The effect of urban micro-climate on indoor-outdoor air exchange

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SUMMARY

An idealised, staggered array of 9 6m^3 cubes was built to gain an understanding of the influence of other buildings on the natural ventilation rate of a building. The instrumented cube contained 24 temperature measurements, 32 surface pressure taps, CO$_2$ sensors and 2 sonic anemometers, with 5 more placed outside to measure wind velocities. Ventilation rate was measured when the cube was sealed, single-sided and cross-ventilated, when isolated and when in the array. Normalised ventilation rate for single-sided cases responded to a range of different flow features, such as channelling and shielding, some of which may cause ventilation rates experienced for the cube in the array from certain directions to be higher than for an isolated cube. The array and wind-angle influenced the internal conditions, causing the internal jet to shift in position with a 10° wind direction change.

PRACTICAL IMPLICATIONS

This unique full-scale experiment and data-set will lead to a greater understanding of how urban-type flows around buildings potentially influence the ventilation rate, and it will aid in the design of ventilation systems. The supporting wind tunnel experiments test how ventilation might change if an area becomes more built-up, which helps to future-proof the ventilation system.

KEYWORDS

Urban environment, natural ventilation, full-scale experiment, pressure coefficients, idealized buildings

1 INTRODUCTION

The effectiveness of a building's ventilation system is influenced by the urban microclimate in which it is located. Wind flow and temperature patterns around urban buildings are complex and difficult to predict, especially when additional development changes local building morphology (Barlow and Coceal, 2009). However, pressure coefficients and thus the natural ventilation performance of a building are often calculated as if the building were isolated (Awbi, 2003). If the ventilation systems in a building are designed without taking urban microclimate into account, the system may underperform and may have a negative effect on the building's occupants, affecting their health and performance.

This research problem is being tackled as part of the Refresh project (Refresh: Remodelling Building Design Sustainability from a Human Centred Approach, www.refresh-project.org.uk), the aim of which is to explore the impact of urban microclimate on building ventilation for optimal performance of occupants. The project includes full-scale and wind tunnel work, CFD modelling and human performance tests, and is a collaboration between the

UK Universities of Reading, Leeds, Southampton, Surrey and Birmingham. This paper focuses on describing a full-scale experiment into natural ventilation, with Paper ID 355 describing CFD simulations of indoor-outdoor air flow and Paper ID 953 investigating the effect of unsteady flows on natural ventilation rates for the same full-scale experiment as described here. Paper ID 1059 discusses the effect of social factors on office air quality within the same project.

The aim of the full-scale experiment was to investigate how natural ventilation of a building is modified by being surrounded by a staggered array of similar buildings over a range of atmospheric conditions. The buildings and their layout was designed to be as idealised as possible, combining the methodologies of meteorology and engineering. Pressure coefficients and tracer gas methods were used to determine the ventilation rate. This short paper focuses on the effect of wind direction on ventilation rate calculated using pressure measurements for an isolated cube and a cube in an array.

2 MATERIALS AND METHODS

Idealizing buildings as cubes is undertaken within both urban meteorology and wind engineering communities, and represents a simplified urban area which is free from human influence, irregular structures and street furniture. The urban canopy work by Cheng and Castro (2002) used cubes to approximate an urban environment in the wind tunnel. A staggered array of packing density 25% was also used by Coceal *et al* (2006) in their CFD study of urban turbulent flow. However, both approaches lack the largest turbulence scales experienced by full-scale buildings in a real atmosphere that are driven by shear or buoyancy, and can be of order (of size) 1km (Barlow and Coceal, 2009). There are few idealised field studies and they can lack relevance to ventilation studies: Davidson *et al* (1995) used an array of 39 cuboids of approximate size 2.3 m in dimension in a field to assess their effect on the dispersion of tracer gas released within the array, but the cuboids had no openings to permit ingress.

To date there has not been a systematic study of natural ventilation for an idealized array of buildings at full-scale for a range of atmospheric conditions. An idealized full-scale set up was chosen to generate results of general applicability for a simple case, rather than just being applicable to a specific building. The full-scale experiment captured a wide range of wind directions and atmospheric stabilities to test their impact on ventilation characteristics, surface pressure and internal flow in a test building, whereas other work such as Robins and Macdonald (2001), Coceal *et al* (2006) and Davidson *et al* (1995) focused solely on external flow patterns and gas dispersion.

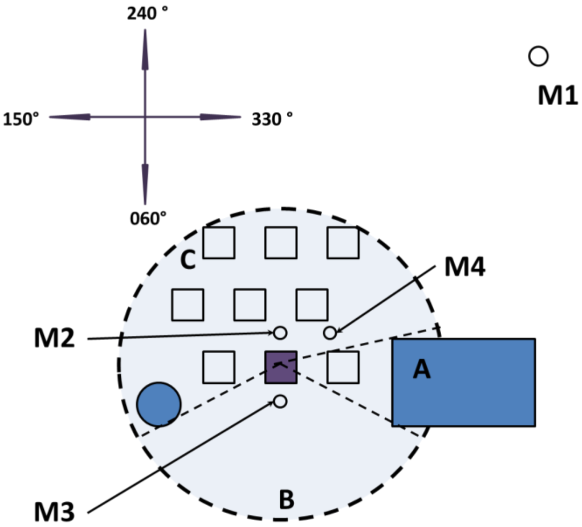
Experimental set-up and equipment

The present experiment consisted of a temporary, staggered array of eight solid straw cubes with very low porosity (dimensions 6 m by 6 m by 6 m) around an instrumented “test” cube, see Figure 1a. The experiment took place at Silsoe, UK (Latitude 52.01088°, Longitude -0.410979°) which is a rural experimental wind engineering facility consisting of a metal, cubic test structure (each side 6 m long) previously used by Richards and Hoxey (2008), Kasperski and Hoxey (2008), Yang (2004) and Straw *et al* (2000). The focus of the experiment was on the bulk flow patterns generated by the array, which are dominated by the form drag of the building, rather than the viscous drag due to the building surfaces, meaning that the choice of material was assumed not to have a large effect on the results; and the winter season was chosen for experimentation when heating of the surfaces by the sun is reduced. Future work would need careful design of model materials to match the thermal inertia of real buildings, to capture local buoyancy driven flows on building surfaces.

The prevailing wind direction is south-westerly with the site having good exposure to winds from south-west to east over a grass surface with a roughness length of around 0.01m (Richards and Hoxey, 2012). Winds from 240° are perpendicular to the front face of the cube (see Fig. 1b). The staggered array was built in September 2014 and was removed in April 2015, with the test cube left isolated from May 2015 to July 2015.

The positioning of the instrumentation and the ventilation rate measurement methodologies were influenced by the work of Yang (2004) and Straw *et al* (2000). Fig. 1b shows a schematic of the instrumentation layout outside the cube. A mast with reference pressure measurements and a Gill R3 sonic anemometer at 6 m and 10 m was positioned outside the array (Mast 1), with two other Gill R3 sonic anemometers being positioned at opening height in front and behind the instrumented cube (Masts 2 and 3). North-west of the instrumented cube was a mast monitoring meteorological conditions (Vaisala WXT 520 automatic weather station) and background CO_2 levels (LICOR-7500 infra-red gas analyser) (Mast 4). The experimental layout remained constant for the entire experimental period with all components, unless otherwise specified, logging at 10 Hz continuously.

a)



b)

Figure 1. The Silsoe experimental facility. a) Drone photograph of the straw cube array, instrument masts, the instrumented cube (blue) and the surrounding areas. The camera is facing to the north-west. b) A schematic of the cube array, with the instrumented test cube highlighted in purple. The blue rectangle denotes the storage shed shown in Figure 1a), which is approximately 15 m wide, 25 m long and 6 m in height. The blue circle represents a storage tank, approximately 2 m high. The wind directions can be split into sectors; Sector A: possible influence by the storage shed; Sector B: no array effects; Sector C: array effects.

The test structure was a cube clad in flat steel sheets with the external dimensions 6 x 6 x 6 m^3. The cube's front panel faces 240° and will be referred to as the west face. The back panel will be referred to as the east face. Both of the east and west faces have removable panels, of 0.4 m width and 1 m height with a centre-point 3.5 m above ground level, that represent windows, allowing the cube to be sealed, or to have single-sided or cross ventilation. For single-sided ventilation cases, only the west face panel was removed. Two Gill R3 sonic anemometers were put inside the cube set back 0.3 m from each potential opening to measure flow-rate. The test cube had 9 surface pressure taps on the east and west faces, 4 on the roof, north and south faces and 2 internal pressure taps positioned on the east and west internal walls.

16 type K thermocouples were positioned inside the cube, in four vertical arrays from ground level to approximately 4.5 m, due to access limitations, with another 8 thermocouples forming a horizontal array running east to west at 3 m height, positioned just under the centre of the openings. The thermocouples were logged at 10 Hz and allow for analysis of temperature gradients and changes caused by incoming flow.

6 CO_2 release points were positioned internally along the east and west faces, at heights of 3 m and 0.5 m to provide a more spatially homogenous tracer gas release. 3 release points were also positioned around the centre of the cube. Indoor CO_2 concentration was measured by three K-30 FR non-dispersive, infra-red CO_2 sensors with a range of 0-10000 ppm and sampled at a rate of 2 Hz.

Ventilation rate estimated using pressure tap measurements

This paper will focus on the ventilation rates calculated through use of the pressure data. A ventilation flow rate can be defined using the pressure difference measured across an opening, ΔP:

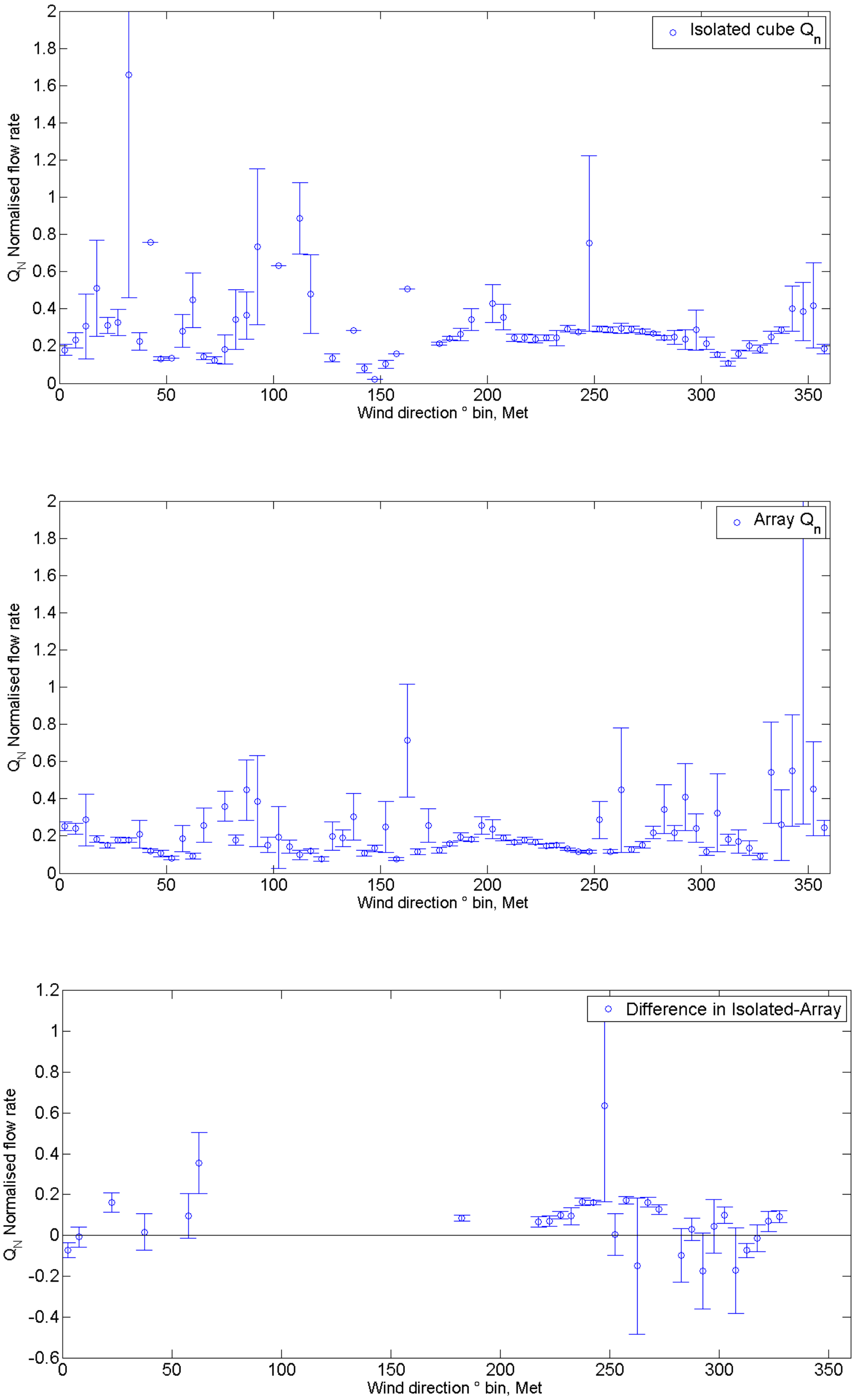
$$Q = C_d A\sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

where Q is the volumetric flow rate, C_d is the discharge coefficient, measured to be 0.61 for both openings (Robertson and Hoxey, personal communication, 2015), A is the area of the opening, ρ is the density of the flow. ΔP is taken as being the pressure difference between the 4 external taps around the opening and the nearest internal pressure tap for that face (Awbi, 2003). This can be normalised using a reference wind speed (U) and the opening area:

$$Q_n = \frac{Q}{UA} \tag{2}$$

Errors on the ventilation rates were calculated based on the instrumentation error, variability of Q within the averaging period, and calibration error.

3 RESULTS



a)

b)

c)

Figure 2. Normalised, west face, single-sided ventilation rate Q_n as a function of wind direction measured at reference mast M1 for a) isolated case, b) array case, c) difference Q_n (isolated) - Q_n (array).

The normalised ventilation rate, Q_n, was plotted as a function of wind direction for both the isolated and array cases, to test whether the array substantially alters the ventilation characteristics compared to the isolated case. For brevity, only the west face, single-sided ventilation case is discussed here. Data has been normalised by the reference wind speed at 6 m taken from mast M1 and the area of the window (0.4 m^2) and is averaged over half-hour periods. Q_n values were averaged into 5° wind direction bins, based on the average wind direction for each period. To give more robust statistics for the difference plot, only bins with more than 5 samples were included and the error bars are the standard error of the normalised Q_n for each bin. For wind directions in the 330-010° range ventilation rates were likely to be affected by the presence of the storage shed (Sector A) for both the isolated and array cases due to it blocking the approaching flow. Throughout the discussion, all data in this range will be excluded.

4 DISCUSSION

From Figure 2, it is clear that the influence of the array on the normalized volumetric flow rate depends on wind direction. Figures 2a) and 2b) show the half hour averaged Q_n values as a function of wind direction for the isolated and array cases respectively. For the isolated case (Fig. 2a), for the sector between 175° and 330°, data-points are numerous and consistent, and thus error bars are generally small. For 215°-285°, mean Q_n varies only slightly between 0.2 and 0.3 $m^3 s^{-1}$ with a broad peak. Flow is within ±45° of being perpendicular to the west face in this sector. The large peak of 0.8 $m^3 s^{-1}$ at 240°-250° is possibly due to an erroneous reading as it does not fit the otherwise smooth trend. There are small increases with higher variability around 200° and 290° that correspond approximately with an oblique flow at 45° to the front face that require further investigation.

Data between 10° and 165° show a lot more scatter, in part due to these wind directions being far less common. A lack of data for a similar range of wind directions at the same site was also noted by Richards *et al* (2007) and Straw *et al* (2000). Values between 45° and 75° with small error bars are generally low, due to the instrumented cube itself shielding the west face opening. Values around 150° are also low, which may be due to the oncoming flow impacting on the south/side of the cube, rather than the west/front face with the opening.

Figure 2b for the single-sided, array case shows some similarities, but also key differences. Around the perpendicular direction, 240±45°, data-points with small error bars show that there is a broad minimum rather than a maximum. For the array at 240°, average values of around 0.1 compare with 0.3 for the isolated case, suggesting that the array causes a reduction in the magnitude of Q_n by 33-50% for the angles where it has the largest effect. More variation and higher values are noted in the array results for the 275°-300° range. As there are only two neighbouring cubes and a gap upstream of the test cube for this direction (see Fig. 1b), the relatively high values may be due to channeling effects. For flow coming from around 50°, values are similar to the isolated case, suggesting that for flow incident on the opposite face to the opening, the array has a smaller effect. Values increase from around 0.1 at 150° to a maximum of 0.2 at 200°, again suggesting that the array may be creating local flow patterns near the opening that enhance ventilation rate.

The differences plotted in Figure 2c are only generated for wind angle bins where there are more than 5 cases for both the isolated cube and the array case, meaning no data is available for the angle range 75° to 175°. A positive difference means the isolated Q_n values for that angle bin are greater, with a negative difference suggesting the array Q_n rates are larger. For 200 - 330° (most of sector C in Fig. 1b) the difference in the magnitude of Q_n between the isolated and array cases was around 0.1-0.2 as seen in Figures 2a and 2b. At 260°, 280°, 290° and 310° the difference is negative, with 285°, 295° and 300° being positive, possibly suggesting that the array flow patterns display two different behaviours: flow channeling (which enhances ventilation) and blocking (which inhibits ventilation) which are highly sensitive to the oncoming flow direction and array configuration. The standard deviation of the direction of the oncoming flow will need to be considered further before any conclusions are drawn, as well as atmospheric stability and effect of averaging time.

It is important to note that the results shown in Figure 2 are normalised by the reference flow, taken from mast M1, at the building height of 6 m. Whilst this is reasonable for the isolated case, the upstream 6 m mast is not likely to be representative of the flow directly affecting the opening on the cube within the array, due to the complex interaction of the cube wakes. Future work will involve understanding the limitations of this normalisation method. Cross ventilation cases will also be studied to determine if the array has different effects for different types of ventilation.

5 CONCLUSIONS

Results from a field experiment investigating the impact of an urban array on single-sided ventilation of an idealized building have shown both reductions and increases in ventilation rate when incoming flow direction is changed. Early results suggest that even a 10° change in wind direction may alter the normalized ventilation rate of a building positioned within an array. The magnitude of this change in normalized ventilation rate is heavily dependent on wind direction, with the array causing reductions of 25-67% when the oncoming wind is in the sector perpendicular to the opening in the front face of the building. Of particular interest are the angles when the oncoming wind direction is oblique to the array and when the building is on the edge of the array. On further investigation, the results will be of interest to city planners as so-called “channeling flows” within urban streets may enhance ventilation rather than inhibiting it.

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