ventilation operation system of the catcher, as illustrated in Figure 1. 'D' and 'V' refer to the roof geometry. This is associated with either 'o' to indicate that roof apertures are opened, or 'c' to indicate they are closed. In addition, 's' and 'r', respectively, refer to the square and rectangular main volume geometry. Two more numbers follow the resulting symbol: the first one indicates wind angle – 0°, 45° or 90° – and the second one indicates reference wind speed – 1 or 3 m/s. For example, T1Do-s-0-1 refers to the first catcher system, integrated with a domed roof that has opened apertures, the building form is square, wind direction is 0° and wind velocity is 1 m/s.

It is important to mention that this study is not a design project. The main concern here is to observe the effect of specific parameters on the resulting natural ventilation performance, regardless of the actual values of airflow rates. Summation of airflow rates through the different openings has been found to be zero in all cases. This shows the reliability of the results obtained according to the Law of Conservation of Mass.

EFFECT OF UTILIZING WIND CATCHER ON AIRFLOW RATE THROUGH DOME OPENINGS

Figures 2, 3 and 4 summarize airflow rates recorded through the dome in different wind directions. These airflow rates are recorded before utilizing the catcher (the first case) and afterwards (the rest of cases), and for both square and rectangular cases. It is clear that both reference wind velocities have presented the same behaviour, but with a higher rate at the higher reference velocity.

In the case of 0° wind direction, it has been observed that the generation of an air vortex in front of the dome inlet has reduced its inflow rate. In the case of utilizing the catcher, inflow rate has been reduced to zero, namely in the first two wind-catcher systems (T1 and T2). This is a result of the sheltering effect of the catcher body, which is located in front of the dome inlet. Concerning the outflow rate, Figure 2 shows that the rectangular cases have recorded higher outflow rates. This is because airflow separation at the roof sharp windward edge is stronger here because of the elongated nature of the rectangular geometry. Thus, larger amount of airflow blows above the building instead of around it, following the path of least resistance. This leads to higher suction forces acting on the dome. After utilizing the first two wind-catcher systems, T1 and T2, the outflow rate through the dome has increased. This increase is slightly higher in T1, where the wind catcher supplies air to the building centre, i.e. directly under the dome. Numerically, this increase is about 20% in square cases and 23% in rectangular ones. In the case of utilizing the catcher as a wind chimney, a significant reduction in outflow rate has been recorded. This reduction is about 28% in the square cases and 23% in the rectangular ones. This is because the catcher here causes some of the air to leave through it, instead of the dome.

In the case of 45° wind direction, airflow rates have presented different behaviours before utilizing the catcher. Inflow rate through the dome has increased due to the absence of the air vortex observed in the normal wind direction. Outflow rate has significantly increased in the square cases (about 30%) due to the higher suction acting on the roof because airflow passes and separates over both windward edges of the flat roof. This is also true for the rectangular cases. After utilizing T1 and T2, a slight change has been observed in the inflow and net outflow rates through the dome, since air provided by the catcher is more affected by suction forces acting on building walls. This is supported by the fact that the outflow rate through wall openings is higher after using the catcher. In the case of utilizing the catcher as a wind chimney, a significant reduction in the outflow rate through the dome has been recorded (about 30% in both square and rectangular cases).

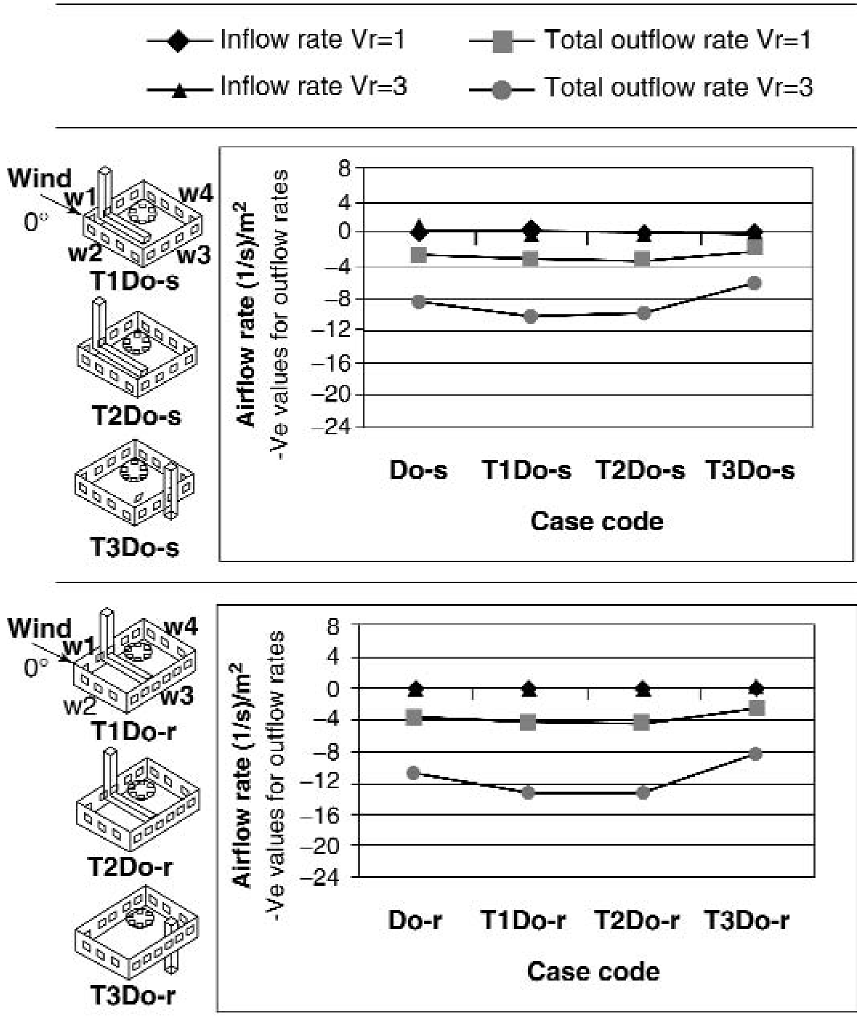

FIGURE 2 Airflow rate through the dome after utilizing the different proposed wind-catcher systems, where wind angle is 0°, and reference wind speed is 1 or 3 m/s

In the case of 90° wind direction, both inflow and outflow rates for the square configurations show the same tendency observed in the case of 0° wind direction. This is a result of the building's symmetry. In the rectangular building form, outflow rates through the dome are originally lower because buildings of greater depth result in reduced suction forces acting on the roof. This is also the case after utilizing the catcher. In the first two wind-catcher systems, T1 and T2, the outflow rate is about 40% lower, compared with the normal wind direction. In the third system, T3, this reduction reaches about 55%. This is because the deep plan reduces the kinetic energy of airflow travelling over the building. Consequently, this reduces the effect of airflow separation over the roof windward sharp edge in generating suction forces around the dome, which is positioned away from this edge.

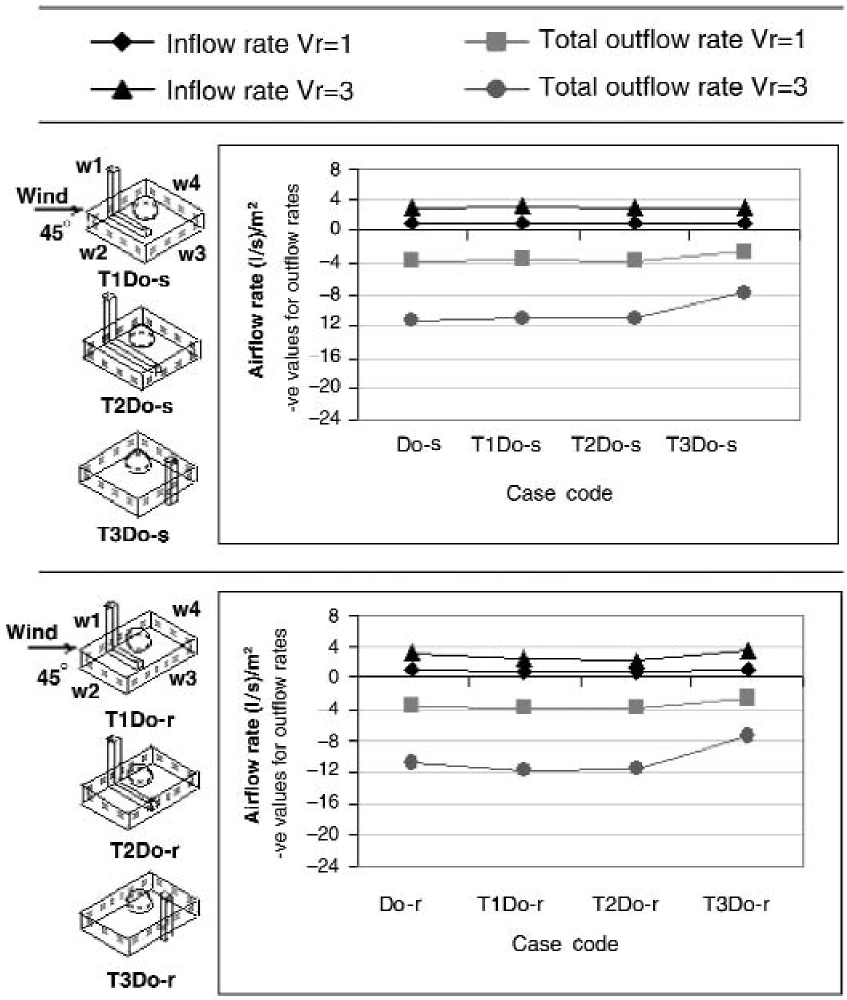

FIGURE 3 Airflow rate through the dome after utilizing the different proposed wind-catcher systems, where wind angle is 45°, and reference wind speed is 1 or 3 m/s

EFFECT OF BOTH WIND CATCHER AND DOME ON AIRFLOW RATE THROUGH WALL OPENINGS AND INTERNAL AIRFLOW DISTRIBUTION

Mass flow rate through each of the 16 wall openings in every case has been computed using Fluent 5.5 software. It has then been converted to volumetric flow rate for the floor unit area. In order to assess the internal airflow distribution, contours of air velocity magnitude have been used. This has been recorded on a horizontal plane passing through the building at a height of 1.7 m, which is the window level. Air velocity scale attached to these contours has been unified for all the cases tested. Using AutoCAD software, the area of four velocity zones has been estimated as a percentage of the total plan area. This has been done before and after the utilization of the curved roofs and wind catchers.

Data obtained from analysing contours of air velocity magnitudes have been arranged in tables to compare the internal airflow distribution in the following cases:

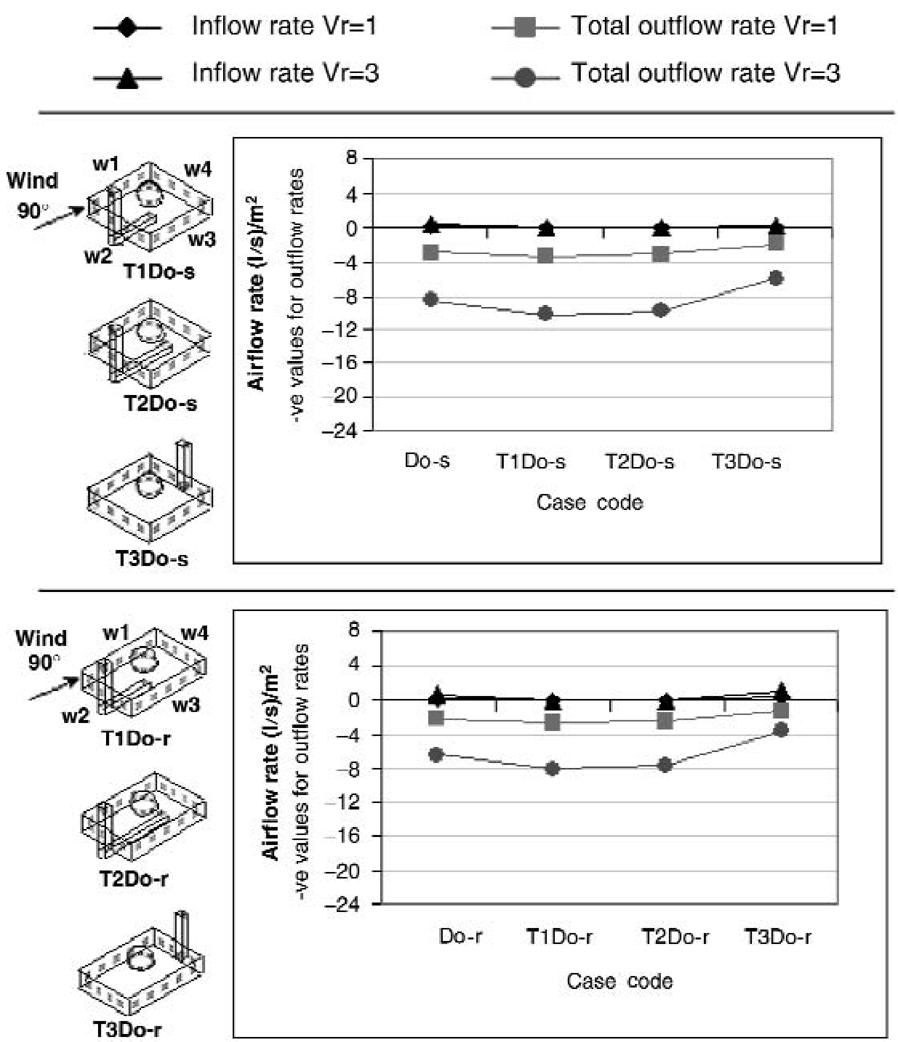

FIGURE 4 Airflow rate through the dome after utilizing the different proposed wind-catcher systems, where wind angle is 90°, and reference wind speed is 1 or 3 m/s

- configurations with cross ventilation through wall openings only
- configurations with cross ventilation through wall and dome openings
- configurations with cross ventilation through wall, dome and catcher openings. This includes the three wind-catcher systems tested here, as illustrated in Figure 5, which enables comparison of these systems.

Table 2 presents airflow rates and internal airflow distribution assessment, as recorded in the case of 0° wind direction, before and after integrating the catcher with the dome. This table shows that utilizing the catcher has caused a slight change in inflow rate through the windward wall openings. However, a significant increase in outflow rate in the first two wind-catcher systems has been recorded. This increase is about 15% in the square cases and about 10% in the rectangular ones, mainly as

TABLE 1 Different zones of internal air velocity

Velocity zone	Internal velocity, Vi	
	Vr = 1 m/s	Vr = 3 m/s
A	0.0	0.0
B	0.07	0.2
C	0.14	0.4
D & above	$0.14<Vi<Vi_{max}$	$0.4<Vi<Vi_{max}$

a result of the air provided by the catcher. Some of this air leaves the building through the dome, and the rest leaves through the wall openings. In the square cases, the amount that leaves through the dome is less than in the rectangular cases. This is because of the lower suction that acts on the dome, as has been explained above in 'Effect of utilizing wind catcher on airflow rate through dome openings'. Utilizing the catcher as a wind chimney increases the suction forces acting over the leeward building face. Thus, a significant increase in the outflow rate through the leeward wall openings has been observed. This is matched by an equivalent decrease in the outflow rate through the literal wall openings. This is why there is no significant change in the total outflow rate after utilizing the catcher.

Thus, utilizing the catcher helps to redistribute the internal airflow in different patterns. It also helps to attract more airflow to the still-air zone in the building downstream wing. This is why internal airflow distribution has been generally improved in both square and rectangular configurations. In the square configurations, the still-air zone is significantly smaller, when comparing Do-s to T1Do-s, T2Do-s and T3Do-s. The drop percentages are 12%, 21.4% and 8%, respectively. This resulted in an increase in air velocity in zone C for all three cases, and in zone D for the first two. The improvement is more significant in T1 and T2. Airflow entering the catcher is restricted by its walls, which increases airflow velocity. Thus, air pressure is reduced to compensate the observed increase in its kinetic energy (Moore, 1993). In contrast, when airflow leaves the catcher, its velocity slows down and its pressure increases. This increases the potential of this air to be driven towards the dome or the adjacent wall openings, depending on the intensity of the surrounding suction forces. The second system seems to be even more effective, since the catcher outlet is located more deeply in the building, which reduces the area of the still-air zone. However, airflow distribution at the corners can receive further improvement using an appropriate air distribution system.

In the rectangular configurations, two differences can be distinguished:

- The improvement observed in the first wind-catcher system is less. This is because air is provided at the centre of the plan, and directly attracted by the dome, which is subjected to higher suction.
- The improvement observed in the third wind-catcher system is the most significant. This is because the catcher has limited the role of the dome. This allows more air to penetrate the space, which has a smaller depth, so that it leaves through the tower instead of the dome. Thus, the still-air zone has nearly disappeared (only 4%) and the higher velocity zone has increased by about 13%.

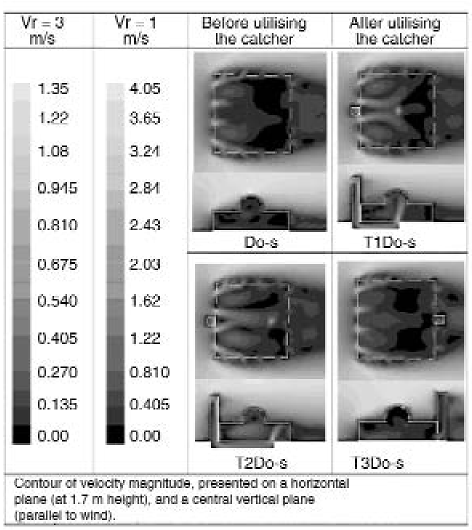

FIGURE 5 Comparison of internal airflow distribution, presented by internal air velocity Vi, before and after utilizing the different wind-catcher systems with the dome, in the square building form normal wind direction

TABLE 2 Assessment of airflow rate through wall openings, and internal airflow distribution, in the case of 0° wind direction and a 3 m/s reference wind speed, before and after the use of the catcher with the dome

AIRFLOW RATE*							
INFLOW RATE				OUTFLOW RATE			
BEFORE	AFTER		DIFF. (%)	BEFORE	AFTER		DIFF. (%)
	T1Do-s	55.2	+1.9		T1Do-s	–53.2	+15.3
54.2	T2Do-s	54.3	+0.3	–46.2	T2Do-s	–52.9	+14.6
	T3Do-s	54.8	+1.3		T3Do-s	–45.2	–2.1
	T1Do-r	66.0	–0.6		T1Do-r	–60.9	+9.5
66.4	T2Do-r	66.3	–0.1	–55.6	T2Do-r	–61.3	+10.3
	T3Do-r	67.4	+1.6		T3Do-r	–55.4	–0.2

* All airflow rate values are in (l/s)/m², Vr = 3 m/s.

INTERNAL AIRFLOW DISTRIBUTION **					
VELOCITY ZONE	INTERNAL VELOCITY, VI (% OF TOTAL PLAN AREA)				
	DC-S	DO-S	T1DO-S	T2DO-S	T3DO-S
A	37.0	31.2	18.6	9.4	22.6
B	28.8	37.8	32.9	35.1	37.0
C	15.9	14.1	19.9	22.3	24.5
D	18.3	16.9	28.6	33.2	15.9
VELOCITY ZONE	INTERNAL VELOCITY, VI (% OF TOTAL PLAN AREA)				
	DC-R	DO-R	T1DO-R	T2DO-R	T3DO-R
A	27.8	21.7	19.1	13.0	3.90
B	36.8	40.5	42.5	44.3	43.7
C	16.4	21	19.8	19.0	22.1
D	19.0	16.8	18.6	23.7	30.3

** Has been estimated from horizontal contours of velocity magnitude, at a height of 1.7 m. Vr = 1 m/s, and 3 m/s.

In the case of 45° wind direction, cross ventilation between the opposite walls is more effective. However, the balance observed in ventilation between both building windward faces is no more valid after the utilization of the first two systems of the catcher. This is because of the existence of the catcher body on the wall (w1), which weakens the role of the inlets located in this wall. This resulted in some of the air entering the building through wall 2 (w2) and being attracted to the leeward wall (w4), which causes an internal curved air motion. This curved air motion can be observed using the tool of velocity magnitude contours, presented in Figure 6. This curved air movement has also been observed in the rectangular configurations, but without air being reversed towards the windward facade (w1).

Table 3 presents airflow rates and internal airflow distribution assessment, as recorded in the case of 45° wind direction before and after integrating the catcher with the dome. In the square configurations, inflow rate in cases T1Do-s and T2Do-s has been reduced, compared with case Do-s. This is because one opening in wall 1 (w1) operates as an outlet due to the sheltering effect of the catcher body on this wall. Concerning outflow rate, the central rotating air movement has resulted in:

- reducing outflow rate at wall 4, because of the conflict between the curved air motion and the suction force acting on this wall
- increasing outflow rate through the openings of wall 3, which are at the wake of the curved air motion.

In the rectangular configurations, inflow rates in cases T1Do-r and T2Do-r has slightly increased, compared with case Do-r. This is in spite of the fact that one opening in wall 1 works as an outlet, as discussed

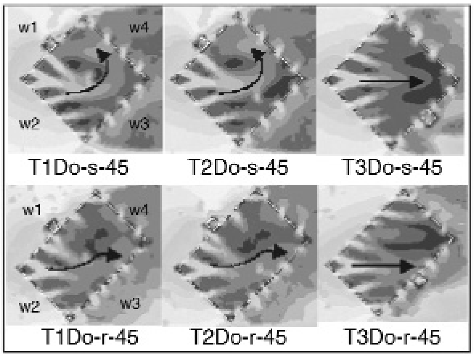

FIGURE 6 Contours of velocity magnitude showing different patterns of the internal air motion for the indicated cases, in the case of 45° wind direction

above. This is because the internal suction forces generated by the wind catcher are strong enough to increase the total inflow rate, due to the smaller depth of the building. Concerning outflow rate, the central rotating air movement has resulted in:

- insignificant change in inflow rate, since air is not reversed as observed in the square configurations
- increasing outflow rate through the openings of wall 3, as a result of the curved air deflection on that wall, and because of air provision by the catcher.

In the third wind-catcher system, where the catcher is employed as a wind chimney, both square and rectangular cases have presented a balanced and straight internal air movement, as can be seen in Figure 6. As a result of the suction force caused by the catcher, both inflow and outflow rates have slightly increased in the square and rectangular cases compared with the values recorded before employing the catcher.

TABLE 3 Assessment of airflow rate through wall openings, and internal airflow distribution, in the case of 45° wind direction and a 3 m/s reference wind speed, before and after the use of the catcher with the dome

AIRFLOW RATE*							
INFLOW RATE				OUTFLOW RATE			
BEFORE	AFTER		DIFF. (%)	BEFORE	AFTER		DIFF. (%)
	T1Do-s	63.7	–3.0		T1Do-s	–61.1	+6.3
65.7	T2Do-s	63.2	–3.7	–46.2	T2Do-s	–60.1	+4.5
	T3Do-s	69.0	+5.1		T3Do-s	–59.9	+4.2
	T1Do-r	67.7	+1.8		T1Do-r	–63.3	+7.9
66.4	T2Do-r	67.5	+1.7	–55.6	T2Do-r	–63.5	+8.1
	T3Do-r	69.2	+3.9		T3Do-r	–59.9	+2.1

* All airflow rate values are in (l/s)/m², Vr = 3 m/s.

INTERNAL AIRFLOW DISTRIBUTION **					
VELOCITY ZONE	INTERNAL VELOCITY, VI (% OF TOTAL PLAN AREA)				
	DC-S	DO-S	T1DO-S	T2DO-S	T3DO-S
A	11.2	13.3	4.6	7.3	12.9
B	52.9	45.5	25.4	26.1	44.7
C	18.7	16.8	29.9	29.2	19.9
D	17.2	24.4	40.1	37.4	22.5
VELOCITY ZONE	INTERNAL VELOCITY, VI (% OF TOTAL PLAN AREA)				
	DC-R	DO-R	T1DO-R	T2DO-R	T3DO-R
A	17.8	15.7	3.7	3.6	9.4
B	43.8	44.1	32.1	34.8	30.7
C	16.2	18.5	32.5	29.6	35.4
D	22.2	21.7	31.7	32.0	24.5

** Has been estimated from horizontal contours of velocity magnitude, at a height of 1.7 m. Vr = 1 m/s, and 3 m/s.

This internal curved air motion has improved the internal airflow distribution. The drop percentages in the area of the still-air zone are 8.7% and 6%, respectively, for T1 and T2. This resulted also in a reduction in air velocity in zone B and an increase in zone C. A significant increase has been observed also in the high-velocity zone, i.e. zone D, by 15.7% for T1, and 13% for T2. This is also true for the rectangular building form. The observed reduction is about 12%. This resulted also in a reduction in zone B and an increase in zone C. A significant increase has been observed also in the high-velocity zone, i.e. zone D, by about 10% for both cases. However, this is not the case in T3, as insignificant improvement has been observed in the square cases.

Table 4 presents airflow rates and internal airflow distribution assessment as recorded in the case of 90° wind direction before and after integrating the catcher with the dome.

In the square cases, airflow rate and distribution behave in the same way as explained in the case of 0° wind direction. This is a result of the building's symmetry. Using T1 and T2 in the rectangular cases has significantly reduced outflow rate in the leeward openings for the benefit of the literal ones. However, outflow rate has increased in total. This increase is higher compared with the normal wind direction. One reason is the effect of the reversed flow in the wake of the building. This is caused by the significant increase in building depth, which dissipates more kinetic energy of the airflow before it reaches the wake zone. Thus, this reduces airflow resistance of the vortices existing in the wake zone, which consequently causes this reversed airflow. Using the catcher as a wind chimney is effective in attracting air to penetrate the deep plan of the building. This is because of the weak suction acting on the dome, as explained above in 'Effect of utilizing wind catcher on airflow rate through dome openings'.

Concerning internal airflow distribution, utilizing the dome alone has an insignificant effect. This is because the central zone of the building only benefits from that utilization, leaving the deep downstream wing of the building still. Utilizing the first wind-catcher system has resulted in a similar behaviour. However, the still-air zone has been significantly reduced in the second wind-catcher system by 14%. This has resulted in a significant increase in zone B as well, since the catcher provides air directly to the downstream zone, instead of the central zone. In the third wind-catcher system, the still-air zone has been significantly reduced by 18.5%. This has resulted in a significant increase in zones C and D. This is an interesting result because the large building depth is expected to prevent air from penetrating the space. However, as explained above, the reduced suction acting on the dome, in addition to the observed reversed airflow, has allowed this improvement to occur.

TABLE 4 Assessment of airflow rate through wall openings, and internal airflow distribution, in the case of 90° wind direction and a 3 m/s reference wind speed, before and after the use of the catcher with the dome

AIRFLOW RATE*							
INFLOW RATE				OUTFLOW RATE			
BEFORE	AFTER		DIFF. (%)	BEFORE	AFTER		DIFF. (%)
	T1Do-r	40.7	+1.7		T1Do-r	–40.7	+18.9
40.0	T2Do-r	39.9	–0.3	–55.6	T2Do-r	–39.5	+15.5
	T3Do-r	40.8	+2.0		T3Do-r	–34.9	+1.9

* All airflow rate values are in (l/s)/m², Vr = 3 m/s.

INTERNAL AIRFLOW DISTRIBUTION **					
VELOCITY ZONE	INTERNAL VELOCITY, VI (% OF TOTAL PLAN AREA)				
	DC-R	DO-R	T1DO-R	T2DO-R	T3DO-R
A	36.2	30.6	43.9	16.6	11.7
B	32.5	36.2	26.3	50.6	30.8
C	17.5	19.3	14.0	13.2	29.6
D	13.8	13.9	15.8	19.6	27.9

** Has been estimated from horizontal contours of velocity magnitude, at a height of 1.7 m. Vr = 1 m/s, and 3 m/s.

EFFECT OF UTILIZING WIND CATCHER ON AIRFLOW RATE THROUGH VAULT OPENINGS

Figure 7 summarizes airflow rates recorded through the vault at 0°, 45° and 90° wind directions.

In the case of 0° wind direction, catcher integration has been found to cause a significant improvement in terms of airflow rate through the vault. Location of the wind catcher at the middle of the windward facade of the building has caused a wind-shadow area between the catcher and the vault, as illustrated in Figure 8. Thus, the inflow rate through the vault openings, which are located at the wake of the catcher, has been reduced. Both the sheltering effect of the catcher and the air vortex observed in front of the vault inlets have reduced the inflow rate to a very low value in square cases and to zero in the rectangular ones. This significant decrease in inflow rate has increased the potential of the vault outlets for inducing ventilation by suction. Thus, significant increase in outflow rate has been recorded (28% in the square cases and 60% in the rectangular cases). This, in fact, shows the advantage of closing the vault inlets in this wind direction in order to maximize the outflow rate through the vault. The significantly higher increase in outflow rate in the rectangular cases has occurred because of the smaller depth of the building, which allows more air provided by the catcher to leave the building through the vault.

In the case of 45° wind direction, the same observation explained above regarding the reduction of inflow rate is true. However, inflow rate was originally high, because there was no air vortex occurring in front of the vault inlets. Therefore, the inflow rate value does not approach zero. Using the velocity vector tool in Fluent 5.5, it has been observed that the reduction in inflow rate has only occurred at the top windward inlet of the vault, which is sheltered by the catcher. The other inlet is subjected to a positive pressure and provides a larger volume of air to the closer vault outlet. Thus, outflow rate has mainly increased at the lower leeward outlet of the vault. The observed increase in outflow rate here is significant, but less than the one observed in the normal wind direction (16% compared with 28% in the square cases, and 35% compared with 60% in the rectangular cases).

In the case of 90° wind direction, the inflow rate recorded through the vault is always zero. Thus, the vault mainly works in suction. Utilizing the catcher has reduced outflow rate through the vault by 13% for the square case and 6% for the rectangular one. This means that the airflow provided by the catcher has supported the role of the wall openings in suction on account of the vault openings. This means that providing air to the internal space via the catcher has helped to improve the internal airflow distribution, as will be discussed in the following section.

EFFECT OF BOTH WIND CATCHER AND VAULT ON AIRFLOW RATE THROUGH WALL OPENINGS AND INTERNAL AIRFLOW DISTRIBUTION

Table 5 presents airflow rates and internal airflow distribution assessment, as recorded in the case of 0°, 45° and 90° wind directions, before and after integrating the catcher with the vault in the square and rectangular configurations.

In the case of 0° wind direction, utilization of the catcher in both square and rectangular cases has slightly increased the inflow rate. This is balanced by an increase in outflow rate, which is higher because of the air provided by the catcher. However, the observed increase is only significant in the square case. This is because air provided by the catcher in the rectangular case mainly leaves the space through the vault instead of the wall openings, as discussed in the previous section. Thus, the outflow rate through the vault openings is significantly higher for the rectangular case, while the outflow rate through the wall openings is significantly higher for the square case. This is why the internal airflow distribution has been improved more significantly in the square case. The still-air zone area has been reduced in the square case by about 25% with an equivalent increase in velocity zone D. However, the still-air zone in the rectangular case has been reduced by about 5% and increased by about 7% in velocity zone D.

In the case of 45° wind direction, the observed behaviour of airflow rates in the square case is similar to the one observed in the case of utilizing the catcher with the dome, as explained above in 'Effect of both wind catcher and dome on airflow rate through wall openings and internal airflow distribution'. However, differences in airflow rates are less here. The airflow pattern, illustrated in Figure 9, shows that the curved air motion seems to be weaker than the one observed when the catcher was integrated with the dome.

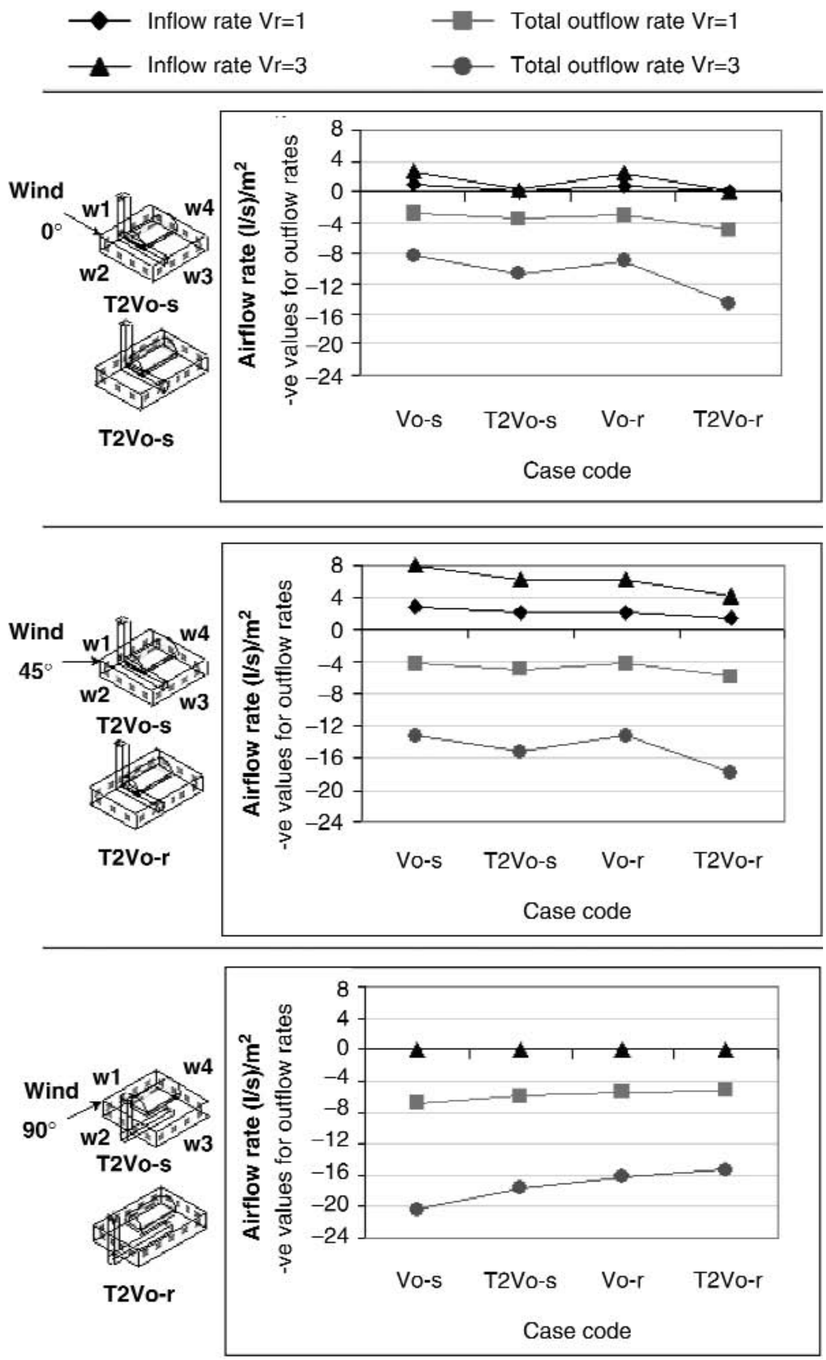

FIGURE 7 Airflow rate through the vault after utilizing the proposed wind-catcher system, where reference wind speed is 1 or 3 m/s

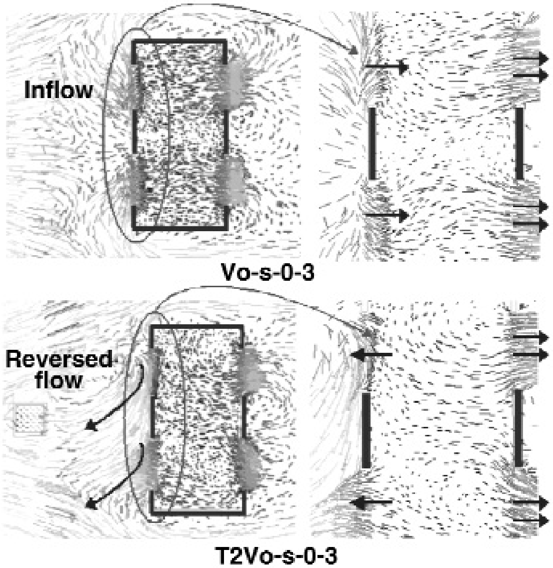

FIGURE 8 Velocity vectors showing the effect of wind catchers in reducing inflow rate through the vault windward openings at 0° wind direction

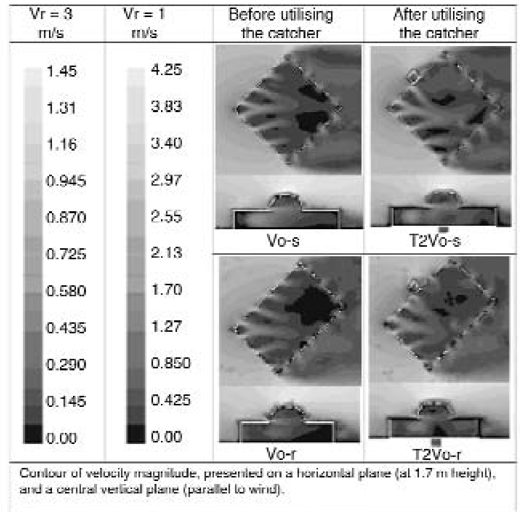

FIGURE 9 Comparison of internal airflow distribution, presented by internal air velocity Vi distribution, before and after utilizing the wind catcher with the vault, at 45° wind direction

This is more pronounced in the rectangular building form, where the effect of the vault is more dominant than the potential of the curved air movement for reforming the internal airflow pattern. This is because the net outflow rate through the vault is higher than the one recorded through the dome by about 13% in the square form and 50% in the rectangular form. This increases the potential of the vault for air suction on account of the leeward walls, and thus weakens the internal curved air motion. In the rectangular case, this has significantly increased the inflow rate. Thus, internal airflow distribution has been improved. In the square cases, the area of the still-air zone has been reduced in the square case by about 6%, with a 15% increase in velocity zone C. This is more significant in the rectangular cases. The still-air zone area has been reduced by 18%, with an increase of 7% in velocity zones B and C.

In the case of 90° wind direction, the inflow rate for both rectangular and square configurations has increased as a response to the integration of the catcher. However, this increase is higher in the rectangular cases as a result of the observed reversed airflow through wall 4 (w4), as explained above in 'Effect of both wind catcher and dome on airflow rate through wall openings and internal airflow distribution'. Concerning outflow rate, a significant increase has been observed in both square and rectangular cases. This increase is about 25%, compared with a reduction in outflow rate by about 30% before utilizing the catcher. This is because the outflow rate through the vault has been significantly reduced after the utilization of the wind catcher, as explained above in 'Effect of utilizing wind catcher on airflow rate through vault openings'.

The significant reduction in the vault outflow rate in addition to the air provided by the catcher increases the role of wall openings in sucking the air out of the building and thus improves the internal airflow distribution. The still-air area zone has been reduced in the square case by about 20%, with an increase in velocity zone D of 10%. In the rectangular case, the still-air zone area has been reduced by about 12%, with an increase in velocity zone B of 10%.

DESIGN GUIDELINES

The previous analysis leads to the following general design guidelines:

TABLE 5 Assessment of airflow rate through wall openings, and internal airflow distribution, in different wind direction tested, and a 3 m/s reference wind speed, before and after the use of the catcher with the vault

AIRFLOW RATE*							
INFLOW RATE				OUTFLOW RATE			
BEFORE	AFTER		DIFF. (%)	BEFORE	AFTER		DIFF. (%)
Wind angle = 0o							
54.8	T2Vo-s	55.3	+0.9	–49.3	T2Vo-s	–53.1	+7.9
66.2	T2Vo-r	67.0	+1.2	–59.5	T2Vo-r	–60.5	+1.7
Wind angle = 45o							
65.49	T2Vo-s	65.45	-0.1	–60.25	T2Vo-s	–61.24	+1.6
65.18	T2Vo-r	69.88	+7.2	–58.20	T2Vo-r	–61.14	+5.1
Wind angle = 90o							
54.29	T2Vo-s	55.27	+1.8	–36.54	T2Do-r	–46.02	+25.9
39.1	T2Vo-r	41.49	+6.1	–27.00	T3Do-r	–34.37	+27.3

* All airflow rate values are in (l/s)/m², Vr = 3 m/s.

INTERNAL AIRFLOW DISTRIBUTION **						
WIND ANGLE = 0°						
VELOCITY ZONE	INTERNAL VELOCITY, VI (% OF TOTAL PLAN AREA)					
	VC-S	VO-S	T2VO-S	VC-R	VO-R	T2VO-R
A	44.6	39.8	13.2	34.3	31.4	26.1
B	26.2	33.3	33.4	33.1	38.8	35.2
C	15.2	15.5	18.9	15.2	16.2	18.2
D	14.0	11.4	34.5	17.4	13.6	20.5
WIND ANGLE = 45°						
VELOCITY ZONE	INTERNAL VELOCITY, VI (% OF TOTAL PLAN AREA)					
	VC-S	VO-S	T2VO-S	VC-R	VO-R	T2VO-R
A	13.5	14.1	7.8	17.4	22.3	4.0
B	43.5	48.1	34.3	38.0	39.6	46.8
C	18.7	16.8	32.0	22.4	18.6	25.5
D	24.3	21.0	25.9	22.2	19.5	23.7
WIND ANGLE = 90°						
VELOCITY ZONE	INTERNAL VELOCITY, VI (% OF TOTAL PLAN AREA)					
	VC-S	VO-S	T2VO-S	VC-R	VO-R	T2VO-R
A	22.1	29.3	10.6	50.4	36.0	23.5
B	36.1	35.1	36.2	23.5	39.2	51.3
C	20.8	15.2	21.7	14.3	15.0	12.6
D	21.0	20.4	31.5	11.8	9.8	12.6

** Has been estimated from horizontal contours of velocity magnitude, at a height of 1.7 m. Vr = 1 m/s, and 3 m/s.

- There are many similarities between domed and vaulted roofs in terms of internal airflow behaviour after the integration of the catcher.
- Utilizing the catcher for air provision increases the outflow rate through wall openings in all cases. This increase is proportional to the intensity of the suction forces acting on these openings. This generally improves the internal airflow distribution.
- Utilizing the catcher for air suction is more effective when the building depth is smaller, or when the suction force acting on the roof is weaker. This latter case is effective in the case of deep-plan buildings, as it allows more air to penetrate the downstream

wing of the building, which improves airflow distribution.

- Installing the catcher in the middle of the building windward face improves the performance of roof openings by inducing air by suction. This is a result of the sheltering effect of the catcher, which reduces the inflow rate through the roof inlet.
- This results in an internal curved motion in the case of 45° wind direction as a result of the existence of the catcher on one windward face, which has caused an imbalance in the cross ventilation between the building windward and leeward faces. This improves the internal airflow distribution. This curved air motion is more pronounced when the suction force acting on the roof is weaker.

CONCLUSION

This paper has investigated the potential of integrating wind catchers with curved roofs to improve natural ventilation in buildings. Different building configurations have been compared before and after the utilization of the catcher in terms of airflow rate and internal airflow distribution. It has been concluded that utilizing the architectural elements of curved roofs and wind catchers for natural ventilation is an effective strategy, especially under the undesirable conditions of deep-plan buildings or low reference wind velocities. This is despite the fact that the inflow rate provided by the wind catcher tested is relatively small (about 12% of the total inflow rate).

It has been observed that there is always a conflict between the different driving forces acting on the airflow. The use of CFD modelling has helped to understand this conflict and how to utilize it to improve natural ventilation. Thus, utilizing the catcher has helped to redistribute airflow between building openings, which has improved internal airflow distribution and airflow rates.

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