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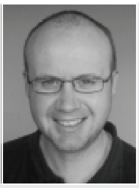

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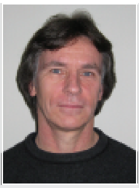

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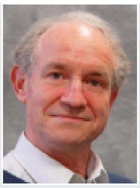

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Measurements of the performance of a wind-driven ventilation terminal

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This paper presents the results of the measured ventilation flow rates through a roof-mounted inflow/outflow natural ventilator and of the wind pressures measured on the terminal under real conditions. The experiments were conducted at full scale at the former Silsoe Research Institute wind engineering test site using a 6 m cubic test building, referred to as the Silsoe cube, and using a test house. Ventilation rates and free-stream wind speed were measured using ultrasonic anemometers. The nominally 800 mm × 800 mm ventilation terminal on the Silsoe cube achieved a peak ventilation rate of 0·06 m^3/s per m/s wind speed although the data also indicated periods when the ventilation rate dropped to approximately zero for a specific wind direction due to the vent then being in the position of flow re-attachment following separation at the windward leading edge of the roof. This has led to better knowledge in relation to the siting of such terminals. A similar terminal monitored on the test house achieved a peak ventilation rate of nearly 0·1 m^3/s per m/s wind speed. The ventilation unit proved to be an effective means of providing natural ventilation and is likely to broaden the application of natural ventilation. The results of pressure measurements on the terminal louvres and the internal pressure in the cube, coupled with the measurements of the corresponding ventilating flow rate mechanisms, provide unique data with which to establish procedures for the rational design of such terminals, which is also outlined in the paper.

1. INTRODUCTION

The UK government has committed to reduce greenhouse gas emissions by 80% on 1990 levels by 2050. In 2007, the total of all energy consumed in the UK was 6891 PJ and the use of fossil fuels accounted for emissions of 529 metric tons of carbon dioxide (MtCO$_2$) (BERR, 2008). It is estimated that almost half of UK carbon dioxide emissions can be attributed to energy consumed in buildings (Hinnells, 2008). A growing proportion of these emissions is caused by the increased use of air conditioning. In a business-as-usual scenario, Hitchin and Pout (2000) estimate that up to 40% of UK commercial floor space will be air conditioned by 2020 compared with approximately 10% in 1994.

Naturally-ventilated buildings produce significantly less carbon dioxide than do their air-conditioned counterparts; they have also been linked to improved indoor air quality and increased occupant productivity. The popularity of innovative systems to ventilate buildings naturally has grown over recent years as a result of increasing awareness and concern regarding the burning of fossil fuels used to provide energy to modify indoor environments artificially. Studies show that naturally-ventilated buildings can consume considerably less energy than do air-conditioned buildings (Littlefair *et al*., 2000), and that full air conditioning can add 50% to the running costs of a building (CIBSE, 2004), with obvious implications for increased carbon dioxide emissions. In addition, studies by van der Linden *et al*. (2006) suggest that occupants may prefer naturally-ventilated buildings, partly because of their closer link to the external environment. In an attempt to reduce the amount of energy consumed by space heating in the winter period, modern buildings are constructed with increasing levels of thermal insulation. In addition, factors such as improvements in materials technology, off-site assembly and improved construction techniques have resulted in much lower levels of building envelope air permeability, which has the desired effect of further reducing heating energy consumption. However, increased insulation and reduced air infiltration can exacerbate the level of occupant discomfort due to high humidity, aerial pollutants and high internal temperatures during the summertime, which coupled with UKCIP predictions (Hulme *et al*., 2002) that UK temperatures could rise by between 1 and 5°C by the 2080s, may lead to increased retrofitting of mechanical cooling systems with corresponding increases in energy consumption and carbon dioxide emissions.

Environmentally-aware building designers are pursuing passive means to achieve indoor thermal comfort with reduced energy consumption. Effective, controlled natural ventilation, including rapid ventilation using cooler night-time air, can help to pre-cool the building interior and so reduce peak daytime temperatures and eliminate, or at least reduce, the use of mechanical ventilation and cooling.

2. EXPERIMENTAL STUDIES

The ventilator concerned in this study was a square Passivent Airscoop terminal. The ventilator is divided internally by two diagonal plates that create four vertical ducts each of triangular cross-section (Figure 1). A rain-rejecting louvred panel on each of the four exterior faces enables air to flow in or out of the building through the triangular ducts depending on the wind pressures generated over the four louvred faces and the internal pressure. Air travels upwards or downwards within one or more of the four triangular ducts.

The flow around bluff bodies such as sharp-edged buildings is mainly characterised by large separation regions, which in most cases are highly turbulent. The separation region, or wake, often extends over a larger cross-section than the cross-section of the body, leading to a large pressure difference between front and rear surfaces (Grosche and Meier, 2001). Fundamentally, the ventilator is driven by the differences in pressure between the windward and side or leeward faces. The positioning of discrete inlet and outlet vents is critical to any natural ventilation design (Liddament, 1996), but in the case of this ventilator the inlets and outlets are contained within the same roof-mounted unit. If the unit is positioned in an 'exposed' roof location then significant pressure differences are likely to arise across the ventilator, which will provide a strong driving mechanism for ventilation. The pressure differences will be affected by the geometry of the terminal and by the angle of attack of the wind. If the unit is placed within a 'sheltered' or less favourably exposed region, lesser differential pressures will arise across the unit for the same wind speed and less strong driving mechanisms will prevail. However, the unit may instead be driven by buoyancy forces arising from a temperature difference between the inside and the outside.

A test structure constructed at the former Silsoe Research Institute comprised a cube with external dimensions of 6 m × 6 m × 6 m. A prototype 800 mm × 800 mm Passivent Airscoop ventilation terminal was fitted onto the roof of the cube (Figures 2 and 3). The Silsoe cube is situated on a flat and exposed open field site at Wrest Park, Silsoe, Bedford, UK, at a location north 52°01′, west 00°25′. The site provides a clear fetch extending approximately 600 m over an arc from south west through west to north. The general terrain category is 'open country with scattered windbreaks'. Site altitude is 60 m above mean sea level. The cube can be rotated on a turntable to achieve any desired incident angle of wind, whatever the wind direction. Figure 4 presents a view of the long fetch to the west of the cube.

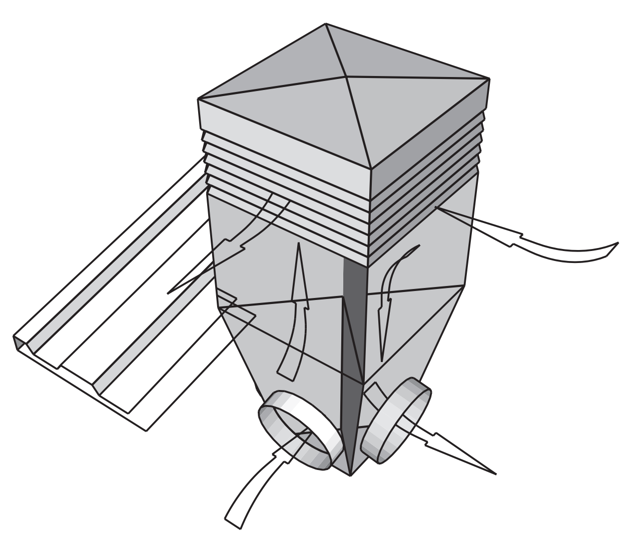

Figure 1. Cut-away view of a typical roof-mounted Airscoop ventilator

Figure 2. The 6 m Silsoe cube with Airscoop (background), and mast-mounted reference anemometer, directional pitot tube, and static pressure probe (foreground)

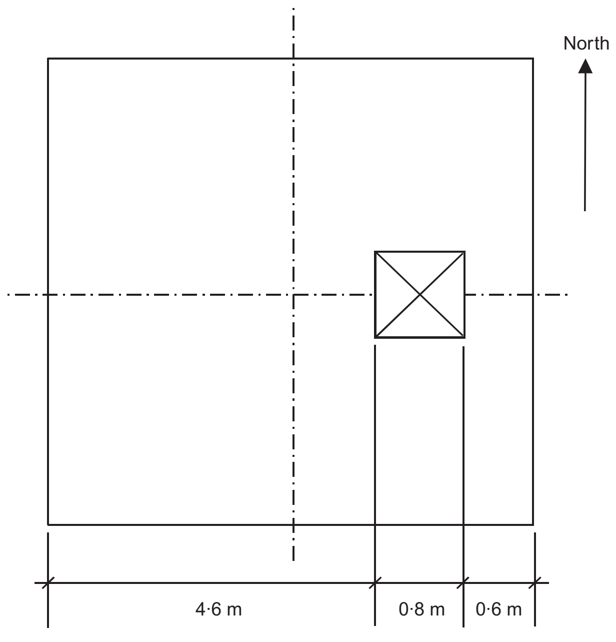

Figure 3. Roof plan of 6 m Silsoe cube showing location of the Airscoop

The velocity profile at the Silsoe site has been measured at

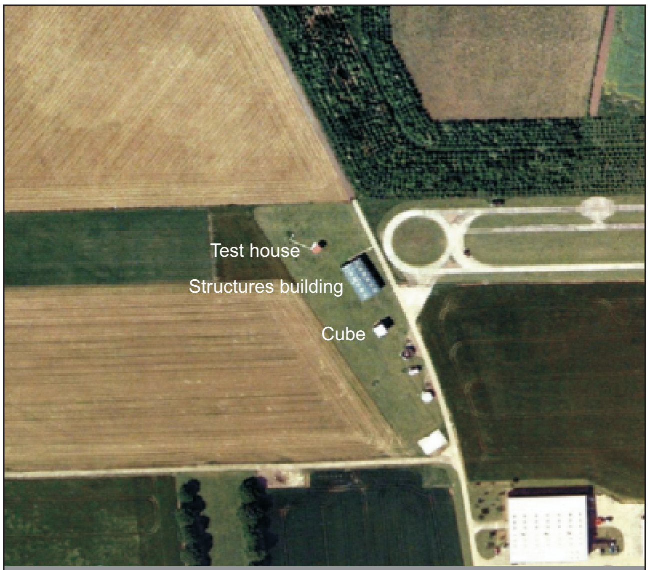

Figure 4. Aerial photograph of the Silsoe cube on the wind-engineering test site of the former Silsoe Research Institute

various times and is well matched by a logarithmic profile. The roughness length (z_0) for the westerly fetch to the site was calculated using Equation 1.

$$U(z) = \frac{1}{\kappa} u_{*} . 1\text{n}\left[\frac{z}{z_0}\right] \tag{1}$$

Where $U(z)$ is mean wind speed at height z, κ is von Karman's constant (equal to 0·4), u_{*} is surface friction velocity, z is height above ground and z_0 is the aerodynamic surface roughness. The roughness length z_0 was determined from datasets of wind velocity recorded using a three-component ultrasonic anemometer positioned upstream of the test structure at the same height as the ventilator in the field. A value of 0·04 m was determined and this is consistent with measurements made by other investigators on the same site (Hoxey and Richards, 1992).

The air velocity in each duct of the ventilator was measured using ultrasonic anemometers positioned within each of the four compartments, all referenced to a fifth ultrasonic anemometer mounted externally 25 m upstream of the cube at the same height as the ventilator. The velocity components were all recorded at a frequency of 10 Hz, for 15 min per record. Importantly, three-component ultrasonic anemometers give flow vectors, meaning that both the air speed and its direction were monitored within each duct. The anemometer samples over a volume with a representative dimension of 150 mm, which is of a size consistent with that of the duct dimension. Measurements were taken on overcast days when internal temperatures were negligibly different from external temperatures, meaning that all ventilating flows were wind driven only.

Following a 22-day period of velocity measurement, the four internal ultrasonic anemometers were removed and the Airscoop terminal was fitted with 20 pressure tapping points positioned at mid-louvre height (Figure 5) in order to determine the distribution of pressure on the faces of the ventilator at the external louvre position. It is these that drive the ventilating flows and so data on these are needed for design.

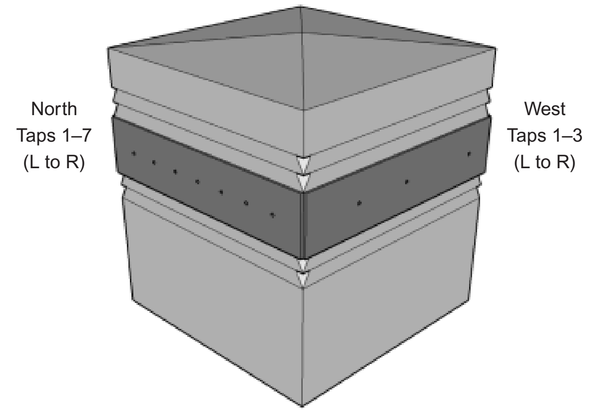

Figure 5. Ventilator pressure tapping locations: north and west faces (pattern is repeated on opposite faces)

The tapping boards were 800 mm wide × 250 mm high × 9 mm thick plywood placed at mid-louvre height; each tap was of 5 mm internal diameter and was mounted flush with the board. The north and south faces each contained seven taps spaced at 100 mm centres. East and west faces each contained three taps; one at the centre, one 200 mm from the north face and one 100 mm from the south face. Pressure signals were transmitted pneumatically by means of 6 mm internal diameter plastic tubes that were routed down the ventilator ducts to pressure transducers within the cube. Up to 16 taps could be monitored simultaneously. Two configurations of taps were used during the investigation in order to record pressures from all 20 taps on the ventilator.

The internal pressure within the cube was measured at all times. All pressures were measured relative to a reference static pressure that was sensed by a static pressure probe mounted close to the reference ultrasonic anemometer, which can be seen in the foreground of Figure 2. At the same location, a reference dynamic pressure was taken from a directional pitot tube, which was used to calibrate the pressure transducers. Pressures were logged at a frequency of 10 Hz and each run had a total duration of 20 min, which comprised: 30 s of zero measurements, 150 s of calibration of the pressure transducers, 14 min of pressure measurements (8400 measurements), 150 s of calibration of the pressure transducers and 30 s of zero measurements.

The repetition of the zero and calibration measurements at the start and at the end of each run was to ensure that any zero drift and calibration variations could be detected and corrected.

3. RESULTS

Figure 6 presents the results of records taken over a 22-day period in April and May 2004. The data in Figure 6 are presented as air changes per hour,[1] based on a room volume of 216 m^3, and on a range of mean wind speeds from 2 to 7 m/s plotted against wind direction. In addition to a general

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[1] Air changes per hour equals hourly volume flow rate/room volume.

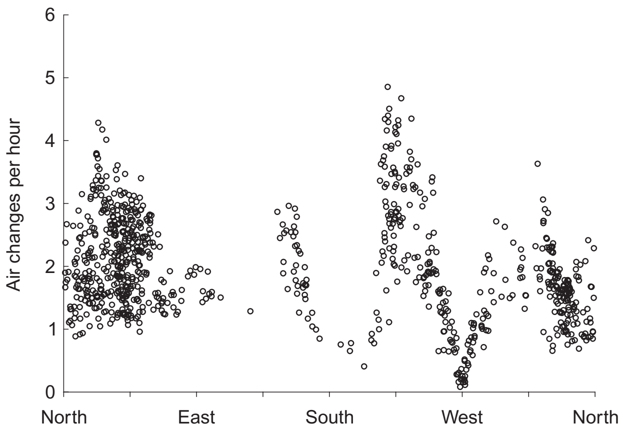

Figure 6. Variation in ventilation rate with wind direction for the 6 m Silsoe cube

indication of ventilator performance, the chart also indicates some effect of more turbulent incident flow for north to north-west winds, which approached over the Silsoe structures building situated approximately 30 m north to north-west of the Silsoe cube (Figure 4), although much of the scatter in this plot is attributable to the different wind speeds (2–7 m/s) embraced by the records.

Figures 7–10 present the mean net pressure coefficients, C_p ($C_p = C_{pe} - C_{pi}$ where C_{pe} and C_{pi} are external and internal pressure coefficients, respectively), as a function of wind direction. The pressure coefficient is the ratio of the static pressure (relative to that at the reference probe) measured at a tap on the surface of the ventilator to the dynamic pressure of the free-stream wind at the same height. For clarity, Figures 7 and 9 present the results of three of the seven taps on the north and south faces, respectively.

The simultaneous recording of pressure was limited to 15 surface taps plus one internal. During the investigation period, the measurement configuration was changed to incorporate the five remaining taps. To account for the variations in internal pressure between the two measurement configurations, the appropriate corresponding internal pressure was subtracted from each record. The internal pressure coefficient (C_{pi}) is presented in Figure 11.

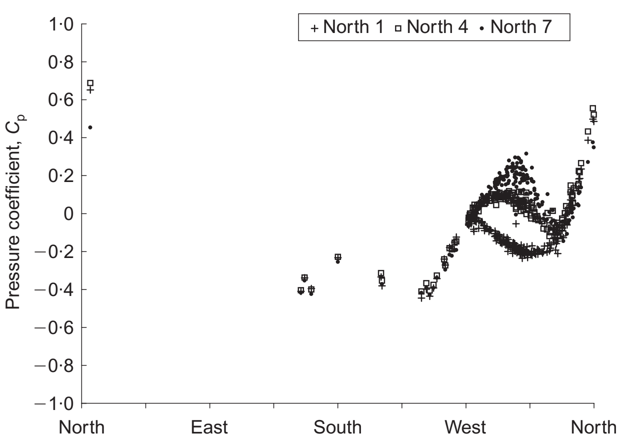

Figure 7. Variation in C_p with wind direction for three north-facing pressure taps

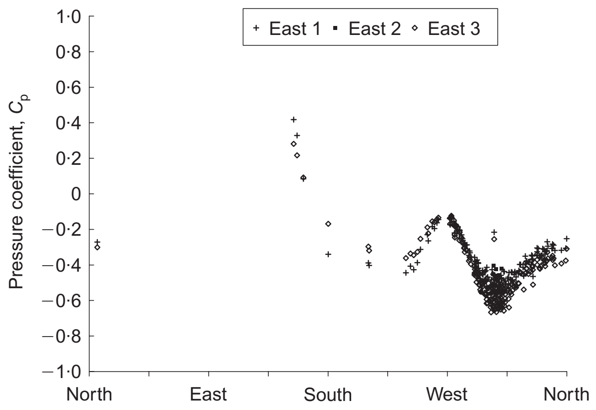

Figure 8. Variation in C_p with wind direction for three east-facing pressure taps

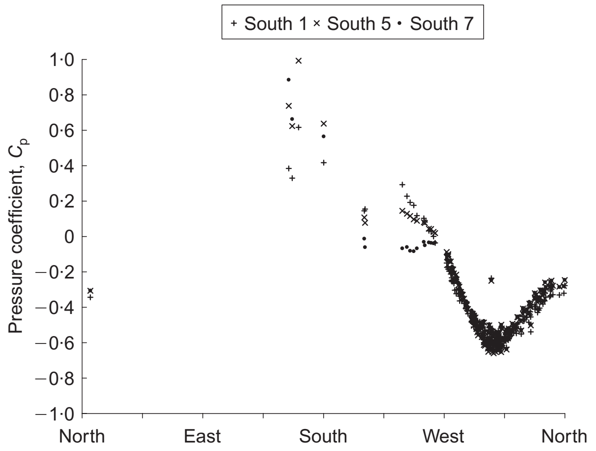

Figure 9. Variation in C_p with wind direction for three south-facing pressure taps

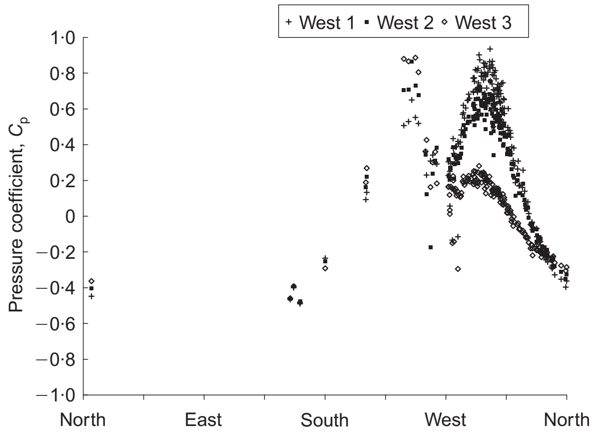

Figure 10. Variation in C_p with wind direction for three west-facing pressure taps

The average C_p value for each face of the ventilator is presented in Figure 12, beneath which, for comparison, the

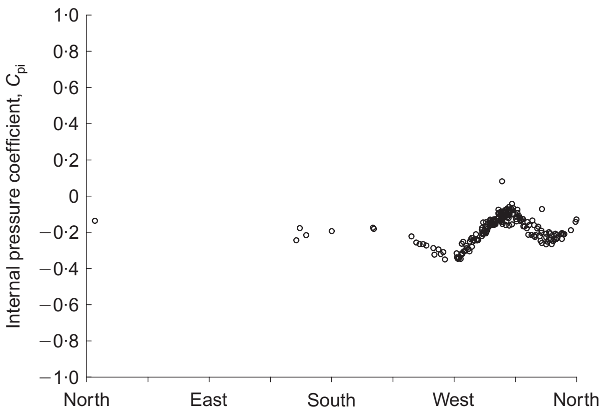

Figure 11. Variation in C_{pi} with wind direction for the internal pressure taps

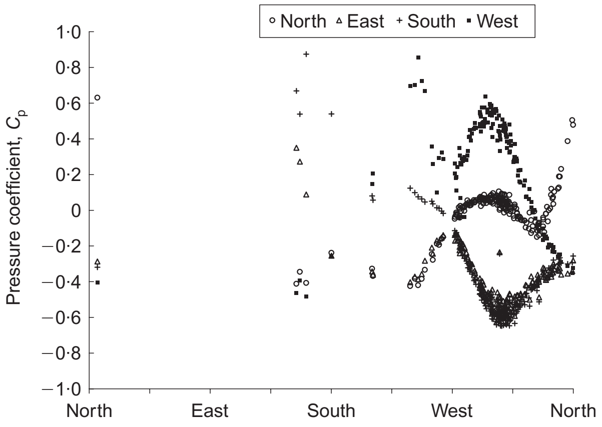

Figure 12. Variation in average face pressure C_p with wind direction

velocity ratio (duct air speed/reference wind speed) measured during the earlier stage of the study is presented (Figure 13). Each record presented in Figure 13 represents a 15-min mean from an ultrasonic anemometer operating at a frequency of 10 Hz.

Figure 14 presents the variation in overall ventilator performance with wind direction. Separate analysis of the ventilation-rate data confirmed that ventilation rates varied linearly with wind speed, as would be expected. Figure 14 indicates that the peak flow rate occurs for 45° wind directions in which two ducts act as inlets and two as outlets. The measured peak ventilation rate is sufficient to satisfy the Education (School Premises) Regulations (1999) requirement of 8 litres of fresh air per second per person, based on an occupancy of 30 people, at a relatively modest 4 m/s wind speed. The typical performance of the unit during the period of this study equates to a school classroom daily average requirement (5 litres per second per person) at a wind speed of 4·1 m/s.

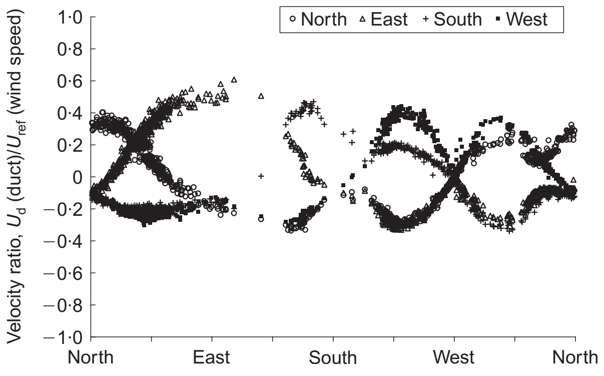

Figure 13. Variation in velocity ratio with wind direction

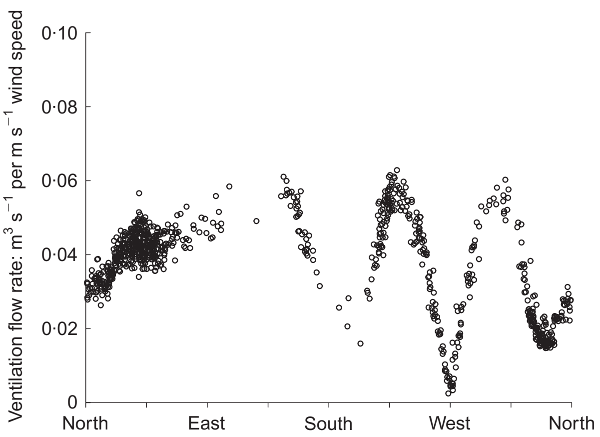

Figure 14. Variation in overall ventilator performance with wind direction

4. DISCUSSION

The majority of the pressure coefficient data were recorded for winds prevailing from ±45° of the north-west wind direction. Within this range, the pressure distributions for the north and west faces might be expected to display symmetry, and be positive, and for the south and east faces to display symmetry, and be negative. The data presented in Figure 7, for the north face, confirm that for wind approaching from the normal-to-face direction the greatest positive C_p is observed (C_p approximately 0·5) and there appears to be little variation between the pressure taps across the north face under normal-to-face wind conditions. On the north face it is reasonable to expect that as flow moves from the north through west (parallel-to-face) to the south, the C_p values will change from positive, through zero, to negative producing a suction pressure, resulting in air being extracted through the north-facing quadrant of the ventilator, and this was observed in the investigation. However, it would similarly be reasonable to expect that the west-facing quadrant would experience the greatest positive pressures at its normal-to-face wind direction and that there would be symmetry about this point, whereupon C_p values would become less positive and then negative as winds approached from parallel-to-face directions. Neither of these conditions was observed in the investigation (Figure 10). As winds approach from the west, when the C_p values were expected to be at their highest positive value, the net C_p values recorded on the west face were approximately zero. The data presented in Figure 10 show two separate peak positive pressure coefficient values corresponding to wind approaching from approximately 23° to either side of the normal-to-face direction. Interestingly, C_p falls rapidly from the positive peak at a wind direction of west-north-west ($C_p = 0·9$) to approximately zero at the normal-to-face direction, rising equally rapidly to the second peak positive C_p (0·9) for winds approaching west-south-west. This finding may be attributable to the effects of delta-wing vortices forming off the leading-edge corners at the top of the cube.

Pressure taps on the south and east faces show the highest negative (suction) pressures on these faces to occur for a north-west wind direction ($C_p = -0·6$). On the south face (Figure 9), over the range of wind directions west, through southwest, to south, the ventilator experiences a change from suction pressure to a positive net C_p value, resulting in this duct becoming an inlet. At normal-to-face flow, the three taps on the south face all present positive net C_p values with a representative average of $C_p = 0·54$. Negative pressure on the east face (Figure 8) unexpectedly decreases from a peak of −0·6 for a prevailing north-west wind to approximately zero when wind is from the west, suction pressure then increases steadily to a value of $C_p = -0·45$ for winds approaching from the south-west.

The data presented in Figures 7–10 capture the variation in pressure across each face of the ventilator for a range of wind directions. Winds approaching the ventilator at oblique angles result in variations in pressure between the taps across the respective faces; however, as winds approach normal-to-face the data are generally well ordered and there is little variation between taps. North and south faces behave generally as expected in that windward faces display positive C_p values reaching a peak at approximately normal-to-face wind directions; however, this was not observed on the west or east faces. At the west wind direction net pressure coefficients on all faces were approximately zero, which is an interesting and slightly surprising finding. However, this may be explained by the ventilator being in a re-attachment zone for this particular wind direction. Computational studies conducted by Straw (2000) used computational fluid dynamics to predict the flow regime over the roof of the Silsoe cube without any ventilation device fitted. A RNG model predicted flow separation over the leading edge of the roof with a re-circulating flow forming within the separated zone. For flow normal to a face, the separated flow in the mid-width plane re-attached with the roof at a position 68% of the way along the streamwise length of the roof. Experimental measurement by Straw determined that the peak suction pressure on the roof of the cube occurs approximately 1·5 m from the leading edge. Subsequent experimental investigations of pressures and flows over the Silsoe cube have been reported by Hoxey *et al.* (2002). For a wind perpendicular to a side, they found the re-attachment point on the roof to be at a mean distance of 3·42 m from the leading edge (or 57% of the cube dimension), although the re-attachment point varied with time between extremes of the leading and trailing roof edge. For flow approaching from the west it is likely that the ventilator is submerged in a region of re-attaching flow. This evidently has the effect of producing small pressures of very similar magnitude on all four faces, to which the internal pressure tends, resulting in negligible ventilating flows through the terminal ducts.

The record of velocity measurements presented in Figure 13 encompasses almost a full 360° range of approach flows. For winds approaching from the west the flow in each compartment tends to a velocity ratio of zero, resulting in a negligible ventilating effect. Winds approaching from the south, east and north produce a good ventilating effect that has near symmetry about the east wind direction, as one might expect as a result of the ventilator being positioned near the east-facing edge and, therefore, experiencing on-coming airflow that may even be favourably directed in relation to the angle of the louvres on the windward face. The pressure measurements (Figures 7–10) corroborate the velocity records and provide insight into the distribution of pressure across the faces of the ventilator.

4.1 Further measurements and assessment of design capability

Further measurements were made on a similar prototype Passivent Airscoop terminal of 800 mm square size mounted on the roof of the test house at the former Silsoe Research Institute (Figure 15). The ridge of the test house was 4·7 m above ground and the 20° roof slope on which the terminal was mounted measured 7·5 m from eaves to ridge and was 4·6 m wide; the eaves height was 2·2 m. For winds approaching within approximately ±90° of perpendicular to the lower eaves, the terminal is well exposed to the wind. As with the Silsoe cube tests, buoyancy mechanisms were avoided by conducting measurements under overcast conditions; relatively high and continuous ventilation rates also helped to ensure negligible temperature differences between the inside and outside.

The ventilation rates, measured as described earlier, are shown in Figure 16 for this 180° range of wind directions (90° being perpendicular to the lower eaves). These data represent one of the more orderly sets because of the relatively small disturbances to the incident wind flow imparted by the building for these wind directions. They clearly show again the 'peak' ventilation rates (of nearly 0·1 m^3/s per m/s) for the 45° diagonal wind directions and the 'trough' rates (of approximately 0·06 m^3/s per m/s) for perpendicular wind directions. When on the lee of the house roof, the performance of the terminal reduced to levels similar to those found in

Figure 15. Airscoop terminal on the Silsoe test house and reference anemometer

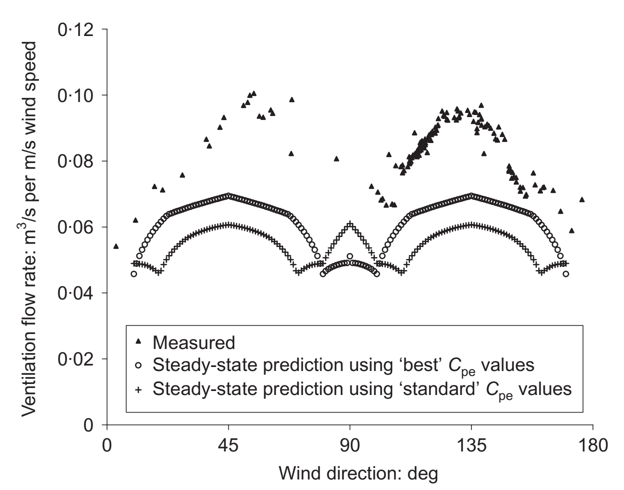

Figure 16. Measured ventilation rates for 180° range of wind directions for which the Airscoop is on windward roof slope of the test house, and steady-state predictions using 'standard' (i.e. CIBSE guide A) and 'best' (i.e. most favourable from measurements) external pressure coefficients C_{pe}

Silsoe cube measurements (Figure 14), although fewer data were acquired for these wind directions (180–360°).

Also shown are 'steady-state' predictions using mean pressure coefficients – both 'standard' ventilation-design C_{pe} values similar to the rural terrain values presented in CIBSE guide A (CIBSE, 2006) and 'best' (i.e. most favourable) C_{pe} values as determined from measurements. The discharge coefficient used in determining the calculated values for the terminal was measured using a special 'fan test rig' and so was as reliable and accurate a measure as was possible (Robertson, 2008), the $C_{d*}A$ value so measured for one duct of the prototype unit used in the tests was found to be 0·046 m^2 where C_d is the discharge coefficient and A the corresponding area in m^2. The measured ventilation rates exceed even the 'best' predictions by some 30%. This is an unsurprising finding as several other studies have identified that steady-state (mean pressure coefficient) models generally under-predict ventilation rates, often substantially, as they ignore the significant contributions of pressure fluctuations (Etheridge, 2000; Etheridge, 2002; Etheridge and Stanway, 1988; Straw *et al.*, 2000), Helmholtz oscillations (Ginger *et al.*, 2008; Holmes, 1980; Liu and Saathoff, 1981; Straw *et al.*, 2000), and eddy penetration/ shear-layer flow (Haghighat *et al.*, 1991; Haghighat *et al.*, 2000; Straw *et al.*, 2000). It is likely that this underestimation is related to the turbulence intensity in the wind and so would be still greater in the event of ventilators in towns and cities where winds have significantly higher turbulence intensities than the 15–20% that applied to the rural terrain winds in these measurements. There is evidently a need to develop design models to embrace 'turbulent-driven' natural ventilation modes in order that they may better predict true rates, and so be more reliable; this need applies, possibly even still more forcefully, in relation to single-opening ventilation cases.

5. CONCLUSIONS

Detailed measurements have been made to determine the performance of a roof-mounted natural ventilation terminal (an Airscoop) when driven by wind. Such four-duct terminals also function as buoyancy-driven devices but buoyancy mechanisms were deliberately avoided in these experiments. The ventilation-rate performance of the terminal varies linearly with wind speed, as would be expected, and separately with wind direction. For a given wind speed and exposure, maximum ventilation rates occur for diagonal winds onto a corner of the terminal when the windward two ducts act as inlets and the leeward two as outlets. For winds perpendicular to a face, the windward duct acts as an inlet and the remaining three ducts act as outlets, and ventilation rates are consequently reduced.

For a space ventilated by a terminal only, the ventilation flows are driven by the external pressures on the four louvred faces. These have also been measured in a dedicated experimental programme, which produced several revealing findings. The pressures generated on the terminal faces are highly dependent on the flow structures in which the terminal is submerged. These flow structures depend on the location of the terminal on the building roof, and on the size and geometry of the building. Importantly, the studies have revealed that the terminal performs less well when located in a region of flow re-attachment as only small differential driving pressures are then generated. This provides important insights into the appropriate positioning of such terminals for best performance. When well exposed, the terminals perform well. Significantly, it has been shown that ventilation rates are such that existing design predictions using steady-state mean pressure coefficients underestimate performance by some 30% when even the most favourable pressure coefficients that could be justified are used. This finding is consistent with those of many other similar studies of simpler natural ventilation arrangements. This provides further evidence of a clear need for the development of an improved design model that takes account of non-steady-state ventilation mechanisms so that natural ventilation systems can be designed with better accuracy and reliability.

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