MARKET OPPORTUNITIES FOR ADVANCED VENTILATION TECHNOLOGY

22nd ANNUAL AIVC CONFERENCE

BATH, UNITED KINGDOM, 11-14 SEPTEMBER 2001

Evaluating the Performance of a Windcatcher System Using Wind Tunnel Testing

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Abstract

Increased global warming and deterioration of the ozone layer have stimulated interest in the use of renewable energy systems. Natural ventilation is increasingly being employed in modern buildings to minimize energy consumption and the release of harmful emissions to the environment. Innovative natural ventilation techniques such as the windcatcher and solar chimney have facilitated the effective use of natural ventilation in a wide range of buildings for increasing the ventilation rate. In addition to bringing energy savings, these environmentally friendly technologies also help create healthier interiors for occupants.

This paper presents an experimental study for evaluating the performance of windcatchers for natural ventilation in buildings. Wind tunnel and smoke visualisation tests were carried out on a full scale circular windcatcher to evaluate its performance when attached to a model test room. The windcatcher was divided internally into four segments for the purpose of air supply and extract. Pressure coefficients distribution and volumetric airflow were measured for various wind speeds and three different wind directions. The tests were carried out for wind speed in the range of 0.5-5 m/s giving an air change rate in the test room (13.8m^3 in volume) of 1.5 to 6.8 ac/h. The external pressure coefficient distributions were complemented by the smoke visualisation tests. The smoke tests indicated that the air was supplied into the test room through segments with positive external pressure coefficients and extracted out of the test room through segments with negative pressure coefficients with little short circuiting. The results of this experimental investigation demonstrate the potential of the windcatchers for natural ventilation purposes in buildings.

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1. Introduction

The Building Industry is considered to be one of the main contributors to environmental emissions as it is associated with the use of high level of energy as modern buildings depend heavily on highly serviced equipment for cooling, heating and lighting. Recently, natural ventilation is increasingly being deployed in modern buildings to minimise energy consumption and the release of the harmful gases to the environment. However, very often lack of ventilation in winter and lack of cooling in the summer makes a naturally ventilated building less reliable in providing comfortable environment. Windcatchers can help creating more effective ventilation and better indoor environment by passive means. Windcatchers are one of the old techniques which are currently being re-employed for natural ventilation purposes in modern buildings. However, these systems require careful design and integration with the building envelope to work effectively.

1.1. The windcatcher system

The windcatcher system is a passive ventilation system which not only extracts air using passive stack principles but also utilises the concept of a wind tower to supply air to the spaces as well. Traditionally, windcatchers systems were employed in buildings in the Middle East for many centuries and they are known by different names in different parts of the region (Battle MacCarthy, 1999). They were constructed, traditionally, from wood-reinforced masonry with openings at height above the building roof ranging from 2 m to 20 m. With taller towers capturing winds at higher speeds and with less dust (Bahadori, 1994, 1985; Karakatsanis et al, 1986). Their application in the hot arid region of the Middle East is to provide for natural ventilation/passive cooling and hence thermal comfort. Windcatchers are traditionally used in places of high urban densities where surrounding buildings obstruct free stream air flow (Sharag-Eldin, 1994). Traditional windctachers can be beautiful objects, feasible architectural feature additions to buildings and are inherently durable (Gage, and Graham, 2000; Fathy, 1973, 1986).

In the modern design of windcatchers, 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 length of the stack (Yaghoubi, et al, 1991; Harris D J and Webb R S, 1996). As the wind direction changes so do the functions of each of the halves or the quadrants in the windcatcher. This renders the windcatcher as being operational whichever way the wind is blowing. As there are no free parts to the windcatcher so the system is virtually maintenance free. It has the benefit of taking supply air at roof level, which is often cleaner than air supplied at ground level, particularly where the building is adjacent to a road in urban areas.

In modern buildings, the windcatcher systems come in various configuration to suit various building type and requirements such as the incorporation of solar panel (solar chimney) and light pipes to boost stack effect (Elmualim et al, 1998; Bansal et al 1994; Swainson, MJ, 1997). Recently, the windcatcher systems are increasingly being employed in buildings around the UK by many architects and engineers and many companies provide design and installation services of windcatcher systems within the UK. However, these systems require careful design and integration with the building fabric to work effectively.

2. Experimental set-up and measurement procedures

2.1. Experimental set-up

The experimental investigation was carried out using an open working section wind tunnel located at the laboratories of the Building Services Research and Information Association, BSRIA, Bracknell. The wind tunnel consists of three main sections; one circular section with 1.250 m diameter and two octagonal fanned shaped sections (2x2m) connected together with a total length of 17.5 m approximately. The open working section of the wind tunnel, where the windcatcher is positioned is about 3.6 m long. The wind tunnel was built on metal frame and raised approximately 3 meters above ground floor level.

A circular windcatcher with a diameter of 550 mm and a length of 1.2 m (aspect ratio of 2.2) was connected to a model test room of size 2.4x2.4x2.4 m (13.824 m^3 in volume). The model room is erected beneath the wind tunnel and silicon sealant and duct tapes were used to seal the test room from the laboratory (Figure 1). The windcatcher is divided into four segments with every two opposite segments equal in areas. The segments run the full length of the windcatcher. As can be seen from Figure 3, segments 1 and 3 are equal with an area of 0.071 m^2 each while segments 2 and 4 are slightly larger with an area of 0.095 m^2 each. The windcatcher and the model test room were positioned centrally within the wind tunnel in order to maintain a uniform wind profile over the windcatcher (Figure 2).

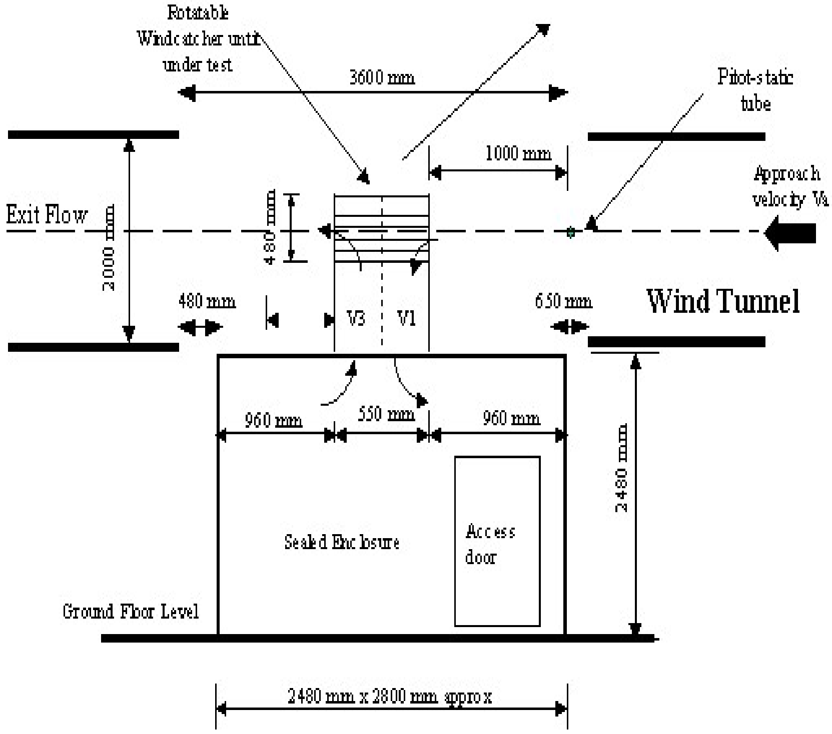

Figure 1. experimental test set-up.

Figure 2. location of windcatcher and test room in relation to the wind tunnel.

2.2. Measurement procedures

Tests were performed for nominal wind speeds of 0.5, 1, 2, 3, 4 and 5 m/s and for three directions. In the first case, the wind direction was directly on segment 4 (α = 0°), in the second case the wind was blowing in the middle partition between segments 1 and 4 (α = 45°) and in the third case, the wind direction was directly onto segment 1 giving an angle of α = 90°. Table 1 summarises the test conditions for each case.

Upstream static and total pressures were measured using a pitot-static tube. Internal and external pressure taps were fixed to the windcatcher in the inward and leeward direction of the wind and inside the room to allow the measurement of static and stagnation pressures. Each windcatcher segment was fitted with an internal pressure tap and three external pressure taps at the top, the end of louvers and the middle of the duct connecting windcatcher to the room.

In segment 4, two additional internal pressure taps were fixed to investigate the circumferential variation of pressure. The pressure taps were connected to a selection box (Furness FC091MKII) and micromanometer (Furness FC0510) using plastic tubes of 2mm diameter. The plastic tubes were run around the windcatcher to eliminate their interference with the wind flow around the windcatcher and inside the test room (Figure 2). The selection box and micromanometer were in turn connected to a PC to facilitate data entry.

The air flow was measured at the centre of each segment at the same height as the pressure tap using a TSI digital hot wire anemometer (model no: 8357-M-GB) fixed to a metal post. In case 4 (see table 1), mass continuity was assumed (i.e. total air supplied is equal to total air extracted through segments) and the internal air speed within the supply segment of the windcatcher was measured at seven points at ceiling level and averaged to obtain the internal air supply speed. Figure 3 shows the measurement points for the four cases of the three wind directions tests.

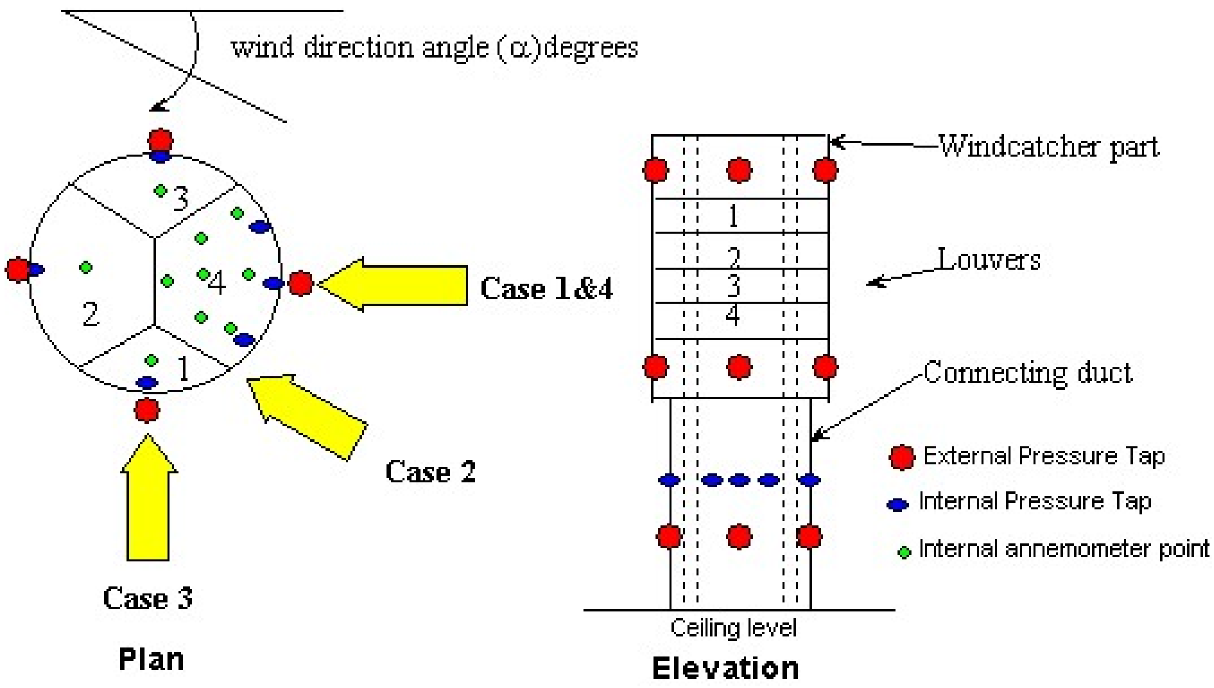

Figure 3. measurements points.

Prior to tests, the wind profile at the outlet from the wind tunnel was measured to assure the uniformity of wind blowing across the windcatcher. Although the fan speed could be controlled, this was not sufficient to produce wind speeds below 3 m/s, hence, perforated cards were used to adjust the wind velocity to obtain lower speed values in the range of 0.5 – 3 ms/s. The manometer was set to read an average measurement every 20 seconds. Ten readings were taken sequentially for every pressure and wind velocity port with time interval of one minute. The recorded readings were then averaged to give the measured values. All pressure measurements were referenced to the dynamic pressure upstream using the reference velocity in the wind tunnel. The pressure coefficients Cp were then calculated using the following formula:

$$C_p = \frac{p_w}{0.5\rho v^2}$$

Where C_p is the static pressure coefficient.

v is the mean reference wind speed in the wind tunnel (m/s).

p_w is the measured time mean pressure generated by the wind action on the surface of the windcatcher.

ρ is the air density kg/m^3.

Smoke visualisation tests were carried out to identify the supply and extract segments prior to internal air velocity measurements. Additional internal air velocity measurements were carried out directly underneath the windcatcher at heights of 1.2, 1.5 and 1.8 m from ground floor level. For smoke visualisation a Dräger Cumulus hand-held smoke generator was used. The volumetric air flow through each windcatcher extract/supply segment was calculated by multiplying the average air speed inside the segment by the area of that segment.

3. Results and discussion

For all the cases investigated representing different wind directions (α), the test results showed some variation of pressure coefficients with wind speeds, particularly at the lower wind speed, 0.5-1 m/s. This was due to the difficulty in the measurement of pressures less than one Pascal. If the low speed values are ignored, the results show that Cp is almost independent of wind speed in the range tested. Table 1 gives a summary for the test cases showing wind speed, direction and measurement angles around the windcatcher.

Table 1. test cases summary.

Case No.	Wind direction (α°)	Wind speed range (m/s)	Measurement angle (θ°)	Measurement of internal air speed in segment
Case 1	0	0.5-5	0-270 at 90° intervals	1 point measurement
Case 2	45	0.5-5	0-270 at 90° intervals	1 point measurement
Case 3	90	0.5-5	0-270 at 90° intervals	1 point measurement
Case 4	0	0.5-5	0-270 at 90° intervals	7 points measurement

Figure 4 shows the angles of wind direction (α) and the angles of measurements for pressure coefficients around the windcatcher (θ) starting from the stagnation point in each case.

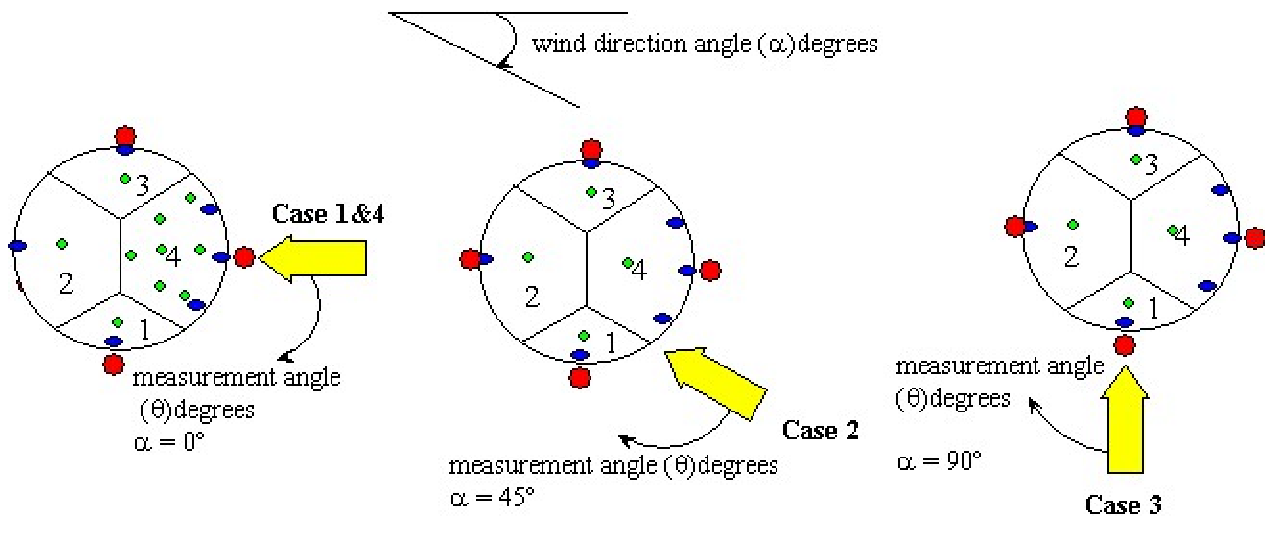

Figure 4. wind direction angles and measurement angles for each test case.

For case 1, the pressure coefficients for wind speeds in the range of 2-5 m/s was averaged. An average pressure coefficients of 0.87, -0.71, -0.02 and –0.64 were measured at θ = 0º, 90º, 180º, and 270º from the front stagnation point respectively at the top of the windcatcher. Results for test cases 1 and 3 showed very similar trend as would be expected.

In case 3 an average pressure coefficients of 0.84, -0.58, -0.16 and –0.63 were measured at θ = 0º, 90º, 180º, and 270º respectively at the top of the windcatcher. The average pressure coefficients measured in cases 1 and 3 are given in Figure 5. Values of 0.85, -0.64, -0.09, and –0.63 were measured directly above the windcatcher louvers at angles (θ) of 0º, 90º, 180º, and 270º respectively. The measured Cps at an angles of 90º and 270º are similar with a difference of less than 8%. The smoke visualisation tests clearly indicated that segments with positive external pressure coefficient were acting as air supply openings into the test room while segments with negative pressure coefficient were extracting air out of the test model room.

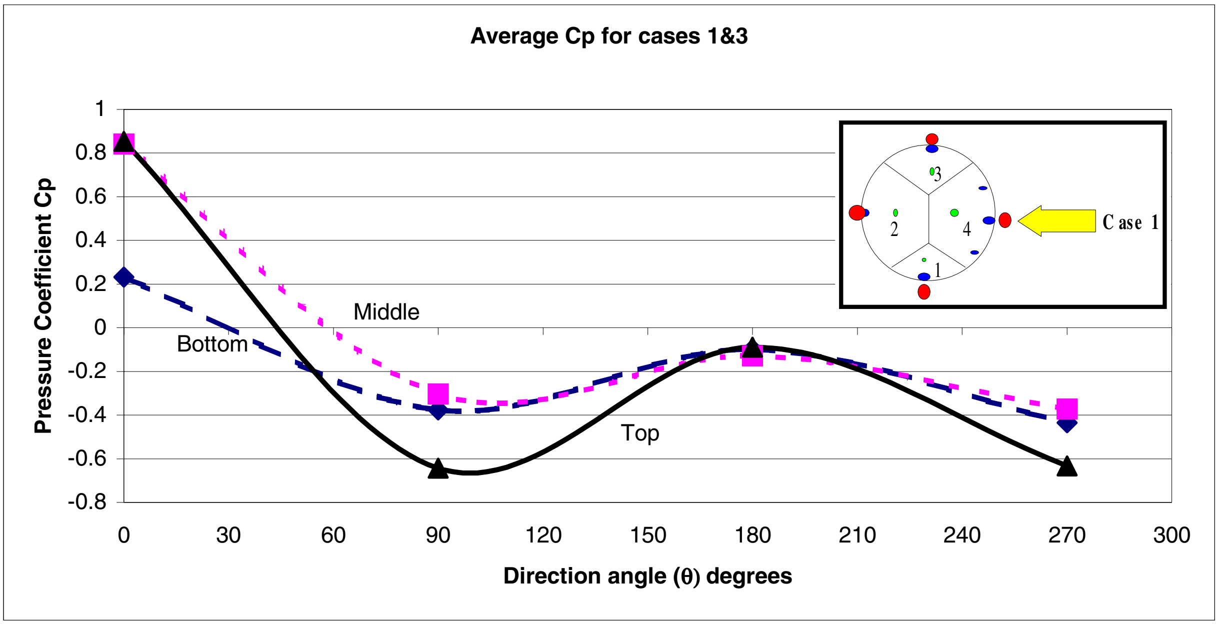

Figure 5. pressure coefficients for a circular windcatcher system.

In test case 2, it was found very difficult to establish the air extracting and supplying segments. It was observed that the upstream segments were acting as air supply as well as air extract openings simultaneously. From the direction of the wind hitting the windcatcher in between segments 1 and 4, it was expected that part of segments 1 and 4 will act as air supply into the model test room. However, the measured pressure coefficients on at least parts of these segments were found to be negative values (Figure 6). This shows that the windcatcher was mainly acting as an extract. However, more pressure taps were required in order to measure the pressure coefficient between segments 1 and 4 and provide some explanation of the true flow direction.

Figure 7 shows the results of the measured volumetric air flow through the windcatcher segments. In this case, case1, it was established through smoke visualisation tests that segment 4 was the supply while segments 1,2 and 3 were acting as air extracts. A volumetric airflow of 0.023 m^3/s was achieved through the main supply segment for an average wind speed of 3 m/s. The flow reached a volume of approximately 0.034 m^3/s for an external wind speed of 5.4 m/s.

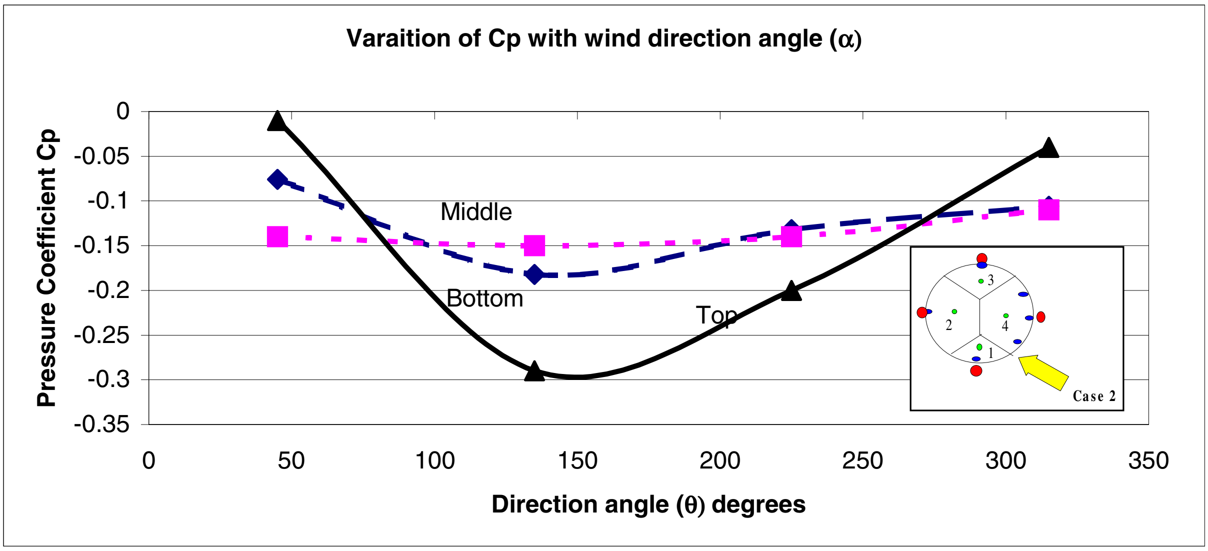

Figure 6. averaged measured pressure coefficients in case 2.

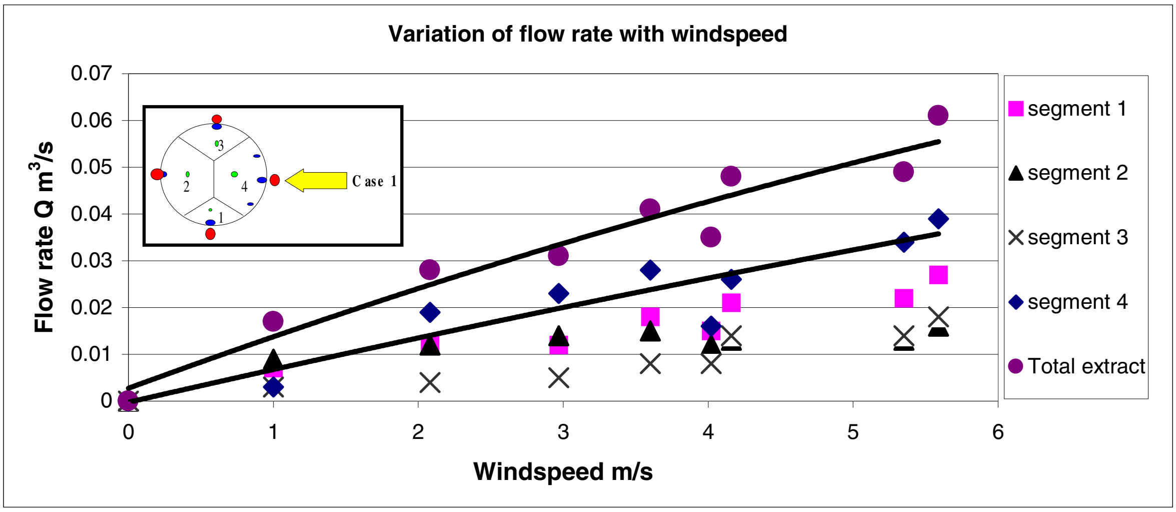

Figure 7. measured air flow through the windcatcher system for case 1.

For this case, the air change rate for the test room increases with the increase in external wind speed, giving a ventilation rate of 1.8 ac/h at wind speed of 1m/s, 5.2 ac/h at an average wind speed of 3m/s and reaches a maximum of 8.6 ac/h for the maximum external wind speed of 5 m/s employed during the tests. In these tests the extracted volume flow rate was found to be greater than the supplied volume flow rate. At a wind speed of 5.59 m/s the extracted volumetric air was twice the supplied volume of air, which indicated that mass continuity was not maintained. This emphasised the need for more internal air movement measurement points inside the windcatcher segments so as to evaluate the air supply and the extract correctly. Strictly, allowance should be made for air infiltration through the windcatcher and the test room.

In the tests for case 3, much lower supply air flow was measured than in case 1 due to the reduction in the cross sectional area of the supply segment, segment 1. The results showed a similar trend regarding the increase of the volumetric air flow with the increase in external wind speed as can be seen in Figure 8.

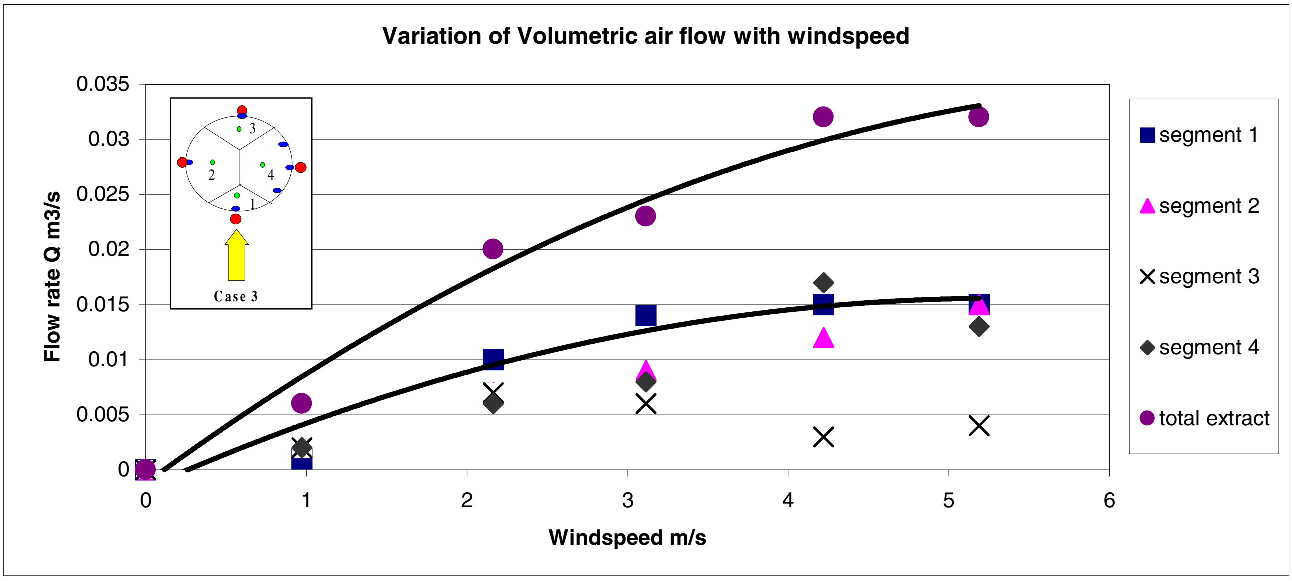

Figure 8. measured volumetric air flow for case 3.

Despite the difficulty in establishing the supply and extract segments in case 2, the tests results showed that the volumetric air flow through all segments increases with the increase in wind speed as shown in Figure 9. However, it was difficult to determine the supply flow rate to the room from these results.

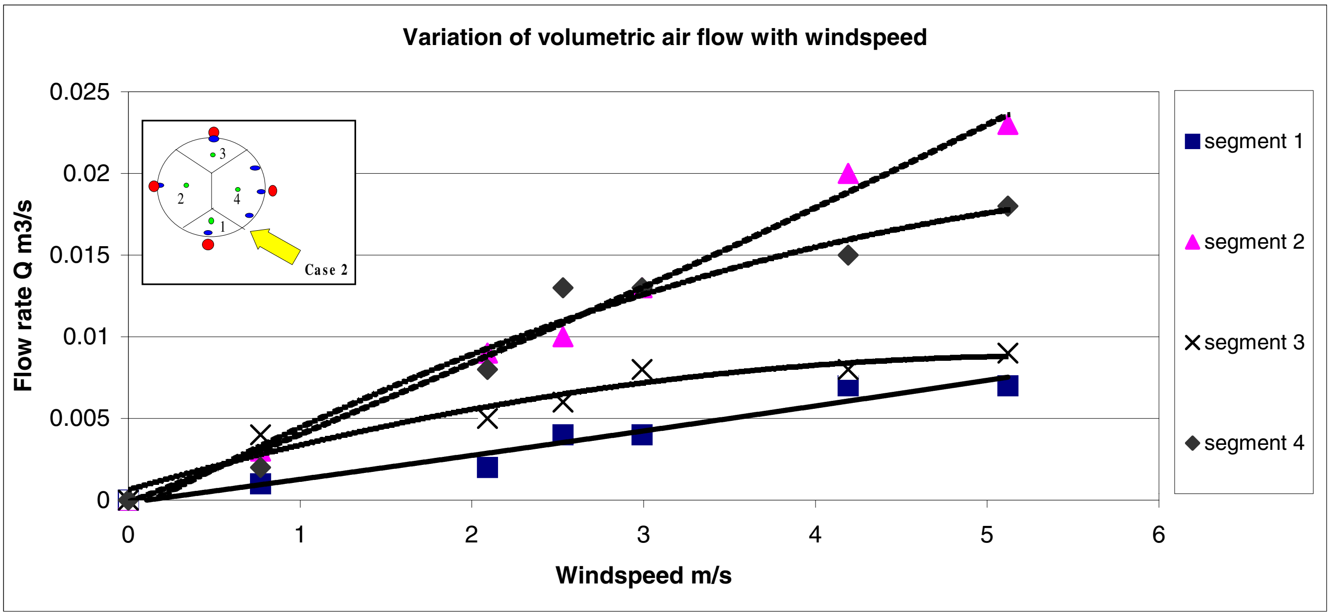

Figure 9. measured volumetric air flow for case 2.

In the tests for case 4 continuity was assumed and the internal air speed in the supplying segment was measured at seven locations at test room ceiling level. The results for the measured volumetric air flow showed no variation with the single point internal speed measurement results, particularly at lower wind speeds 1-3 m/s. For tests with higher wind speeds, however, variation in the two results were observed as can be seen in Figure 10.

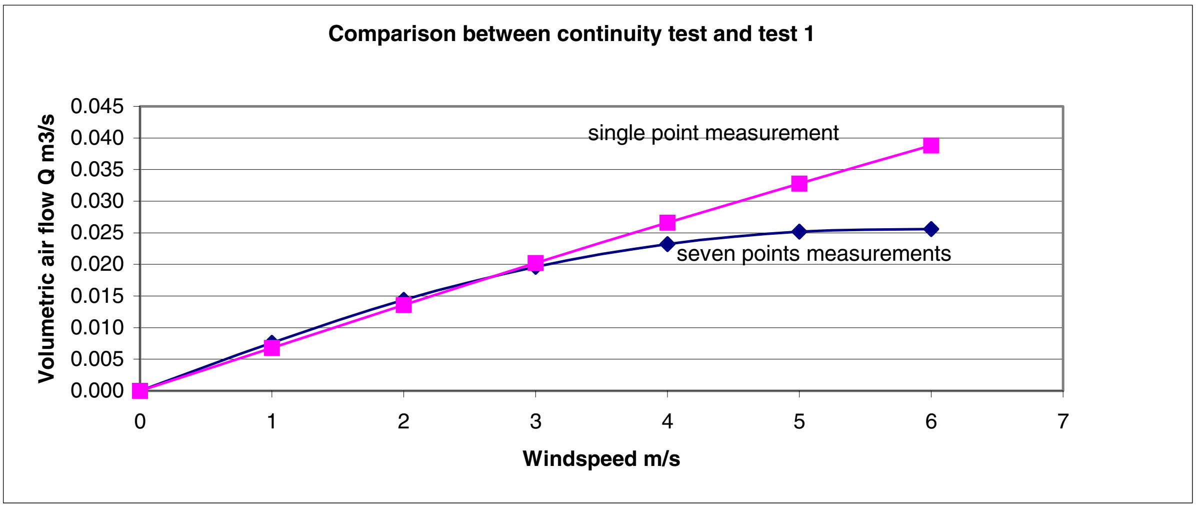

Figure 10. comparison of the measured volumetric air flow rate with single and seven points air speed measurements at segment 4.

Having said that, during the mass continuity tests, the ventilation rate due to the windcatcher system installation increased with the increase in wind speed. A ventilation rate of 4, 5, 6 and 6.8 ac/h were achieved at wind speeds of approximately 1, 2, 3, 4, and 5 m/s respectively as can be seen in Figure 11.

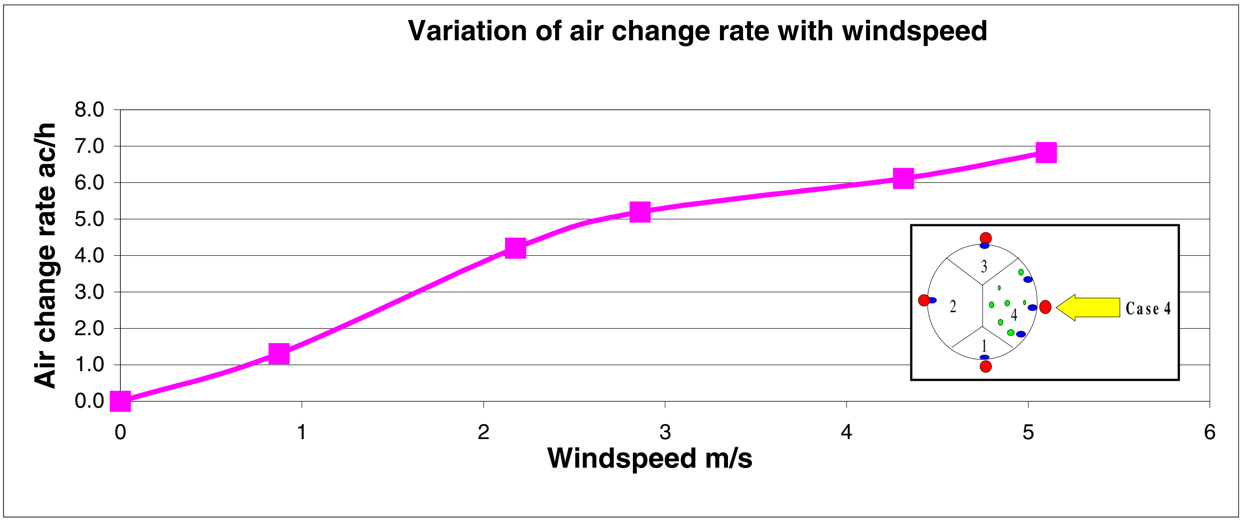

Figure 11. measured air change rate with seven points measurements using hotwire anememoter.

A further investigation was carried out to evaluate the flow rate through individual louvers. Each individual louver and each two adjacent louvers were investigated while other louvers were tightly sealed. Tests were carried out for wind speeds of approximately 3 and 5 m/s. It was found that the position of louver, i.e. 1, 2, 3 or 4 (see Figure 3), has no significant effect on the volumetric air flow through the windcatcher, due to the close proximity of louvers (the distance between each adjacent louvers is less than 0.035 mm). However, the increase of number of louvers will lead to an increase in the air flow as was expected due to the increase of the free louvers area. It was established that each individual louver will provide volumetric air flow between 0.005-0.010 m^3/s for a wind speed in the range of 3-5 m/s. However, the design of louvers to eliminate the ingress of dust, hails, birds and insects reduces the opportunity of having larger free louvers area.

Despite the observed short circuiting, an average internal room air speed of 0.05 m/s at height of 1.5 m beneath the air supply was measured at wind speed of approximately 2 m/s. An average internal air speed of 0.03 m/s was achieved for the test with the lowest wind speed of 1 m/s. Generally, the internal air speed increases with increase in the external wind speed with some variation due to the development of the flow inside the test room.

4. Conclusions

This paper presents the results of a wind tunnel testing for a commercial circular windcatcher. The results showed the potential of the windcatcher as a passive device for providing natural ventilation into buildings. The windcatcher performance depends greatly on the direction and speed of the wind in relation to the windcatcher segments.

A ventilation rate of 5 ac/h (for a room of 13.8 m^3 in volume ventilated with 0.550 mm diameter windcatcher) was achieved with an external wind speed of approximately 3 m/s for a windcatcher cross-sectional area to floor area ratio of about 4%. However, for the windcatcher to work efficiently, it is advisable that the supply and the extract air segments should be separated to avoid short-circuiting and to allow the development of the air flow within the occupied spaces.

Larger windcatcher segments should be positioned in a way that the prevailing external wind will be blowing across them, hence, rendering these segments as air supply. The design of moving louvers cowl needs to be investigated to allow the encapsulation of wind by the windcatcher irrespectively of the wind direction. The integration of the windcatcher with the building façade, as traditionally achieved, will further demonstrate the viability of windcatcher for natural ventilation in buildings.

5. Acknowledgment

The authors would like to acknowledge the support of BSRIA and Monodraught Ltd.

6. References

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