Determining the impact of urban canopy flow on building ventilation rates: an experimental study

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1. Introduction

The urban microclimate has the potential to influence the effectiveness of ventilation systems in buildings in urban environments. In turn, this can influence the health and well-being of the buildings' occupants as up to 90% of time can be spent indoors (Leech *et al*, 2002). Engineering guidance for calculating ventilation is often based on assuming pressure coefficients for an isolated building and not for one in an urban environment (Awbi, 2003). Whilst experiments on specific buildings in urban areas are often undertaken, such as work by Li *et al* (2014) and Van Hooff and Blocken (2010), they are driven by a specific set of research objectives, with no standardized experimental procedure. Little evidence is available as to how ventilation is altered when a building is located in an urban area, with flow in urban areas being highly turbulent and difficult to predict (Barlow and Coceal, 2009). It is also unknown as to how much ventilation typical urban turbulence drives aside from the mean flow, as well as the potential benefits of such unsteady air flows for human well-being. With the U.K's drive towards minimizing energy usage, naturally ventilated buildings are seen as a sustainable solution, but without knowledge of the effect of the urban micro-climate on air exchange, designs which work in theory may fail in a complex urban environment, in addition leading to Sick Building Syndrome (SBS) and poor occupant health.

By combining the methodologies of both urban meteorology and engineering, a full scale experiment has been designed around investigating two main themes:

- How does flow influenced by other buildings in urban areas change a building's ventilation characteristics compared to an isolated building?
- What's driving the variability of flow at various time scales and how does this affect ventilation?

These two themes feed into a larger research project: The ReFRESH project (ReFRESH: Remodelling Building Design Sustainability from a Human Centered Approach, www.refresh-project.org.uk). This broader project aims to explore the impact of urban microclimate on building ventilation for optimal performance of occupants. The emphasis is on the relationships between outdoor and indoor air, and humans and their environments, and to how best feedback data which reflect the performance of both the building and the inhabitants. The project draws together a broad range of multidisciplinary expertise from the University of Leeds, University of Reading, University of Southampton, University of Surrey, and the University of Birmingham.

This experiment will provide a full-scale data-set to test the effectiveness of CFD modelling of time-varying ventilation in a building within an array of other buildings undertaken by the University of Leeds. The full-scale experiment will also be interpreted using wind tunnel experiments at the University of Surrey.

2. Methodology

2.1 Urban-type building array and external measurements

The experiment took place at Silsoe UK (Latitude 52.01088°, Longitude -0.410979°), a rural experimental wind engineering facility with a cubic test structure of side 6 m, previously used by Richards and Hoxey (2008), Straw *et al.* (2000) and Yang (2004). The site has good exposure to winds from southwest clockwise to east and a surface roughness length of 0.01m with a prevailing wind direction of south-westerly (Richards and Hoxey, 2012).

Approximating buildings by using cubes is an accepted simplification within both urban climate and wind engineering research (Cheng and Castro, 2002; Richards and Hoxey, 2006). A temporary staggered array of eight approximately 6 x 6 x 6 m^3 straw cubes was built around the instrumented cube as shown in Figure 1, creating a layout that represented a simplified residential area, free from irregular building arrangements, trees and the effect of human activities. The layout was inspired by modelling work by Coceal *et al* (2006) and field work by Davidson et al (1995) with a frontal area density of $\lambda_f = 0.25$. Ideally, a row of cubes should have been built behind the instrumented cube, but due to access and health and safety concerns this was not possible.

Figure 2 details the positions of the different measurement masts and the locations within an array schematic. A mast with reference pressure measurements and a sonic anemometer at 6m and 10m was positioned outside the array (Mast D), with two other sonic anemometers being positioned at a height of 3.5 m respectively in front and behind the instrumented cube (Masts B and A). North-west of the instrumented cube was a mast monitoring meteorological conditions using a Vaisala WXT-520 weather station, Kipp and Zonen CNR4 net radiometer, a Gill R3 Sonic Anemometer and a Campbell LICOR-7500 to measure background CO_2 levels (Mast C). All external sonic anemometers and all other equipment was logging continuously at 10 Hz.

Fig. 1 Drone photograph of the straw cube array, array masts, the instrumented cube (blue) and the surrounding areas. The camera is facing to the North-West.

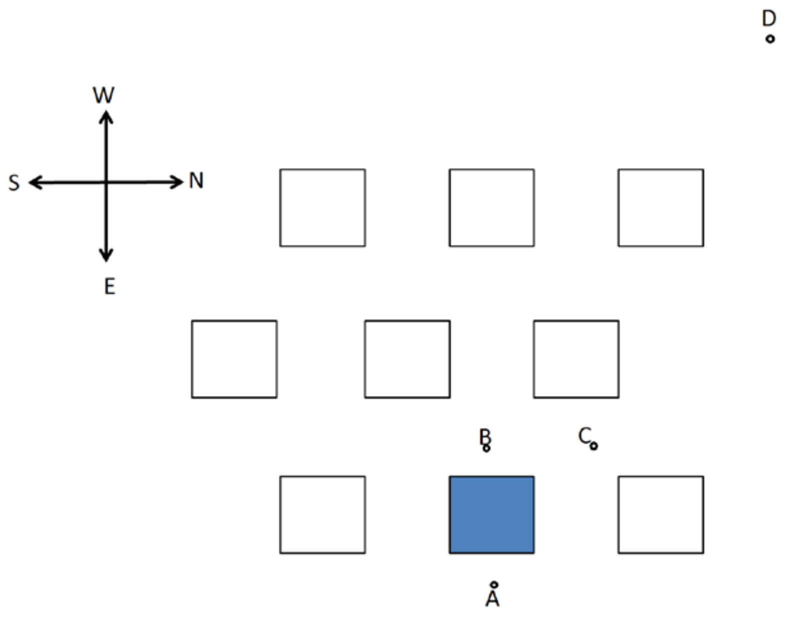

Fig. 2 A schematic of the cube array, with the instrumented cube highlighted in colour. The letters denote the positions of the masts explained in the main text.

2.2 Test structure and internal measurements

The test structure is a metal cube with the external dimensions 6 x 6 x 6 m^3 with an exterior of flat steel sheets. The front of the cube was positioned facing prevailing wind direction 240° with the array arranged in order to provide the largest number of obstacles in this direction. The front face is referred to as the West Face and the rear the East face.

Removable panels were located on the West and East sides allowing for the cube to be tested as both a sealed and ventilated structure. Work by Straw *et al.* (2000) used 1 m^2 windows which led to an extremely high ventilation rate that was difficult to measure, thus the removable panels used in this experiment were 0.4 m wide by 1 m high with the centre point being 3.5 m above the ground (see Figure 3).

Fig. 3 The isolated cube and the sonic anemometer in front of the 0.4 m^2 vent.

The experimental set-up used has been influenced by the findings of Straw *et al.* (2000) and Yang (2004). 9 surface pressure taps were positioned on the East and West faces (small grey rectangles in Fig. 3), with 4 on the North, South and roof panels. 2 internal taps were used after work by Straw *et al.* (2000) suggested there may be internal variations in pressure.

24 type-K thermocouples were positioned within the cube in four vertical arrays of four between 0 to 4 m and in one horizontal array strung east to west at a height of 3.5m in order to capture temperature gradients and changes due to the incoming flow. A sonic anemometer was set back from each opening. Indoor CO_2 concentration was measured by three K-30 FR non-dispersive infrared CO_2 sensors with a range of 0-10000ppm and sampled at a rate of 2Hz. The positioning of these instruments is detailed in Figure 4. All internal instruments unless otherwise stated were set to log at a frequency of 10 Hz. When possible flow visualisation was carried out using a smoke machine, both internally and externally.

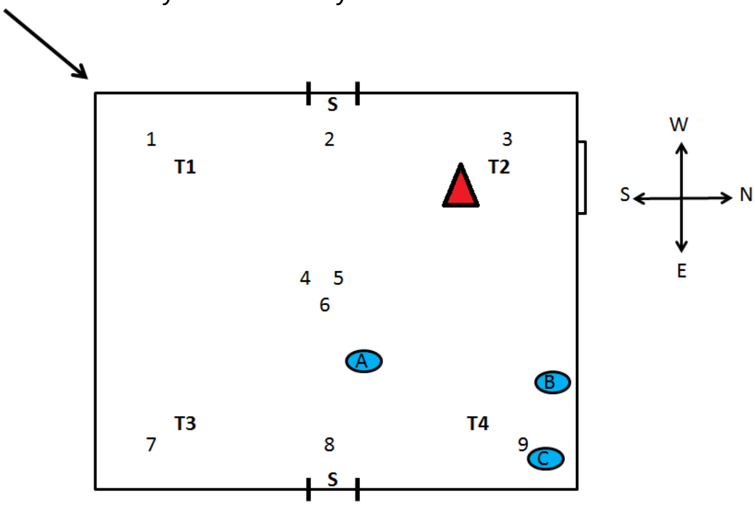

Fig. 4 A plan view of the internal layout of the instrumented cube for experiments undertaken after the 20th November 2014. The arrow marks the prevailing wind direction (South-Westerly), S is the location of the internal sonic anemometers, T1-T4 vertical thermocouple arrays, with the horizontal array being between the two sonic anemometers. Numbers 1-9 are the tracer gas release points, with 4 and 5 being released at floor level and the others at a height of 3m. The tracer gas canister was outside the cube. The circles denote the position of the K-30 CO_2 sensors, A and B are at 3m and C is at 0.3m. The triangle denotes the position of the fan used to aid mixing.

2.3 Experimental configurations

Three ventilation configurations (infiltration for a sealed cube, single-sided and cross-ventilated) were tested for a cube within the array between September 2014 to March 2015 and for an isolated cube between May-September 2015. Single-sided ventilation refers to only the front face panel (i.e. west-facing) being open, with cross-ventilation meaning both the front and back being open. The sealed cube tests were used to measure the infiltration (air-tightness) of the cube and thus no panels were removed. For all six cases the instrumentation set-up remained the same and logged continuously.

3. Two methods of calculating the ventilation

A ventilation rate from the pressure taps is calculated using equation 1

$$Q = C_d A \sqrt{\frac{2\Delta p}{\rho_0}} \qquad (1)$$

where *Q* is the volumetric flow rate, *A* is the area of the opening, ρ_o is the air density at a reference temperature and pressure. *Cd* is the discharge coefficient which is the ratio of actual discharge of the fluid compared to the theoretical discharge. *Cd* is 0.61 for sharp edged orifices (Awbi, 2003). *Δp* is the pressure difference across the opening. Equation 1 does not account for the infiltration of the cube. With the use of cross ventilation it is assumed within the engineering literature that the ventilation is entirely wind driven, especially if the two openings are at equal heights.

The pressure difference, *Δp*, was calculated as an average of the four pressure taps located around the back opening, minus the corresponding internal pressure, as suggested by Richards and Hoxey (2012). The volumetric flow rate was calculated in ten minute intervals with the mean values of *Δp* being used.

Flow rate, *Q*, is converted to units of air changes per hour (ACH), λ, using equation 2

$$\lambda = \frac{3600Q}{V} \qquad (2)$$

where *V* is the volume of the cube (216 m^3). One ACH represents a complete replacement of a room's air with external air within one hour.

To measure ventilation rate directly, the tracer gas decay technique was used (Sherman 1990). The room was temporarily sealed to allow for a high concentration of CO_2 to build during the 10 minute fill time. The cube was then left undisturbed for a period of time, dependent on the wind-speed and ventilation set up. For example, a cross ventilated case in low wind-speeds required only 15 minutes to return to background levels whilst infiltration experiments were left overnight. The equation used to calculate the complete air change rate (λ_T) from the tracer gas decay rate is

$$C_i(t) = (C_0 - C_a)\exp(-\lambda_T t_i) + C_a \qquad (3)$$

where *Ci* is the indoor concentration, *t* is time in seconds, C_0 is the initial tracer gas concentration and C_a is the ambient or outdoor concentration (all in ppm). For ease of presentation Equation 3 is often presented in the form y = mx + c:

$$ln(C_i(t) - C_a) = ln(C_0 - C_a) - \lambda_T t \qquad (4)$$

Equation 4 is applied to each instrument's readings, before the resultant rate is averaged across all sensors, assuming that the room is well mixed (Sherman, 1990).

4. Preliminary findings

Experiments at the site are still ongoing with an expected end date of August 2015. As yet, detailed analysis and quantification of errors has not been completed. However, early results from the pressure derived ventilation rate agree with that found by Richards and Hoxey (2012), with the mean and instantaneous values being within ±2 ACH for a cross ventilated building. Larger but not yet fully quantified differences were found for the single sided set up, possibly due to the greater effect of temperature differences for single sided ventilation, as an opening acts as both an inlet and an outlet. For example, the daily internal temperature trend for the cross ventilated cube resembled a diurnal cycle, suggesting it was in equilibrium with its environment, whereas no such trend was observed for a single sided opening.

Ventilation experiments undertaken during an Intensive Observation Period (IOP) are shown in Figure 6 for the 10th-12th December 2014 over wind-directions of south to west-north-west. The values for ventilation rate in Air Changes per Hour (ACH) plotted in Figure 5 are an average of the three internal sensors, although significant differences were noted between the sensors. No errors have been processed as yet but will form part of the research into the comparison of the tracer gas technique with other calculation methods.

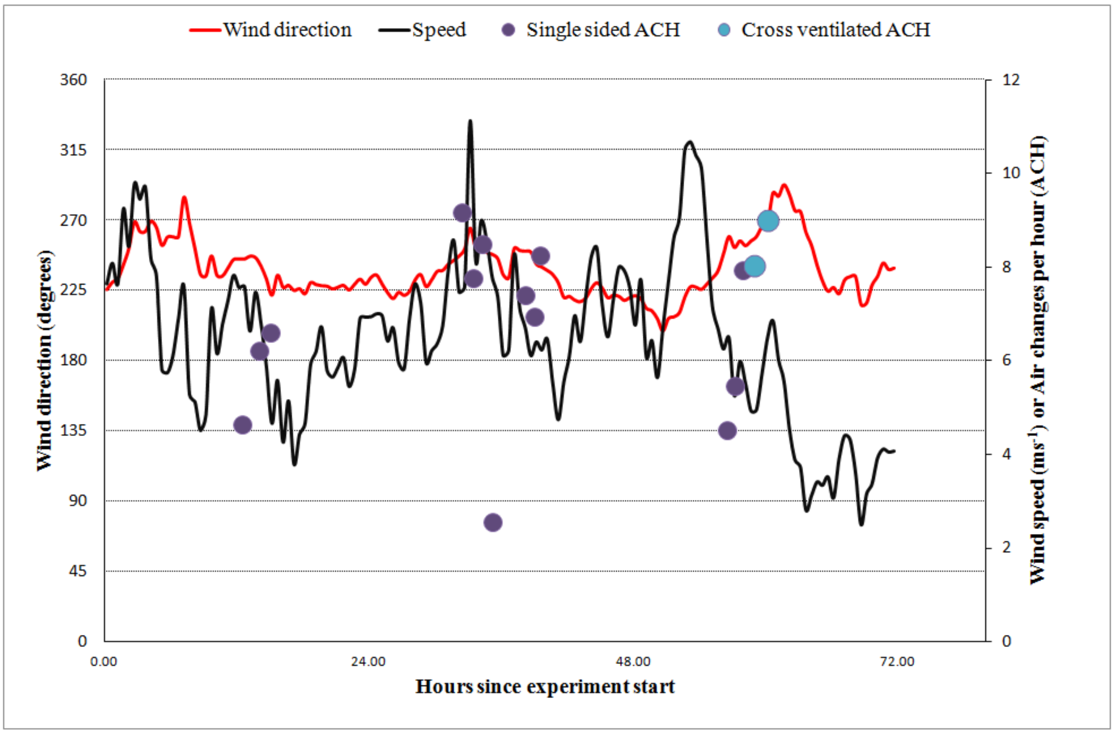

Fig. 5 Time series of wind speed and direction during 10-12 December 2014 compared to ventilation rate for a single sided set-up. Half hourly averaged wind direction (red) and speed (black) measured at a height of 10 m is taken from the reference mast upwind of the array (Mast D in Figure 2). Purple points represent the ventilation rate in Air Changes per Hour (ACH) measured using the tracer gas decay method, with blue points being for the cross ventilated case.

Preliminary wind directions and speed data are taken from the 10 m mast upstream of the cube array (Mast D). Ventilation rates for 10 and 11th Dec are for the single-sided case, with results from the 12th Dec being for cross ventilation. It can be seen that the ventilation rates on 11th Dec are generally higher than for the 10th Dec, as is the windspeed, whereas wind direction is reasonably constant. On the 12th Dec, it is notable that the cross ventilation rates are similar to the single-sided ventilation rates observed on the 11th Dec when they might be expected to be larger. The wind direction shifted from SW to NW, and the wind-speed decreased, both of which changes might alter local flow and pressure patterns to reduce cross-ventilation rate. Further research will be undertaken into the effect of wind conditions immediately adjacent to the cube on the ventilation rate; and how wind-speeds within the openings of the instrumented cube and the pressure coefficients are affected by the external wind speeds. It is likely that the wind directions observed around the cube vary by large amounts due to channelling and blocking effects due to the urban array, see Figure 6. The next aim is to relate variability in ACH values quantitatively to the external wind direction, flow pattern around the cube, and pressure coefficients.

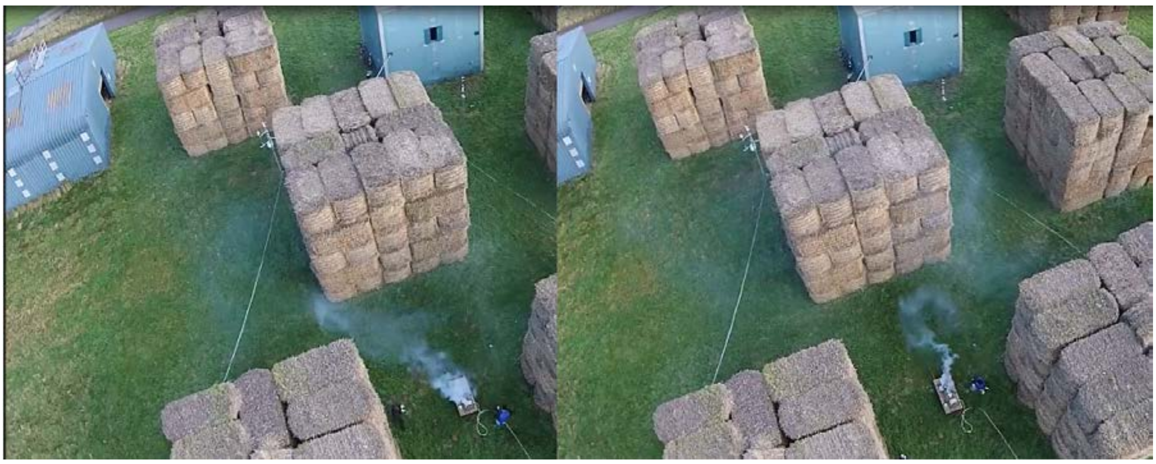

Fig. 6 Screenshots taken from a smoke flow visualisation video, taken on the 11th December at 1pm. The left panel is taken at 33 seconds in, with the right panel being approximately 4 seconds after, highlighting the variability in flow direction due to turbulence around the array.

5. Conclusions

Even from the preliminary results, it can be seen that there is significant variability of ventilation rate over similar wind speeds and directions, suggesting that multiple urban flow processes influence the ventilation rate measured by tracer gas decay method in a building.

Wind tunnel work at the University of Surrey will be conducted with the aim of standardizing the findings of the full scale work. Full control over the wind direction and speed will allow for a complete overview of the effect of the array on the wind pressures and thus the natural ventilation. Extending the array to fully encompass the cube and to create more rows will allow for an understanding of which of the surrounding buildings has the greatest effect. A comparison will be undertaken between full-scale, tunnel and Computational Fluid Dynamics (CFD) as part of the ReFRESH project. Comparisons between the full-scale results and previous work on the isolated cube by Straw et al (2000) and Yang (2004) will also be undertaken, alongside a comparison between the array and isolated cube over a range of similar conditions in order to gain an understanding of which quantities have the largest impact on the variability in ventilation rate of the cube.

Acknowledgements

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