THE PERFORMANCE OF NATURAL VENTILATION WINDCATCHERS IN SCHOOLS: A COMPARISON BETWEEN PREDICTION AND MEASUREMENT

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ABSTRACT

Windcatchers are roof mounted devices that use the action of the wind to provide top down natural ventilation to a room. Here, fresh air is channelled into a room whilst at the same time stale air is drawn out of air room, providing a simple but attractive natural ventilation methodology that is increasing in popularity in U.K. schools. However, an analysis of the performance of Windcatchers has largely been limited to laboratory based measurements and the use of CFD to generate predictions. Moreover, analysis is normally restricted to the operation of an autonomous Windcatcher, whereas in reality a Windcatcher is likely to operate in a building in which other sources of ventilation are present, an open window for example, and this can significantly alter the performance of the Windcatcher. The aim of this article is to provide a tool for estimating the performance of a Windcatcher from basic data that is typically available to the engineer in the building design phase. Accordingly, the methodology uses data that one could reasonably be expected to have for a building's performance prior to estimating the behaviour of the Windcatcher. This article also reviews the ventilation performance of Windcatchers operating *in situ* by measuring their performance in U.K. schools both with and without open windows. Predictions generated by a semi-empirical model are then compared against measurement data and this is shown to deliver generally good agreement between the two, both with and without open windows, provided the theoretical predictions are presented in terms of an upper and lower performance limit. Furthermore, both experiment and theory clearly demonstrate that a large increase in the Windcatcher ventilation rate is possible if one combines the operation of a Windcatcher with, say, an open window, and that this ventilation rate is greater than that which would be achievable from a window operating on its own.

1. INTRODUCTION

A Windcatcher[1] is a roof mounted device that is used to channel fresh air into a room whilst simultaneously drawing stale air out of the room. The Windcatcher works through the action of the wind generating a high pressure on a windward face, forcing fresh air into the room, and turbulence creating a low pressure region on the leeward face, drawing air out of the room. Thus, Windcatchers provide an alternative natural ventilation strategy when compared to more usual methods such as opening windows, or passive stacks. Of course, understanding the performance of a Windcatcher is very important if one is to successfully integrate a Windcatcher into the ventilation strategy for a building; however, very little data currently exists in the literature that quantifies the performance of these devices when operating *in situ*. Furthermore, whilst it is possible for a Windcatcher to operate autonomously, it is common in the summer months for them to be used in conjunction with other methods of ventilation, such as open windows. Accordingly, this article will address both of these issues by reporting new experimental data that quantifies the performance of a Windcatcher operating *in situ*, both with and without open windows. To better understand the measured behaviour, the semi-empirical model of Jones and Kirby (2009) is also extended here to include the effects of openable windows.

A review of Windcatcher operation and performance was recently provided by Jones and Kirby (2009). Here, Jones and Kirby note that the majority of the work on Windcatchers published in the literature centres on theoretical and experimental studies under laboratory conditions. For example, Elmualim and Awbi (2002) used a wind tunnel to measure important Windcatcher parameters such as the coefficient of pressure (C_P) for each face and the losses incurred within the Windcatcher itself. Elmualim (2006), and Li and Mak (2007)

[1] Windcatcher™ is a proprietary product of Monodraught Ltd.

discuss the use of CFD models to predict C_P values, as well as quantifying ventilation rates delivered by a Windcatcher as a function of the incident wind speed. Clearly, it is desirable to be able to predict the performance of a Windcatcher at the design stage of a building. Accordingly, Jones and Kirby (2009) proposed the use of a single semi-empirical model that avoids the use of complex and time consuming CFD calculations by utilising laboratory based measurements of the loss coefficients and C_P. This empirical data is then combined with analytic expressions that enforce conservation of energy and mass in order to deliver a simple set of equations for estimating Windcatcher ventilation rates. However, a disadvantage of this approach is that it is based on empirical data measured under laboratory conditions and so any errors in these measurements will be transferred into the model. Moreover, the parameters measured under laboratory conditions may not accurately reflect the actual values encountered when the Windcatcher operates *in situ*. Therefore, it is important to validate theoretical predictions against *in situ* measurements and here Jones and Kirby (2009) noted that very little experimental data exists in the literature that quantifies *in situ* Windcatcher performance: the only data identified as suitable for comparison with their semi-empirical model were the measurements obtained by Kirk and Kolokotroni (2004) for office buildings. Jones and Kirby note generally good agreement between prediction and measurement provided the predictions for ventilation rates were expressed in terms of limiting values so that wind travelling normal to the Windcatcher generates the maximum predicted ventilation rates and wind travelling at an angle of 45° generates a minimum ventilation rate. However, Kirk and Kolokotroni (2004) only measured a small number of ventilation rates and it is clear that further *in situ* measurements are necessary in order to build up a more accurate and reliable picture of the true ventilation performance of a Windcatcher over a wide range of geometries and wind speeds. Accordingly, this article delivers new experimental data that quantifies the ventilation rates generated by a

Windcatcher in four different buildings. The test buildings chosen here are schools, primarily because schools currently represent a large part of the U.K. Windcatcher market, but they also provide excellent case studies because of their predictable occupancy patterns, long vacation periods allowing for more detailed analysis, and clearly defined indoor air quality (IAQ) benchmarks against which performance may be judged.

An investigation into the use of Windcatchers operating *in situ* also requires one to take account of normal custom and practice within the building. Here, it is common for windows also to be left open in a room that contains a Windcatcher, especially in the summer months. Kolokotroni et al. (2002a), and later Kirk and Kolokotroni (2004) note that opening windows increases ventilation rates by up to 87% when compared to those rates provided by a Windcatcher on its own. This increase in performance was also observed by Su et al. (2008), who use CFD predictions to demonstrate a significant increase in net ventilation rates when combining a single opening in a façade with a circular Windcatcher. This represents a significant improvement in ventilation performance and also offers the potential to improve on rates achieved by alternative natural ventilation strategies. For example, the reliance on manually opening windows in school classrooms often fails to deliver required ventilation rates, see Beisteiner and Coley (2002) and Coley and Beisteiner (2002). In addition, Mumovic et al. (2009) monitored 18 classrooms in nine schools over five days during the winter time, with ventilation strategies that included natural, mechanical, and mixed mode; results show that six classrooms exceeded the required mean CO_2 levels (an indicator of poor ventilation rates) and all of these used a natural ventilation strategy based upon windows only. Clearly, Mumovic et al. and others have identified problems with a natural ventilation strategy based solely on opening windows and that such a strategy is unlikely to suffice for modern school designs. However, the combination of a passive stack with windows is shown by Kolokotroni et al. (2002b) to provide more consistent ventilation rates for a range of environmental and meteorological conditions. Accordingly, the combination of a Windcatcher and open windows appears capable of significantly improving ventilation rates and delivering those rates typically required by building regulations in the U.K., and so this article will examine this effect in detail through the use of theoretical predictions and experimental measurements.

This article begins by extending the semi-empirical model of Jones and Kirby (2009) to include the effects of an opening (nominally a window) in a single façade of a room that also employs a Windcatcher. In Section 3, the empirical constants necessary for the model will be discussed and a preliminary parametric investigation into the behaviour of the system will be undertaken. In Section 4 the experimental methodology is introduced and in Section 5 the semi-empirical model is validated against measured data.

2. THEORY

The semi analytic model used here is a development of the one described by Jones and Kirby (2009) and so is restricted to Windcatchers with a rectangular cross-section divided up into four quadrants. Here, the Windcatcher is subjected to a wind of velocity of u_w incident at an angle of θ degrees to the front face, see Fig. 1a. Each quadrant contains louvers at the top, with dampers and a grill placed at the bottom, see Fig. 1b. The Windcatcher has cross-sectional dimensions $d_1 \times d_2$, the length of the louver section is L_l and the length of the duct from the louvers to the grill is L. For a quadrant that faces into the wind (an "inlet" quadrant), air flows from the surroundings into the room and conservation of energy gives

$$\frac{1}{2}\bar{\rho}u_{\text{in}}^2 K_{\text{in}} = \frac{1}{2}\rho_E u_w^2 C_p - \frac{g z_I p_E}{R}\left(\frac{1}{T_E} - \frac{1}{T_I}\right) - p_I \, . \tag{1}$$

Similarly, air flow from the room to the surroundings through a leeward quadrant (an "outlet" quadrant) gives

$$\frac{1}{2}\bar{\rho}u_{\text{out}}^2 K_{\text{out}} = p_I - \frac{g z_E p_E}{R}\left(\frac{1}{T_I} - \frac{1}{T_E}\right) - \frac{1}{2}\rho_E u_w^2 C_p \, . \tag{2}$$

Here, T_I and T_E denote the internal and external temperature respectively, ρ_I and ρ_E denote the internal and external density respectively, $\bar{\rho}$ is an average value for density over the length of a quadrant, and R is the specific gas constant for air. In addition, u_{in} and u_{out} denote the velocity and K_{in} and K_{out} the loss coefficient for the inlet and outlet ducts, respectively. These energy equations must be solved simultaneously with the statements of conservation of mass, and here it is necessary first to separate different scenarios before writing the continuity equation and solving the problem. These different scenarios depend on whether an open window is present or not, and whether the fabric of the room is assumed to be sealed or not (Jones and Kirby 2009).

The model presented by Jones and Kirby (2009) is extended here to include the effect of an opening in a single façade of the room containing the Windcatcher. Purpose provided openings, such as air vents, windows and doors are generally characterised as sharp-edged openings with negligible thickness (Etheridge and Sandberg 1996). Accordingly, an opening of rectangular dimensions located at the midpoint of a façade in both the vertical and horizontal planes is considered here. The vertical midpoint of the opening is assumed to be at a height z_O from the floor (see Fig. 1b), and it is assumed that the flow incident on the opening is uniform.

For the opening, the flow of air around the building induces a change in pressure on each façade so that those openings with wind incident on them will have a pressure higher than the room, whilst those in the wake/leeward regions will have a lower pressure because of energy dissipation through flow separation and turbulence. If the façade opening (designated the 5th opening in Fig. 1b) is in an area of positive pressure then conservation of energy gives

$$\frac{1}{2}\rho_E u_5^2 K_5 = \frac{1}{2}\rho_E u_w^2 \tilde{C}_{p5} - \frac{g z_O p_E}{R}\left(\frac{1}{T_E} - \frac{1}{T_I}\right) - p_I \,. \tag{3}$$

It is convenient here to refer the incident wind velocity at the opening back to the wind velocity at room level that is used for the Windcatcher computations. This may readily be achieved using the correction equation of Liddament (1996), and writing

$$\tilde{C}_{p_5} = C_{p_5}[z_O/z_E]^{2a}, \tag{4}$$

where a is a topographically dependent constant. If the opening is in an area of negative pressure, then

$$\frac{1}{2}\rho_I u_5^2 K_5 = p_I + \frac{g z_O p_E}{R}\left(\frac{1}{T_E} - \frac{1}{T_I}\right) - \frac{1}{2}\rho_E u_w^2 \tilde{C}_{p_5} \,. \tag{5}$$

The continuity equation is given by

$$\sum_{n=1}^{5} \dot{Q}_n = 0, \tag{6}$$

where $\dot{Q}$ is the volume flow rate. The equations reduce to a series of simultaneous equations that must be solved iteratively, which has been discussed previously by Jones and Kirby

(2009). This semi-empirical model now allows quick estimations to be made of the ventilation rate through a room ventilated by a Windcatcher with and without façade openings. This makes it a very useful iterative design tool when considered against alternative prediction methods such as CFD. The time taken to generate and solve CFD models can be prohibitive for some applications if one needs a quick, easy, and reliable indication of Windcatcher performance; for example, fast calculations are often required in commercial applications.

3. SEMI-EMPIRICAL MODEL

The theoretical model developed in the previous section depends on a knowledge of the loss coefficients for each inlet and outlet quadrant, which we shall call here K_{in} and K_{out}, as well as the coefficient of pressure for each face of the Windcatcher and the coefficient of pressure for the façade where the opening is located. Once these factors have been identified they may be substituted back into the theoretical model to form the semi-empirical approach. Loss factors for the Windcatcher were identified as $K_{\text{in}} = 4.30 + K_{\text{frict}}$, and $K_{\text{out}} = 8.85 + K_{\text{frict}}$ by Jones and Kirby (2009), where K_{frict} represents the frictional losses imparted by the walls of each quadrant, such that $K_{frict} = 0.06L/d_H$ with d_H being the hydraulic diameter of the duct. Losses through a sharp-edged façade opening are shown by Karava et al. (2004) to be a function of its shape and location within the façade, the wind angle of incidence, and a Reynolds Number Re (based on d_H for the opening). Etheridge and Sandberg (1996) show that if Re is high (>>100) losses for a sharp-edged opening can be represented by a single discharge coefficient, which may be shown to vary from $C_d = 0.60$ to $C_d = 0.65$ (Karava et al. 2004). Alternatively, CIBSE (2006) suggests a discharge coefficient of $C_d = 0.61$, which correlates to a loss factor of $K_5 = 2.69$. Accordingly, this latter value will be used in the semi-empirical model that follows as it fits both sets of data, although it is likely that this value is only an approximation of the actual *in-situ* loss factor.

The C_p values used for each face of the Windcatcher, and for $\theta=0^\circ$ and $\theta=45^\circ$, are summarised in Table 1. These have been obtained from measurements made using a 500 mm square Windcatcher in a wind-tunnel and verified using CFD, see Jones and Kirby (2009) for further discussion. The magnitude of C_{p5} for the façade of a building is a function of the geometry of the building, the angle of the wind incident to the façade, and the topography surrounding the building. Estimations of C_{p5} are commonly made from wind tunnel analysis, but can also be made using predictive software, see for example Sawachi et al (2006). Values of C_{p5} covering $\theta=0^\circ$ to $\theta=315^\circ$, for intervals of $\theta=45^\circ$, are given in several sources and Liddament (1996), Orme and Leksmono (2002), and Santamouris and Asimakopoulos (1996) all quote similar values for buildings with an aspect ratio (length to width) of 1:1 and 2:1. Here, a range of C_{p5} values may be obtained depending on the location of the façade and so limiting values appropriate to the facades in the buildings studied here are chosen as -0.38 and 0.06. These values are for a building with an aspect ratio of 2:1 and are based upon the assumptions that the opening is located within the longest wall of the building and that the angle of incidence of the wind to the façade varies from 0° to 315°. The value of $C_{p_5} = 0.06$ corresponds to a façade placed on a windward wall; $C_{p_5} = -0.38$ corresponds to a leeward wall. Although the school buildings measured here have aspect ratios greater than 2:1, these C_{p5} values are for the maximum aspect ratio covered in the literature. Furthermore, those values chosen also take into account that the school buildings in Table 2 are surrounded by obstacles equivalent to their full height, such that aerodynamic flow fields from them and any surrounding buildings or obstacles will interact.

It is interesting first to view the effect of increasing the open area of the façade on the volume flow rate of total air extracted from the room, Q_T, that is, via the Windcatcher and the opening. In Fig. 2, the total extracted volume flow rate is normalised so that $Q_O = Q_T/u_w A$ (where $A = \sum_{n=1}^{4} A_n$) is plotted against a normalised open area of the façade $A_O = A_5/A$, for $C_{p5} = 0.06$ and $C_{p5} = -0.38$, and for $\theta = 0^\circ$ and 45°. Here, $z_0 = 1.65$ m, $z_I = 3.30$ m, $z_E = 4.30$ m, $a = 0.25$, and $L = 1$ m. Fig. 2 shows that when $\theta = 0^\circ$ the flow rate increases significantly once an opening is present and this increase in maintained until a limiting open area of approximately $A_O = 0.7$ is reached when $C_{p5} = 0.06$. When the C_{p5} value changes to -0.38, the extract ventilation rate increases significantly when compared to $C_{p5} = 0.06$ and here the flow rate is seen to rise steadily and only levelling off above $A_0 \approx 1.3$. Here, the predictions suggest that opening, say, a window in a room will improve the ventilation rates delivered by a Windcatcher when $\theta = 0^\circ$ regardless of the value for C_{p5}, although to maximise the flow rate this opening should at least give $A_O > 0.7$. The picture is, however, more complicated when $\theta = 45^\circ$, where it is evident that for $C_{p5} = 0.06$ no change in extract ventilation rates is observed. Conversely, when $C_{p5} = -0.38$ a very large rise in volume flow rate is observed and so it is seen that under these conditions the flow rate is very sensitive to the value identified for C_{p5}. When $\theta = 45^\circ$, this behaviour is thought to be a function of the losses through inlet and outlet ducts, as well as the number of quadrants that are being used to supply or extract air. Generally, when $C_{p5} = 0.06$, air is supplied by the façade opening and is extracted from the room through two or more Windcatcher quadrants, whereas when $C_{p5} = -0.38$ air is also extracted through the façade opening. This is significant because the losses through a Windcatcher are greater when flow is from the room to the surrounding than when flow is from the surroundings into the room ($K_{out} \gg K_{in}$), and because losses are significantly less through the opening ($K_{out} > K_{in} \gg K_5$) than through any Windcatcher quadrant. Therefore, when $\theta = 0^{\circ}$ and $C_{p5} = 0.06$, the façade opening supplies air and three Windcatcher quadrants extract air from the room, but when $\theta = 45^{\circ}$ only two quadrants extract air, thus reducing the overall area of the extract quadrants and significantly reducing the extracted volume flow rate. When $C_{p5} = -0.38$ and $\theta = 45^{\circ}$ all of the Windcatcher quadrants supply air into the room and this effectively overrides the normal function of the Windcatcher reducing overall losses and maximising the ventilation rate.

The influence of internal and external temperatures on the extracted volume flow rate is presented in Fig. 3 for a 1000 mm square Windcatcher, where $A_5 = 1\ \text{m}^2$, $\Delta T = T_{out} - T_{in} = 5°\text{C}$, and $\theta = 45^{\circ}$ (all other data is the same as for Fig. 2). Figure 3 shows that as the wind speed increases, the buoyancy forces are less significant. When $u_w < 1.3\ \text{m/s}$, Fig. 3 shows that the estimates of volume flow rate with and without buoyancy forces diverge, suggesting that the buoyancy forces are an important consideration at low incident wind velocity for any value of C_{p5}. This is similar to the findings of Jones and Kirby (2009) for an autonomous Windcatcher, where the effect of buoyancy is found only to be significant for $u_w < 2m/s$. However, Fig. 3 shows that as the magnitude of C_{p5} increases the predictions of volume flow rate with and without buoyancy forces cannot be said to be similar, and so should be considered whatever the wind velocity.

The accuracy of the ventilation rate predictions for a room containing both a Windcatcher and an opening depends on the constants used for the opening, namely K_5 and $\tilde{C}_{p5}$. Here, varying K_5 by 10% had no discernable effect on the predicted ventilation rates, suggesting that any inaccuracies in the value used will not significantly affect the behaviour observed here. The variable $\tilde{C}_{p5}$ contains two constants, a and C_{p5}. Of these, C_{p5} is the most problematic and Fig. 4 shows the affect of varying this parameter for three different values of A_5 when $\theta = 45°$. Note that the plot is not symmetric because the losses in the inlet and outlet ducts of the Windcatcher are dissimilar (as discussed earlier), and this is why the model predicts greater ventilation rates when the opening is placed in an area of negative pressure. This observation does not agree with the CFD predictions of Su et al. (2008), who show that when a circular Windcatcher is mounted on the apex of a 30° pitched roof on a square exposed building, the opening located on the windward façade delivers the greatest ventilation rates. However, the crucial factor here is that Su et al. (2008) examine an exposed building and Liddament (1996) reports that a windward façade of an exposed building has the greatest magnitude of C_{p5}, and the value one would expect under these conditions is $C_{p5} = 0.7$. Accordingly, running the model developed here with data for an exposed building does deliver a greater extract volume flow rate for the windward face (results not shown here), in accordance with the findings of Su et al. (2008). It is evident in Fig. 4, however, that the volume flow rate is sensitive to the values chosen for C_{p5}, for example if $C_{p5} = -0.38$ is varied by $\pm 10\%$ when $A_5 = 1.5$ m^2, the predicted ventilation rate changes by approximately $\pm 7\%$. Thus, the model is sensitive to the values chosen for C_{p5} and so the accuracy of the semi-empirical predictions that follow in Section 4 will depend on the suitability of the value chosen for C_{p5} for the particular building that is being measured. Of course, accurately identifying this value for individual buildings and for different climatic conditions presents a considerable challenge and this represents a limitation of the semi-empirical approach.

4. EXPERIMENT

Four schools and twelve classrooms are chosen here to investigate the performance of a Windcatcher. Within each school a number of classrooms ventilated by a single roof-mounted Windcatcher have been identified. At roof level each Windcatcher is free from obvious shielding caused by external obstacles or architectural features and each Windcatcher element measured has a square cross-section. In addition, none of the classrooms contain supplementary mechanical supply or extract ventilation. The relevant parameters of the Windcatchers used in this study are given in Table 2. Values quoted in this table for the cross sectional area (CSA) of each Windcatcher quadrant takes into account the presence of an acoustic lining, which is normally made from foam and covers the duct walls and the diagonal dividers (see Fig. 1a). Each school is assigned an alphabetical prefix in Table 2 and each classroom monitored within a school is given a numerical suffix. All of the school buildings have been completed since 2003 and are located in urban areas in the south of England. At school F all of the windows are sealed, but at the other schools some or all of the windows may be opened manually and the estimated maximum openable area (A_5) for these windows is calculated using CIBSE guidelines (CIBSE, 2005).

A total of 56 measurements were made with the Windcatcher open and all windows closed, and 19 measurements were made with both the Windcatcher and windows open. These measurements were undertaken in empty classrooms during normal occupied hours and throughout the year in order to test a range of different environmental conditions. Ventilation rates were measured using the standard single-zone tracer gas decay method, see for example Etheridge and Sandberg (1996), and Liddament (1996). Sulphur hexafluoride (SF_6) was used as the tracer gas and was only applied to the classroom, and not any adjacent rooms or corridors. Mixing fans were used to ensure an even distribution of SF_6 throughout the room, but were not used during the measurements because they are thought to initiate artificial flow paths (Liddament 1996). The SF_6 was measured every 45 seconds by an Innova 1312 dual gas analyser that has a reading repeatability of 1%. Measurements were taken from the centre of the room for periods of no less than 20 minutes and an estimation of the air change rate (ACR) was made by plotting the tracer gas concentration against time in accordance with Liddament (1996), see Figure 5. Note that the single zone gas decay method used here does not measure the rate of air flow though the Windcatcher, rather it measures the ventilation rate for the room and may also include airflow between the room and corridors. Here, Sherman (1990) suggests that ±10% is a reasonable assumption of the overall error in the measured ventilation rate, whilst Persily (2006) finds that typical field measurements have uncertainties of at least ±20%. Accordingly, the error bars in Figs. 6–8 show a 20% margin of error. The wind direction and speed were obtained from the Met Office (2009) for the weather station closest to each school and converted to an estimated velocity, u_w at a Windcatcher height of z_E with terrain coefficients of $k = 0.35$ and $a = 0.25$.

5. RESULTS AND DISCUSSION

The semi-empirical model is now compared against the experimental measurements to determine its suitability for use in the design of a natural ventilation strategy that incorporates a Windcatcher. Two cases are considered: the first is for a Windcatcher functioning autonomously since very little data currently appears in the literature for this device, and the second is for a Windcatcher in coordination with a single façade opening. For a Windcatcher operating autonomously the predicted and measured room ventilation rates are presented for 800 mm and 1000 mm square Windcatchers in Figs. 6 and 7, respectively. Here, the duct length is set to $L = 1$ m in the model because Jones and Kirby (2009) show that an increase in duct length from 1 m to 10 m has a minimal effect on the predictions. However, the measured ventilation rates are separated in Figs. 6 and 7 into dots for $L = 1$ m and crosses for $L > 1$ m. Here, it is immediately obvious that the measured ventilation rates for those Windcatchers with $L > 1$ m are much lower than the rates measured when $L = 1$ m. One possible explanation for this behaviour is that for Windcatchers with $L > 1$ m the diagonal partition extends from the upper louvered element only to about 1m below it, and not for the whole length of the duct. Thus, the model does not fully replicate the geometry of this type of Windcatcher, but more importantly it is possible that so-called "short circuiting" is taking place here, whereby a mixing of air is taking place in the lower half of the Windcatcher and that this is restricting the flow of air from the room through the outlet quadrants. Further evidence for this is provided by the CFD analysis of Hughes and Ghani (2008, Figs. 10 and 13).

The predictions presented in Figs 6 and 7 follow the method of Jones and Kirby (2009) and so two lines are drawn, one for $\theta = 0°$ and one for $\theta = 45°$. This forms a "wedge" that is intended to encompass two extremes of operation for the Windcatcher, depending on the incident wind conditions: $\theta = 0°$ represents the maximum ventilation rate and $\theta = 45°$ the minimum. In Fig. 6, 40% of the measured data lies within this wedge if one ignores data for $L > 1$m, whereas in Fig. 7 this figure is 60%. Here, it is noted that the predictions are generally reasonable correlation with the experimental data given the complexity of the problem and support the observations of Jones and Kirby (2009), who compared their results against data supplied by Kirk and Kolokotroni (2004); however, some of the measured data clearly shows that the Windcatcher is under-performing when compared to the predictions, especially for the 800 mm square Windcatcher. The reasons for this are not fully understood, although it is possible that the external wind conditions estimated from the Met. Office data did not accurately represent the true local conditions when the measurements took place. Alternatively, it is possible that some operational issues with the Windcatcher have occurred and that further investigation is necessary. Nevertheless, the action of the Windcatcher and its ability to act autonomously in the generation of ventilation in a room is clearly evident in Figures 6 and 7.

Predicted ventilation rates are now compared against measured data for a Windcatcher operating in combination with open windows. In this case, the number of variables in the semi-empirical model is greater than seen for an autonomous Windcatcher and so in order to quantify the predicted limits of Windcatcher performance in the form of the "wedge" seen in Figs. 6 and 7, it is necessary to make the following (limiting) assumptions: (i) for A_5 the maximum openable window area is used, (ii) the maximum ventilation rate is predicted when $\theta = 45°$ and $C_{p5} = -0.38$, and the minimum ventilation rate is when $\theta = 45°$ and $C_{p5} = 0.06$ (see Fig. 2), and (iii) the effects of buoyancy are not included because of the wide variation of the difference between measured internal and external temperatures (mean difference of 0.84°C with a standard deviation σ = 5°C). Furthermore, a statistical analysis (not detailed here) showed no link between the measured ventilation rates and the difference between internal and external temperatures. In contrast, the measured ventilation rates were obtained with openable window areas ranging from $A_5 = 0.4\ \text{m}^2$ to $A_5 = 0.9\ \text{m}^2$ for a classroom containing a 1000 mm square Windcatcher, and from $A_5 = 0.3\ \text{m}^2$ to $A_5 = 1.8\ \text{m}^2$ for a classroom containing a 800 mm square Windcatcher. Accordingly, the "wedge" is used to identify the predicted operating envelope for the Windcatcher with the expectation that the measurements should lie within the wedge.

In Fig. 8, measured and predicted ventilation rates are presented for 800 mm and 1000 mm square Windcatchers operating in combination with open windows. It is evident here that the predictions for the 800 mm and 1000 mm Windcatchers are similar, although it is not surprising to see the 1000 mm Windcatcher delivering a higher ventilation rate. For the experimental data, Fig. 7 shows that the 13 measurements for a 800 mm Windcatcher are more widely dispersed than the 6 measurements for a 1000 mm Windcatcher. It is, however, evident that when the windows are open the predictions are less successful and here it is common for the theory to under-predict the ventilation rates. This is in contrast to the previous example in which the over-prediction of ventilation rates was common for an autonomous Windcatcher. It is, therefore, likely that the under-prediction seen in Fig. 8 is caused by an under-estimation of the C_{p_5} values used in the model. What is clear, however, is that opening a window, or windows, has the potential to significantly increase the ventilation rate in the classrooms studied here and the under-performance seen in Figs. 6 and 7 has largely been eliminated.

To further illustrate the influence of opening windows it is constructive to compare the measurements with and without the open windows. Accordingly, in Fig. 9 all of the measured ventilation rates are compared on a single plot. Here, ventilation rates are seen to increase significantly when a Windcatcher is used in combination with an open window. Interestingly, the measured volume flow rates for a Windcatcher with closed windows do not exceed $0.23\ \mathrm{m}^2$, and appear to plateau when $u_w \geq 2\ \mathrm{m/s}$. This is not predicted by the model and the cause of this is unclear, but it may be a function of the internal dynamics of the Windcatcher or an environmental problem such as roof level turbulence.

Figures 8 and 9 clearly demonstrate that opening a window as well as the Windcatcher significantly increases the ventilation rates in a classroom, however it is important to be sure that this is caused by the action of the window and Windcatcher working together and cannot be obtained with a window acting on its own. Accordingly, to investigate this further, specific tests were conducted in classrooms C1, D1, and G1 whereby the ventilation rate through the maximum openable window area was measured with the Windcatcher ducts closed. Results obtained indicate that volume flow rates were, on average, 32% less than those ventilation rates obtained with the windows and Windcatcher operating together. They show that the ventilation rates provided by these windows on their own were greater than those measured by Beisteiner and Coley (2002), Coley and Beisteiner (2002), and Mumovic et al. (2009), and this may be a function of their type, see Table 2. However, the results indicate that, despite the improved individual performance of these windows, Windcatchers are still capable of significantly increasing ventilation rates when combined with the windows. Therefore it is evident that this configuration could be used to achieve high levels of ventilation through a room in order to deliver good IAQ levels, as well as dissipate large heat gains and provide purge ventilation. For example, the purge ventilation requirement for a U.K. school classroom with 30 occupants is $0.24\,\mathrm{m}^3/\mathrm{s}$ (DfES 2006). In order to meet this flow rate using an 800 mm square Windcatcher, then if we choose, for example, $u_w = 3\,\mathrm{m/s}$, Fig. 2 indicates that an opening of area $A_5 = 0.09\,\mathrm{m}^2$ is necessary. Therefore, this suggests that the requirement can be met with a relatively small open area. Ventilation performance can be improved if the building is located in a terrain with few obstacles or surrounding buildings, and Fig. 4 shows that for a given C_{p_5} value the windows should be located so that their orientation is normal or leeward to the prevailing wind, and are, therefore, in an area of negative pressure; however what is important here is the magnitude of C_{p_5} and so it is preferable to open windows that maximise this value and here the appropriate window will depend on the topography of the building as well as the prevailing wind conditions.

5. CONCLUSIONS

This paper has detailed a tool for estimating the performance of a Windcatcher from basic data that is typically available to the engineer in the building design phase. The methodology uses only data that one could reasonably be expected to have for a building's performance prior to estimating the behaviour of the Windcatcher.

The theoretical predictions and experimental measurements presented here demonstrate that a Windcatcher is capable of delivering ventilation for a room when acting autonomously provided that a number of design criteria are met. The semi-empirical predictions generally show good agreement with the *in situ* measurements. This further supports the observations in a previous paper by Jones and Kirby (2009) that this semi-empirical model is capable of capturing the performance of a Windcatcher. However, when operating autonomously Windcatcher ventilation rates are sometimes over-predicted and significant scatter in the experimental data is observed. Accordingly, it appears sensible to view the semi-empirical model as an estimation of Windcatcher performance over a period of time rather than expecting these predictions to accurately replicate ventilation rates for a particular day. The relatively poor performance of Windcatchers with long duct sections was, however, not predicted and here some further investigation into the operation of these devices appears to be necessary.

Both theory and experiment clearly demonstrate that Windcatcher ventilation rates can be significantly improved by the addition of open windows. Here, results indicate that ventilation rates are increased by an average of 47% with the addition of open windows. This effect is likely to help rooms with Windcatchers to meet ventilation standards for buildings, for example BB101 in the U.K. (DfES 2006). Of course, the opening of windows is only practicable in the summer months and one must be careful that "drafts" do not annoy the building's occupants, however the findings presented here clearly demonstrate the potential of a properly designed top-down natural ventilation system to deliver the ventilation requirements for a school classroom.

ACKNOWLEDGEMENTS

This research was carried out with financial support from the Engineering and Physical Sciences Research Council (EPSRC) and Monodraught Ltd.

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FIGURE CAPTIONS

Figure 1 (a) Plan view of Windcatcher (b) Side view of Windcatcher

Figure 2 Prediction of the effect of the area of a façade opening on Windcatcher ventilation rates. ———, $\theta = 0^\circ$; — — —, $\theta = 45^\circ$.

Figure 3 Prediction of ventilation rates for a $1000\ \text{mm}$ square Windcatcher with $A_5 = 1\ \text{m}^2$ and $\theta = 45^\circ$. ———, $\Delta T = 0^\circ\text{C}$ and $C_{p5} = -0.38$; — — —, $\Delta T = 0^\circ\text{C}$ and $C_{p5} = 0.06$; - - - - - - -, $\Delta T = 5^\circ\text{C}$ and $C_{p5} = -0.38$; — - — - —, $\Delta T = 5^\circ\text{C}$ and $C_{p5} = 0.06$.

Figure 4 Prediction of ventilation rate from a room with varying C_{p5} for façade opening. ———, $A_5 = 1.5\ \text{m}^2$, — — —, $A_5 = 1.0\ \text{m}^2$, - - - - - - -, $A_5 = 0.5\ \text{m}^2$.

Figure 5 Example tracer gas tests. Natural log of tracer gas concentration *C(t)* at time *t*, equation of line of best fit, and coefficient of determination.

Figure 6 Ventilation rates for an autonomous $800\ \text{mm}$ square Windcatcher. ———, prediction $\theta = 0^\circ$; — — —, prediction $\theta = 45^\circ$; •, measurement $L \leq 1\ \text{m}$; ×, measurement $L > 1$ m; A, Andrews Field weather station; P, Portland weather station.

Figure 7 Ventilation rates for an autonomous 1000 mm square Windcatcher. ———, prediction $\theta = 0^\circ$; — — —, prediction $\theta = 45^\circ$; •, measurement $L \leq 1\ \text{m}$; ×, measurement $L > 1$ m; H, Heathrow weather station; W, Wisley weather station.

Figure 8 Ventilation rates for Windcatcher with open windows. ——— , prediction (upper and lower bounds) for 1000 mm square Windcatcher with $A_5 = 0.9\text{m}^2$; — — —, prediction (upper and lower bounds) for 800 mm square Windcatcher with $A_5 = 1.8\text{m}^2$; •, measurement 800 mm square Windcatcher, ×, measurement 1000 mm Windcatcher; A, Andrews Field weather station; H, Heathrow weather station; P, Portland weather station; W, Wisley weather station.

Figure 9 Measured ventilation rates for Windcatchers with and without open windows. • , 800 mm square Windcatcher with windows closed; ■, 1000 mm square Windcatcher with windows closed; × , 800 mm square Windcatcher with windows open; □ , 1000 mm square Windcatcher with windows open.

TABLES

Table 1
C_p values used
in semi-empirical model

	$\theta = 0^\circ$	$\theta = 45^\circ$
C_{p_1}	0.84	0.31
C_{p_2}	-0.34	0.31
C_{p_3}	-0.34	-0.2
C_{p_4}	-0.11	-0.2

Table 2
Classroom parameters

Room	Volume (m^3)	Actual Windcatcher Side (mm)	Actual Quadrant CSA*, A_{1-4} (m^2)	Duct length, L (m)	Openable Window Type	Maximum Openable Window Area, A_5 (m^2)	Weather station [distance] (km)
C1	148	1000	0.193	4.8	6×Top Hung	0.9	Wisley [10.0]
C2	172	1000	0.193	1.0	6×Top Hung	0.9	Heathrow [21.6]
C3	148	1000	0.193	4.8	6×Top Hung	0.9	
C4	172	1000	0.193	1.0	6×Top Hung	0.9	
D1	272	800	0.160	1.0	5×Top Hung	1.5	Portland [41.6]
D2	272	800	0.160	1.0	5×Top Hung	1.5	
D3	272	800	0.160	1.0	5×Top Hung	1.5	
F2	549	800	0.145	1.0	None	n/a	Andrews Field
F4	498	800	0.145	1.0	None	n/a	[12.8]
G1	203	800	0.160	5.5	4×Sash	1.8	Andrews Field
G2	185	800	0.160	5.8	2×Sash	1.8	[22.4]
G3	203	800	0.160	5.5	2×Sash	1.8	

*CSA Cross sectional area

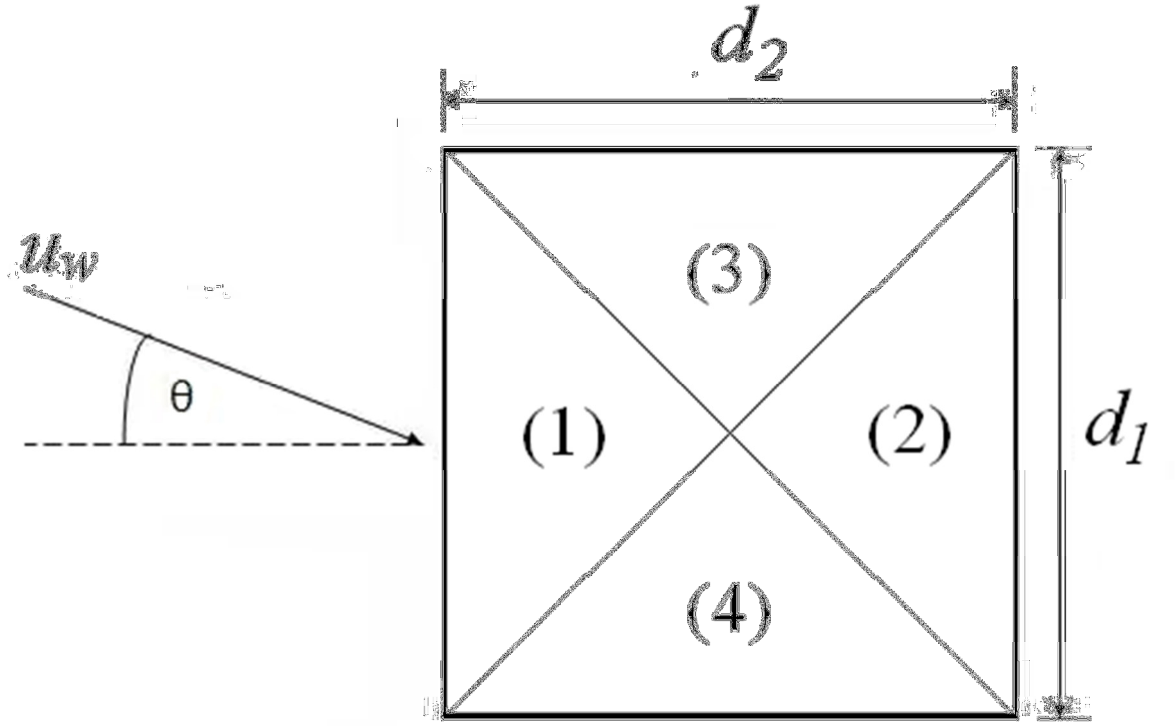


Figure 1a.

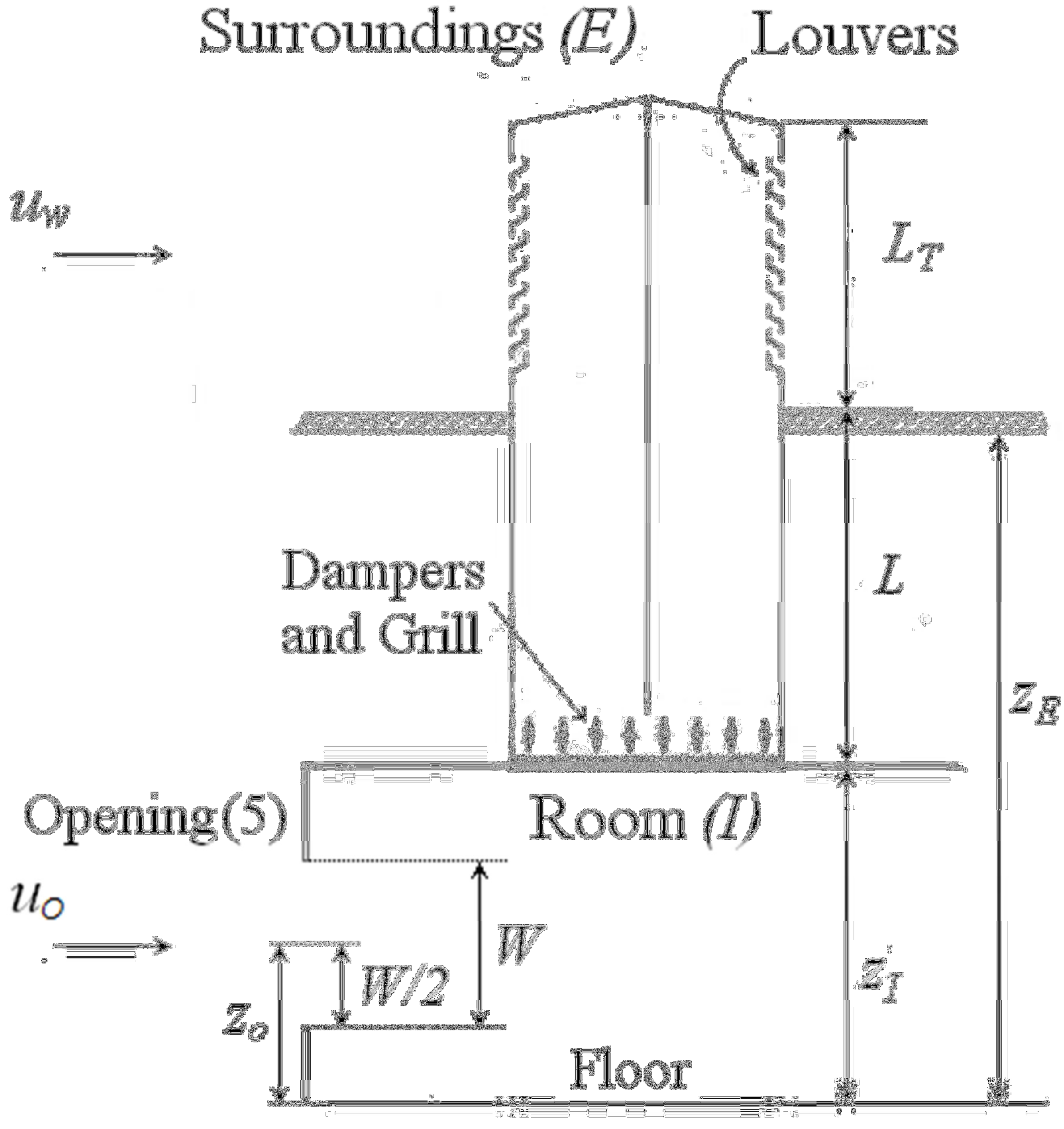

Surroundings (E)
Louvers
u_W
L_T
L
Dampers
and Grill
z_E
Opening(5)
Room (I)
u_O
W
$W/2$
z_O
z_I
Floor

Figure 1b.

FIGURES

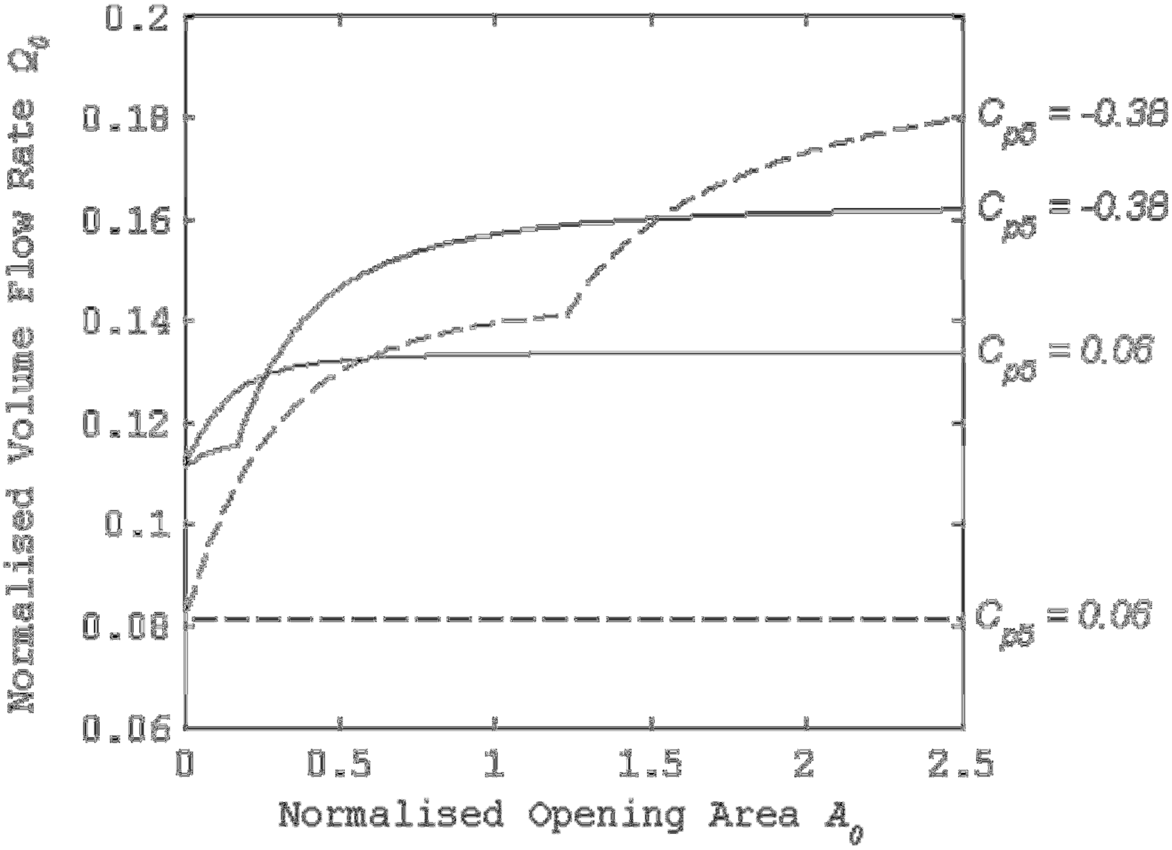


Figure 2.

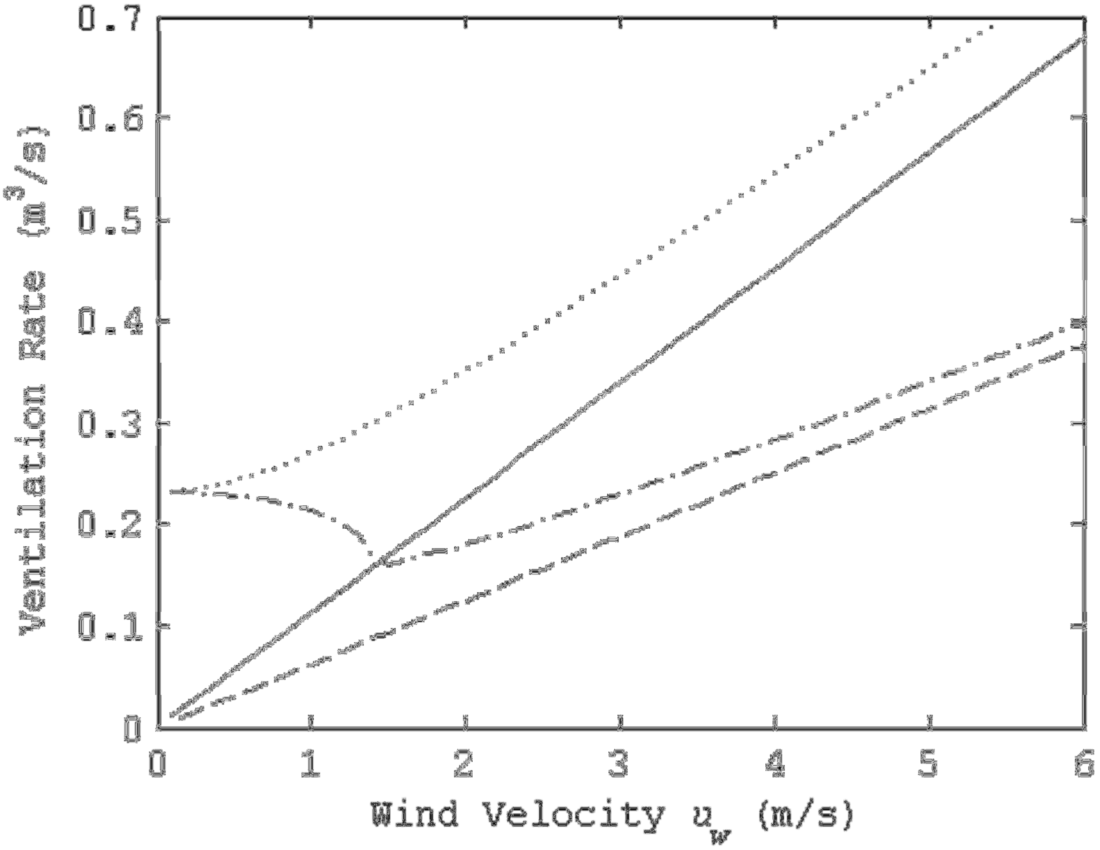
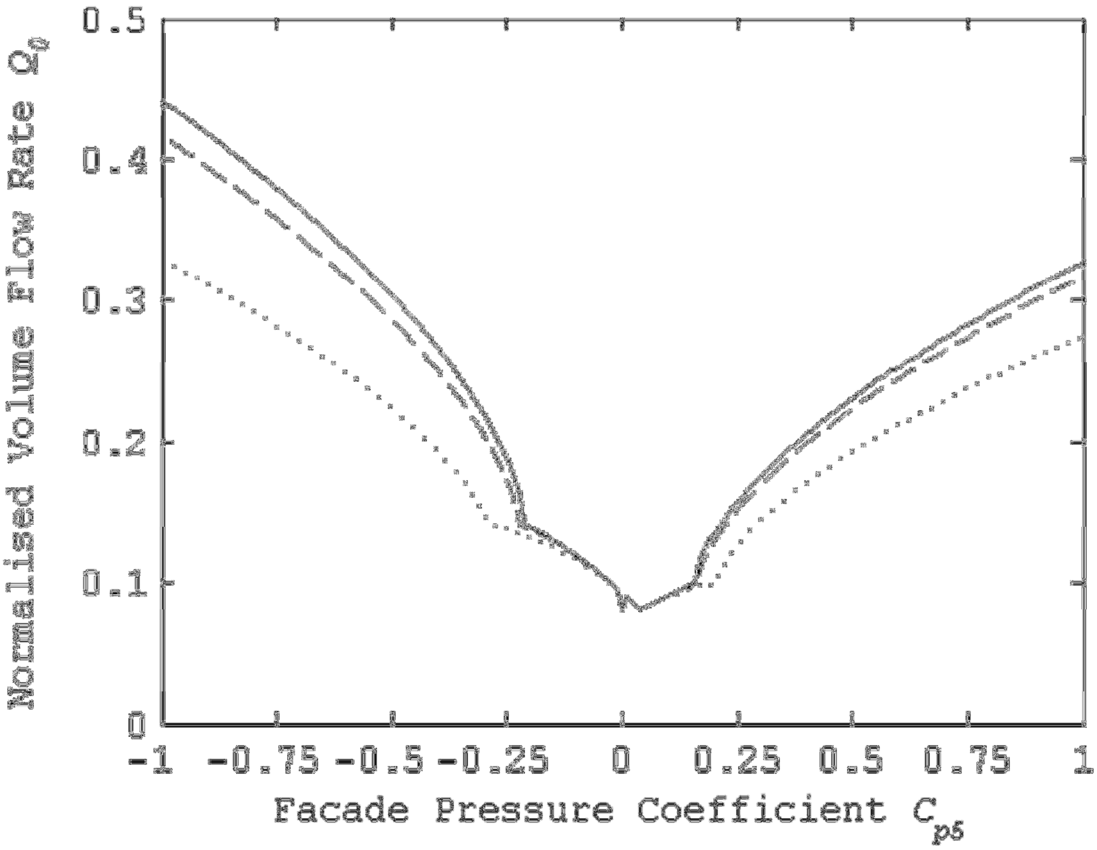
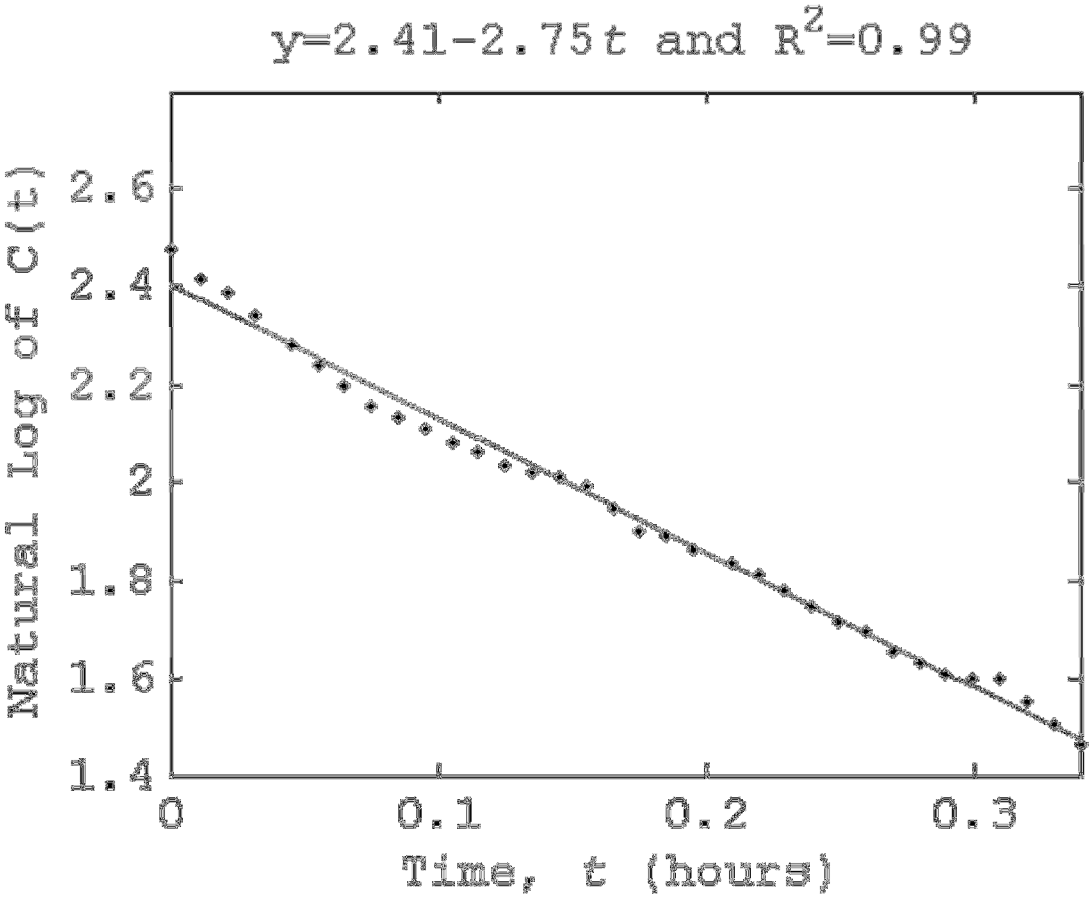

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Ventilation Rate (m^3/s)
0
1
2
3
4
5
6
Wind Velocity u_w (m/s)

Figure 3.



0.5
0.4
0.3
0.2
0.1
0
Normalised Volume Flow Rate Q_0
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
Facade Pressure Coefficient C_{p5}

Figure 4.



y=2.41-2.75t and R2=0.99
Natural Log of C(t)
2.6
2.4
2.2
2
1.8
1.6
1.4
0
0.1
0.2
0.3
Time, t (hours)

Figure 5.

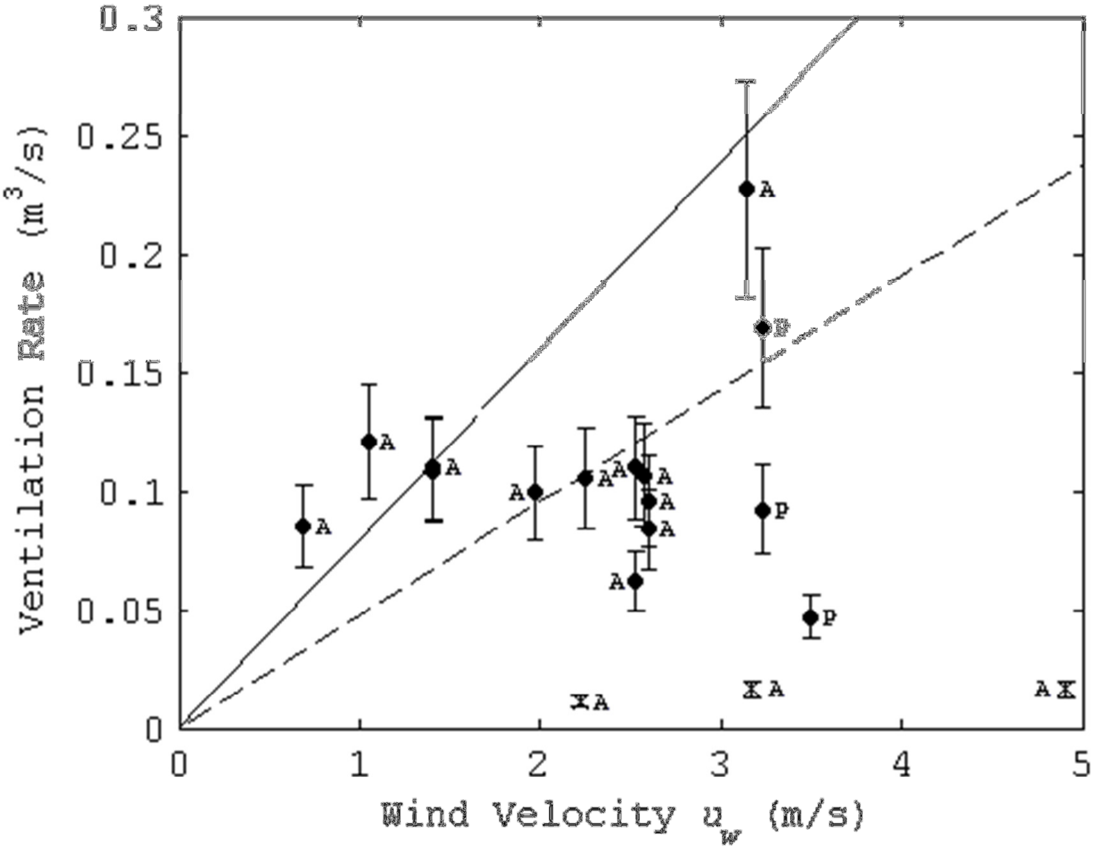
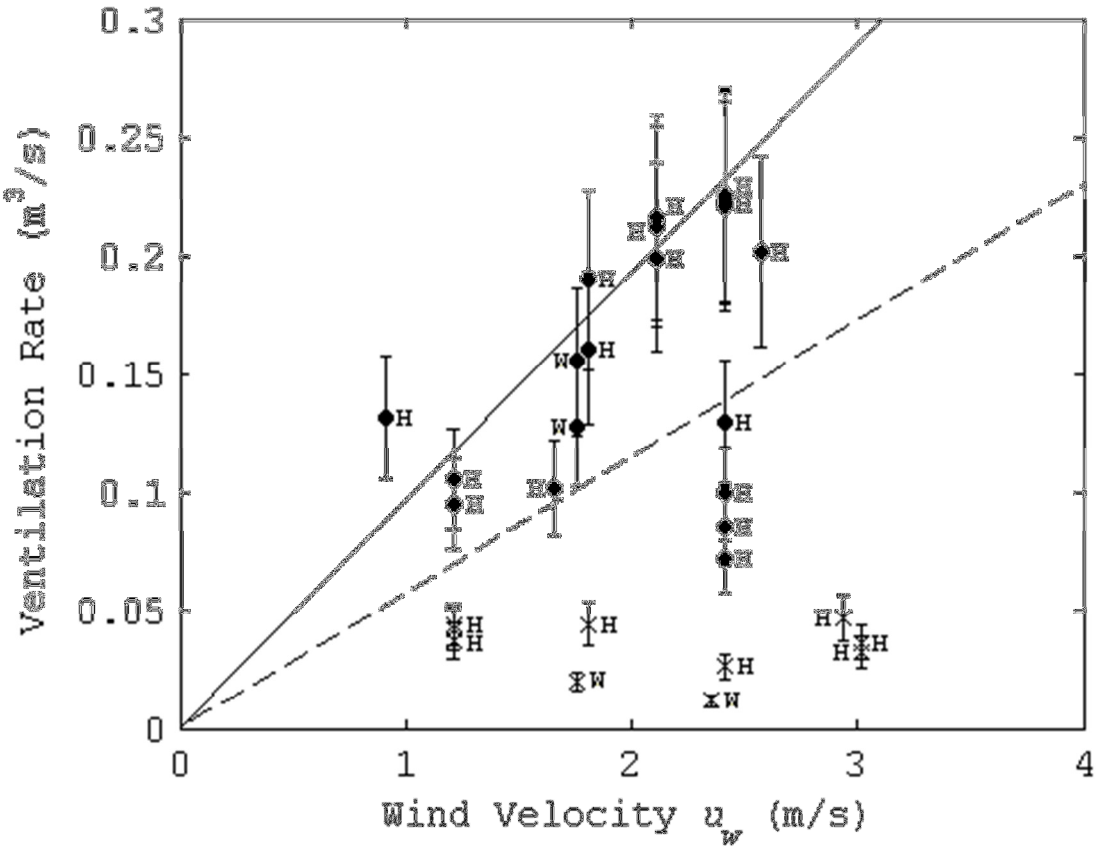

Ventilation Rate (m³/s)
Wind Velocity u_w (m/s)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
1
2
3
4
5
A
P

Figure 6.



Ventilation Rate (m^3/s)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
Wind Velocity u_w (m/s)

Figure 7.

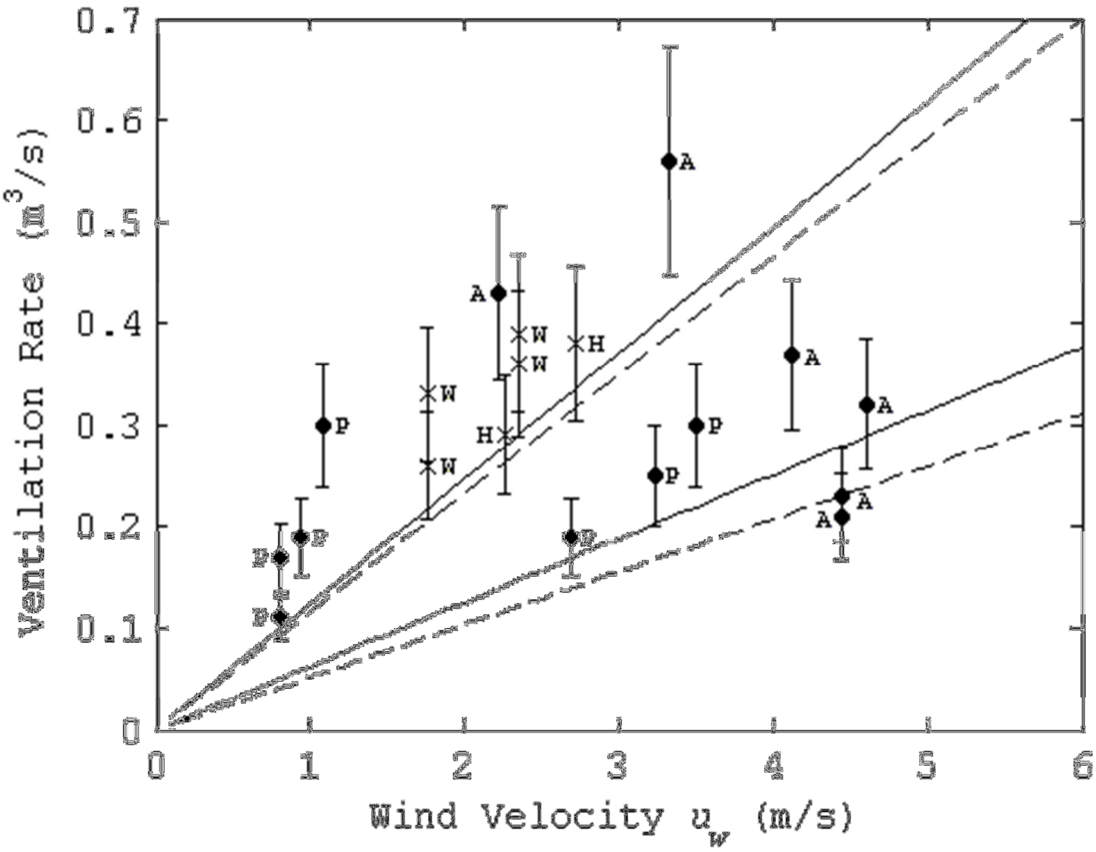

Ventilation Rate (m^3/s)
Wind Velocity u_w (m/s)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
1
2
3
4
5
6
A
W
H
P

Figure 8.

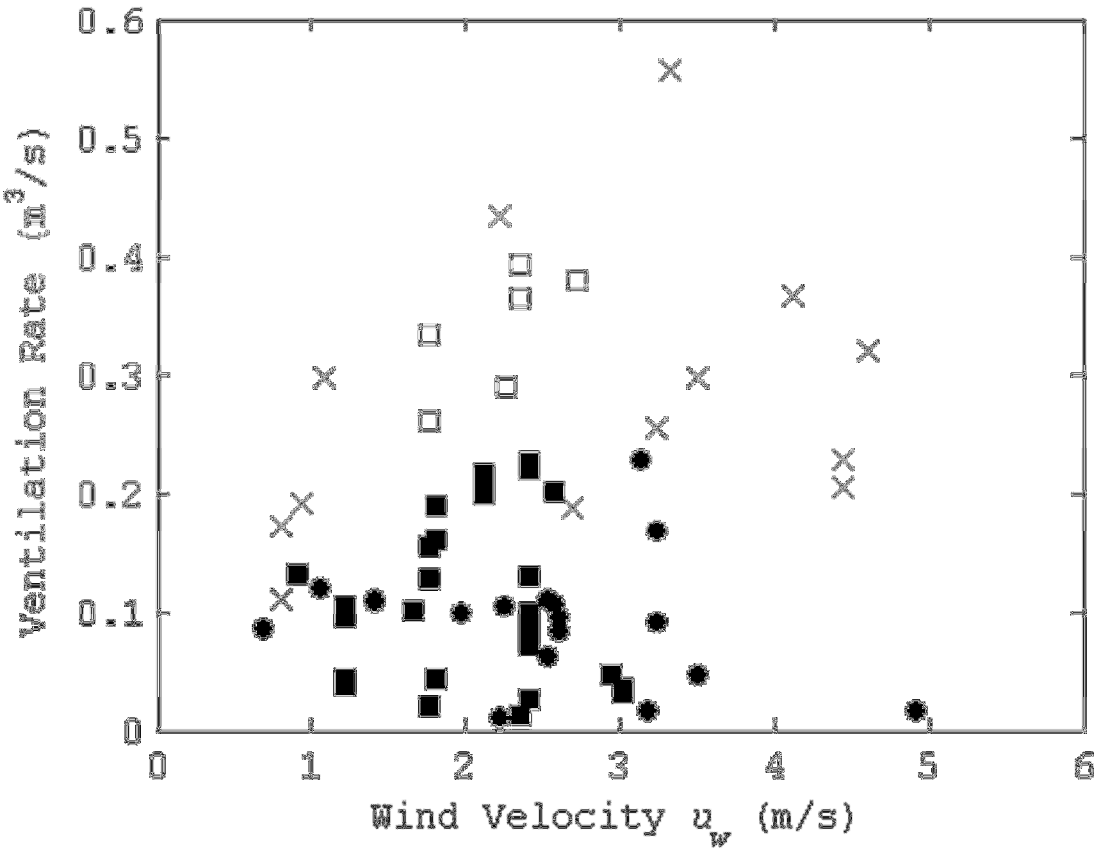

0.6
0.5
0.4
0.3
0.2
0.1
0
Ventilation Rate (m3/s)
0
1
2
3
4
5
6
Wind Velocity u_w (m/s)

Figure 9.