Field measurement of natural ventilation rate in an idealised full-scale building located in a staggered urban array: Comparison between tracer gas and pressure-based methods


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ARTICLE INFO

Keywords:
Natural ventilation
Ventilation rate
Tracer gas
Full-scale
Pressure
Wind direction

ABSTRACT

Currently, no clear standards exist for determining urban building natural ventilation rates, especially under varying realistic meteorological conditions. In this study, ventilation rates are determined using tracer gas decay and pressure-based measurements for a full-scale (6 m tall) cube. The cube was either isolated (2 months of observations) or sheltered within a staggered array (7 months), for both single-sided and cross ventilation (openings 0.4 m × 1 m). Wind speeds at cube height ranged between 0.04 m s⁻¹ and 13.1 m s⁻¹. Errors for both ventilation methods are carefully assessed. There is no discernible linear relation between normalised ventilation rates from the two methods, except for cross ventilation in the array case. The ratio of tracer gas and pressure derived ventilation rates is assessed with wind direction. For single-sided (leeward opening) cases it approached 1. For cross ventilation the ratio was closer to 1 but with more scatter. One explanation is that agreement is better when internal mixing is less jet-dominated, i.e. for oblique directions in the isolated case and for all directions for unsteady array flows. Sheltering may reduce the flushing rate of the tracer gas from the cube relative to internal mixing rate. This new dataset provides an extensive range of conditions for numerical model evaluation and for understanding uncertainty of ventilation rates. Knowledge of the latter is critical in building design.

1. Introduction

Accurate predictions of ventilation rates are required for the health and well-being of the occupants inside a building. Natural ventilation is suited to mild climates [47] to create a comfortable and healthy indoor environment, and save energy compared to mechanical ventilation systems [11,26]. A variety of tools are used to simulate natural ventilation: EnergyPlus (e.g. [54]), TRNSYS coupled with CONTAM (e.g. [31]) and CFD (Computer Fluid Dynamics) models (e.g. [32,33,69]). To verify natural ventilation simulations, detailed datasets are required with temperature, internal gains, operable window position, tracer gas concentrations and air velocity observed [42]. Given natural ventilation’s dependence on the external conditions, many studies use test chambers (e.g. [58,69]) or wind tunnel models (e.g. [35]) to control the boundary conditions, but lose the true information of the impact from varying atmospheric conditions. Full-scale measurements in true atmospheric conditions are limited, because of the variability of external conditions, measurement difficulties and cost limitations [42]. Furthermore, determining natural ventilation rate in the urban environment is more challenging due to the complex wind environment and all scales of turbulence encountered [1].

To date few full-scale studies of natural ventilation within an urban area have been undertaken, though most agree that natural ventilation becomes less effective in urban areas [13,14,63]. For isolated buildings, opening shape, size and location [45,56,65] could affect natural ventilation performance. Instantaneous fluctuations in wind direction and wind speed also have an effect [24]. To our best knowledge, the long-term measurement of natural ventilation for both isolated and array cases under the varying realistic atmospheric conditions, allowing the direct comparison of the two, has never been studied.

In terms of methods for full-scale measurement of natural ventilation rate, both tracer gas techniques and pressure taps are the most...
frequently used [9,46]. Despite the study of ventilation becoming more multi-disciplinary, there is no clear guidance on which method to use and how methods compare for realistic buildings in actual meteorological conditions. Typically, average climate data are used, which by definition, missing both the extremes and the variability.

Comparisons between pressure difference and tracer gas methods for naturally ventilated livestock buildings [10,52] found pressure difference methods were unable to provide ‘accurate’ estimates or of true ventilation rate because of the dependence on wind speed. Unfortunately, the inaccuracy was not quantified.

The objective of this paper is to compare tracer gas and pressure-based methods to determine ventilation rates in a full-scale field environment (both isolated and building array), with a detailed methodology and error analysis. The mean ventilation rates are determined with tracer gas decay (Section 2.1) and pressure-based (Section 2.2) methods for a ventilated 6 m high cube in an isolated and staggered cube array and with cross and single-sided ventilation. Mean ventilation rates are compared over a range of weather conditions and wind directions.

2. Description of tracer gas and pressure-based methods

2.1. Tracer gas decay method

Determining ventilation rates through measurement of tracer gas concentrations is best suited to single zone systems or where sections of a building can be completely isolated [55]. The tracer gas methods commonly used are constant injection (e.g. [66]), constant concentration (e.g. [4]) and tracer gas decay (e.g. [9]). Of the three, the decay method is more common, as smaller amounts of gas are required and it is easier to implement [44].

Despite carbon dioxide (CO2) being naturally present in the atmosphere, it is commonly used as an indoor air quality indicator and as a tracer gas. Advantages include its low cost and straightforward safety requirements. CO2 can be released (e.g. [9,16]) or generated by room occupants (e.g. [39,70]) to be utilised [41]. Other gases used include sulphur hexafluoride (SF6) [57], sulphur dioxide (SO2) [18], carbon monoxide (CO) [59,67] and nitrogen dioxide (NO2) [68].

Few guidelines for sensor positioning are available [21][22]; despite this being crucial to obtaining representative measurements [40]. Within mechanically ventilated rooms, inappropriate sensor positioning can cause tracer gas decay ventilation rate errors of up to 85% [62]. Van Buggenhout et al. recommend siting at the ventilation outlet, while within buildings, the relative role of thermal or wind driven processes poorly understood [8].

If a pressure difference (Δp) between the internal and external environments or between the front and back of a building can be deduced, the flow rate through the opening (Qp) is:

\[ Q_p = C_p A \left( \frac{2 \Delta p}{\rho} \right) \quad (5) \]

where \( p \) is the air density, \( C_p A \) is the effective area of an opening. This changes with the number of openings and their relative positions. \( C_p \) is the discharge coefficient and \( A \) is the opening area. The assumptions required for equation (5) are:

- flow is turbulent under normal pressures,
- kinetic energy is dissipated at the windward opening
- presence of openings does not influence the surface pressure distribution.

For cross ventilation with both inlets and outlets, some of the turbulent kinetic energy can be preserved and directed outside without interior dissipation, underlining the kinetic energy assumption [30,43]. Suggested alternatives (e.g. [23,30,53]) have not replaced the orifice equation.

The largest source of error arises from using a mean rather than instantaneous pressure differences [6]. Uncertainty increases with very large (undefined) openings [46] as non-uniform pressure differences occur and the ventilation opening velocity profiles vary with time. Errors arise if an incorrect discharge coefficient is used, as \( C_p \) is sensitive to opening size and wind direction and also for cross ventilation, the ratio of the two openings [5,29].
Table 1

<table>
<thead>
<tr>
<th>Equipment used for measurements of data analysed.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variable</strong></td>
</tr>
<tr>
<td>Velocity, Direction</td>
</tr>
<tr>
<td>External CO₂</td>
</tr>
<tr>
<td>Internal CO₂</td>
</tr>
<tr>
<td>Surface pressure</td>
</tr>
<tr>
<td>Internal temperature</td>
</tr>
<tr>
<td>Velocity, External temperature</td>
</tr>
<tr>
<td>Shortwave and longwave radiation</td>
</tr>
</tbody>
</table>

3. Experimental design

Observations were undertaken within the REFRESH (Remodelling Building Design Sustainability from a Human Centred Approach) Cube Campaign (RCC). Full details of the array set-up, external and internal flow patterns and an overview of the data gathered within RCC-REFRESH are given in [16,17,32,33]. Details pertaining to the determination of ventilation rates are given here.

Observations (Table 1) were taken at Wreath Park, Silsoe, Bedfordshire, U.K. (52.01088° N, −0.410979° W) using an uninhabited instrumented cube (height 6 m). The cube was clad in flat, steel sheets to ensure uniform external surfaces. It was positioned to be perpendicular to the prevailing site wind direction (Fig. 1). Observations occurred in two phases, with the instrumented cube: (i) surrounded by a limited staggered array of eight cubes (October 2014−April 2015) and (ii) isolated (May−July 2015). Therefore, radiative differences occur between the array (winter−spring) and isolated (early summer) cases. These are accounted for as far as possible within the analysis. The real-world environmental factors are used to characterise the measurements.

The cube’s front and back faces had removable panels (0.4 m wide x 1 m high) allowing both a sealed and a ventilated structure. Both single-sided and cross ventilated set-ups were used with the centre point of the opening 3.5 m above from the ground (Fig. 1a). This is smaller than the 1 m² openings used by [59] as they found the ventilation rates were too large (gas flushed < 30 s) to accurately measure the tracer gas decay curves and meteorological conditions.

3.1. Temperature measurements

Temperature measurements inside the cube (Table 1) allowed determination of thermal stratification, and with the external temperatures on the Channel mast (Fig. 1, Table 1) the thermally-driven ventilation component. The Vaisala WXT520 weather station was positioned to minimise solar gains. Internal temperatures measured at 24 points (Fig. 2, Table 2) were sampled at 10 Hz to allow the average over a large number of samples in the 30 min value and a reasonably accurate mean.

Eight thermocouples (H1 to H8) were horizontally strung between the windows at a height of 3 m (Table 2b). The other 16 were in four vertical profiles of four thermocouples (T1 to T4), put at varying heights (Table 2a) below 4 m given access limitations. The thermocouple errors (0.45% ± 2 °C, junction error plus thermocouple error) are unsuitable for measuring instantaneous fluctuations in temperature [27]. All thermocouples and the WXT520 were calibrated and corrected (on average < 0.5 °C) for instrument bias at the start and end of the experiment using an environmental chamber (Design Environmental Delta 190H) over a –20 °C to 50 °C range, accounting for hysteresis effects due to instrumental time response.

3.2. Tracer gas decay method set-up

The combination of site limitations, safety concerns, affordability, lower environmental impact, wide range of sensors and lower risks (cf. other tracer gases, e.g. Argon and SF₆) led to CO₂ being chosen as the tracer gas. The external CO₂ concentration (Cₑ) was measured with an open path LI-COR LI-7500 on the channel mast (Fig. 1, Table 1). During the 10-month study, Cₑ varied between 365 and 450 ppm (95% between 371 and 403 ppm). Given the low natural variability (standard deviation typically 3–4 ppm) of Cₑ during a decay experiment (Table 3), the mean Cₑ for that period is used in equation (3). The LI-COR LI-7500 was sufficiently distant from the cube to ensure the tracer CO₂ releases did not have an effect.

The three synchronised K30 NDIR sensors measuring internal CO₂ (Cᵢ) (Fig. 3, Table 1) were not electronically shielded. They were encased within modified junction boxes to protect from frost, condensation and to reduce magnetic noise (Fig. 3). Pre-experiment checks ensured there was adequate airflow to the sensors.

The K30 sensors were calibrated by the manufacturer and compared in-house to the LI-7500 in both a constant concentration test, and a decay from the sensor upper limit (10,000 ppm) before and after the field campaign. None of the three sensors drifted over the course of the experiment. Fig. 3 shows the ‘East’ sensor (E) positioned under the east opening (1 m from the wall, 2.75 m above the ground). The ‘Low’ sensor (L) was hung under the steel girder of the east wall, (1 m from the North-East corner of the cube, 0.3 m above the ground). The ‘Middle’ sensor (M) was 3 m above the ground at the centre-point of the Northern wall (~0.5 m from the wall) but near a crack between the floor and building to help understand infiltration effects on the ventilation rate. To reduce the infiltration rates, cracks at the cube base were filled with foam. Ideally more sensors would have been used to give more representative results of the cube over-all ventilation rate.

The cube’s nine inlet pipes (Fig. 3) were used to release the tracer evenly throughout the cube. A large desk fan (estimated effective range...
of 4 m horizontally, 2 m vertically) was used to improve mixing. Eight outlets were 3 m above floor level. Outlet number 6 was placed at floor level in the centre of the room and had a pipe length (outlet to regulator) of 2.2 m, whereas all others were 3.1 m. The CO₂ was heated by the regulator to approximately 10 °C to prevent the outlet freezing during release and to reduce the temperature difference between the tracer gas and the ambient air. Gas release was controlled externally.

The procedural order for each tracer gas decay experiment was:

1) The openings (if used) were blocked from the outside with a temporary panel. The fan was turned on
2) Sensors were checked for any signs of water damage or loose connections before logging initiated
3) The door was shut, and CO₂ released for 10–15 min. The maximum
concentration achieved for all runs was between 3000 and 10,000 ppm. 

4) After 10–15 min, the blocking panels were removed, and the gas switch off (fan remained on to aid mixing).

5) The cube was left undisturbed for at least 20 min. For infiltration experiments, the cube was often left overnight due to the low air exchange rate.

The local air change rate (λ) for each sensor is calculated by linear fit (equation (3)) incorporating errors (e.g. Fig. 5, section 4.1). The instrumental errors are accounted for in λ by fitting curves to measured data plus and minus the instrumental error (Table 1). The final ventilation rate for an experiment is the average of all three sensors when a "well-mixed" criterion is satisfied: (i) flow structure verified by filming smoke release inside the cube or (ii) all 30 min horizontal (difference of the average temperature of H1, H2 and H7, H8) and vertical temperature differences (difference in average temperature of thermocouples at 3–4 m and those at 0–1.5 m) were less than 2.5 °C. The combination of temperature measurements and smoke releases eliminated 15 tracer gas releases from the dataset. Incomplete temperature or smoke data resulted in another 13 being excluded. Thus, 28 out of 156 releases were discarded.

Only the tracer gas method permits infiltration rate measurements, as the area of cracks and gaps could not be determined by other means. The mean infiltration rate (average of 15 infiltration experiments, all wind directions) is 0.562 h⁻¹ (0.034 m³ s⁻¹) (median 0.572 h⁻¹) with an inter-quartile range of 0.426 h⁻¹ (0.026 m³ s⁻¹) and an error of approximately 5% was removed from the total measured ventilation rate in all results presented (see Table 3).

### 3.3. Pressure difference

To measure the cube surface pressure, 30 external and 2 internal pressure taps were used. The external pressure taps had 7 mm holes located centrally on 0.6 m² steel panels. These were mounted flush to the cube cladding. The taps, located closer together where sharper gradients in pressure were expected (Fig. 4), are in identical positions to [59]. Pressure signals were transmitted pneumatically, using 6 mm internal diameter plastic tubes to transducers located within the cube, at a rate equivalent to 10 Hz. The sensors for taps 1–16 were Honeywell 163PC01D75 differential pressure sensors; pressure taps 17–32 were Honeywell 163PC01D76 differential pressure sensors (Table 1). Two internal pressure taps were located directly under the openings on both the front and back of the cube.

To combat instrument drift, the pressure tap system logged continuously (new file every 30 min). At the start and end of each

<table>
<thead>
<tr>
<th>Ventilation case</th>
<th>Isolated</th>
<th>Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qt #</td>
<td>Mean length (min)</td>
<td>Qt #</td>
</tr>
<tr>
<td>Infiltration</td>
<td>15</td>
<td>201</td>
</tr>
<tr>
<td>Single-sided</td>
<td>26</td>
<td>16</td>
</tr>
</tbody>
</table>

Fig. 3. Tracer gas set-up showing locations of: a) tracer gas inlet pipes (purple squares, 1–9; 1–5 and 7–9 at 3 m above floor level, #6 at ground level), K30 CO₂ sensors (E/L/M, position within 0.1 m), openings (door shown open but closes flush with the wall) and mixing fan (blue cross). b) Photos showing K30 sensors (red circles): Low sensor (L), East sensor (E) and Middle sensor (M). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Number (#) of tracer gas release (Qt) experiments, mean length of the decay (min) and number of 30 min average pressure (Qp) measurements for the different ventilation cases when cube was isolated and within the array. Only days with all input data required for calculation are included.
Fig. 4. Location of the pressure taps on each face (T top, B base) of the cube with distance between taps (black) and the opening (white rectangles). Internal taps 15 and 16 are not shown. (drawing not to scale). Front and back faces are symmetrical as are the side faces [17].

measurement file 60 s of zero measurements based on a reference pressure and 60 s of calibration of the pressure transducers to the zero measurements were taken. The last second of data in each file is not analysed as the valves switched to the reference rather than surface pressure.

Reference pressure was measured with a static pressure probe at ground level (custom-built as described in [49]). A reference dynamic pressure was measured using a directional pitot tube [37] at 6 m alongside the 6 m reference sonic anemometer (Fig. 1). External pressure was defined as the mean pressure measured around the opening at the front (Taps 3, 4, 18 and 19) and back (Taps 12, 13, 26 and 27) faces (Fig. 4). Tests undertaken of sealed and ventilated conditions found no effects of the opening on the mean surface pressure measurements closest to the opening.

After the mean of the external taps is calculated, difference calculations (external and internal) are performed for each 10 Hz reading. These differences (averaged per 30 min) is used in equation (5) to calculate $Q_p$ with a flow direction dependent $C_d$ determined from wind tunnel tests. An open-ended wind tunnel (cross section 1.7 m $\times$ 1 m, turbulence intensity $\sim$4%) was used with a model of the openings (0.4 m $\times$ 1 m $\times$ 0.23 m d). The sill pointed inwards for the inlet set up and upwards for the outlet set up. A fan within the rig drew air through the inlet cones. This was calibrated to give flow rates from pressure at the conical outlet. Pressures inside the settling chamber box at the downstream end were measured by micro-manometer [50]. The test opening was mounted at the end of the settling box. Temperature, humidity and barometric pressure measurements allow for an accurate calculation of air density. Flow rates and resultant normalised pressure differences were compared, with the gradient between the two being equal to $C_d A$ (Hoxey and Robertson, personal communication, 2015). When acting as an inlet, $C_d = 0.616 \pm 0.016$ and as an outlet, $C_d = 0.658 \pm 0.022$, with errors on $C_d$ being determined from the standard error of the fitted coefficients. The local mean wind direction (Front mast, Fig. 1) is used to select the $C_d$. If the wind is from $-90^\circ$ to $0^\circ$ the inlet value is used, otherwise ($91^\circ$ to $-91^\circ$) the outlet value is used. Directional fluctuations (e 30-min) will introduce additional errors into the calculations. The errors in $Q_p$ are calculated with the error propagation method using the standard error of $\Delta p$.

Alternatively, the ventilation rates can be calculated for each instantaneous pressure measurement. The average of these is the mean ventilation rate. The two pressure-based methods have approximately a 10% difference in 30-min averages. This decreases to 3–5% for 5-min averages.

3.4. Ventilation measurement summary

Table 3 summarises the ventilation data. The 30 min averaging period for the pressure based ventilation and meteorological variables allows error statistics to be consistent with other meteorological studies [3]. The tracer gas decay length varied with experimental set up. Pressure-based ventilation rates from the full range of observed wind speeds are analysed, unlike earlier pressure coefficient studies which restricted wind speeds (e.g. [19] $> 4\,\text{m s}^{-1}$ [49], $> 3\,\text{m s}^{-1}$). Inclusion of lower wind speeds leads to higher scatter in the range of ventilation rates.

The Archimedes number ($Ar$): ratio of external forces to internal viscous forces can be used to determine whether a flow is being driven by buoyant processes (large $Ar$) or is being affected by external processes (e.g. wind driven, small $Ar$). The dataset has less than 10 cases where buoyant forces are completely dominant; i.e. the most cases are wind driven.

4. Results and discussion

The pressure-based and tracer gas decay results are analysed in three ways: (i) error analysis is discussed and then a single tracer gas release case (< 30 min) is compared to the 1, 5, 10 and 30 min averages for pressure-based ventilation rate ($Q_p$) for the same period; (ii) the tracer gas decay timestamps are used for the $Q_p$ calculation times; and (iii) all $Q_p$ rates are compared to the 30 min $Q_p$ averages for the entire dataset. The array and isolated cube data are treated separately. For more details about the sheltering effect of the array on the ventilation rate see [17].

To enable comparison across different wind speeds, a normalised ventilation rate ($Q_n$) is used:

$$Q_n = \frac{Q}{A U_{\text{ref}}}$$

where $U_{\text{ref}}$ is the reference wind speed taken at 6 m (Fig. 1). Tracer gas decay air changes per hour ($\lambda$) are converted into $Q$ ($\text{m}^3\text{ s}^{-1}$) before being normalised using equation (6).

Pressure difference derived ventilation rates are only used when the data series for that period is complete.

4.1. Case study: isolated cube, cross ventilation

During the isolated cube cross-ventilated case study (21/05/2015) the mean reference wind speed ($U_{\text{ref}}$) is 5.3 m s$^{-1}$ (standard deviation $\sigma_{U_{\text{ref}}} = 0.24\,\text{m s}^{-1}$) and wind direction ($\theta_{\text{ref}}$) is $6^\circ$ ($\sigma_{\theta_{\text{ref}}} = 19^\circ$). The total time when the tracer gas was well-mixed within the cube was 9 min. The decay curves (Fig. 5) are only for the 9 min well-mixed data. There is a gap in the pressure difference ventilation rate data (Fig. 6) linked to the system calibration, meaning it zeroes itself every half hour (Section 3.3).

For the tracer gas results, the “Low” sensor (Fig. 3, L) has the greatest ventilation rate (Fig. 5c, Table 4). This sensor position experiences flow exiting from both the back opening and a small gap at the base of the cube. This suggests that infiltration may reinforce cross ventilation within the cube for this wind direction. However, the recorded average infiltration rate of the cube (0.034 m$^3\text{ s}^{-1}$) is $\sim$5% of the measured ventilation rates (Fig. 5b). The East and Mid [CO$_2$] sensors have similar results (Fig. 5a, c) with the Low sensor being affected by the infiltration rate, leading to faster decay rates in comparison.
For all tracer gas releases, the error is presented as the standard deviation of the measured, maximum and minimum ventilation rates for all sensors. The infiltration rate of the cube may act against or reinforce the ventilation rate and as such is also included as an error on each ventilation rate (Table 4).

Comparison of the pressure-based normalised ventilation rate ($Q_{NP}$) for different averaging times (1, 5, 10, and 30-min) with $Q_{NT}$ mostly agrees within error the bounds for this case (Fig. 6). Within the release period, the pressure measurements were calibrated (gap in instantaneous results, Fig. 6).

Most of the 1-min average $Q_p$ values are within the $Q_T$ range. As expected, the variability of instantaneous $Q_p$ measurements is not entirely captured by these. The 5- and 10-min averages also lie within the $Q_T$ range. The 30-min mean $Q_p$ is close to the lowest $Q_T$ rate as the instantaneous $Q_p$ values decrease after the decay period. Overall, the averaged $Q_p$ values are closer to the lower estimate of $Q_T$, but shorter averaging times capture the variability of the ventilation rate. This case study suggests the pressure method tends to under-predict compared to the tracer gas method, in line with [52]. However, the missing data complicates this result. This conclusion is tested across all array, ventilation and meteorological conditions in the following sections.

4.2. Comparison of tracer gas and pressure-based ventilation rates

The normalised ventilation rates calculated from pressure ($Q_{NP}$) and tracer gas ($Q_{NT}$) data are compared for all the tracer gas release times, for both isolated and array cube cases in single-sided ventilation (Fig. 7a) and cross (Fig. 7b) configurations. There is no obvious linear relation between $Q_{NP}$ and $Q_{NT}$ (Table 5). However consistent with Fig. 6, both normalised ventilation rates (Fig. 7) have a similar order of magnitude. The lack of correlation between the two methods suggests that they are affected by different parameters in dissimilar ways. Straw et al. [59] used a larger (1 m$^2$) opening and found the pressure based method were 21% of the tracer gas ventilation rate. Across the configurations analysed, and consistent with [10] and [52]; the pressure difference method is an unreliable predictor of the ventilation rate measured through tracer gas decay.

The poor agreement for individual periods for the single-sided ventilation cases (Fig. 7a) may be caused by bi-directional flow across the opening. This process is not captured by the pressure measurements surrounding the opening. For the cross-ventilation array case (Fig. 7b), there may be improved internal mixing due to the enhanced unsteadiness of the flow with the array enhancing the effectiveness of the tracer gas measurement. However, the assumptions required for the orifice equation may not hold for cross ventilation. Some of the error for the pressure-based method may arise from the discharge coefficient used not being valid for all wind directions [29].

It must also be acknowledged that the tracer gas derived ventilation rate may not be representative of the entire cube and rather a local ventilation measurement (e.g. large errors Table 5), causing differences...
between the two methods. The representativity of the tracer gas ventilation rate for each experiment is difficult to quantify and the cube itself may not remain well-mixed throughout the decay, as evident in deviations from the exponential decay (Fig. 5).

### 4.3. Effect of wind direction

When the data from Fig. 7 are analysed as a ratio \( Q_{nt}/Q_{np} \) with the reference wind direction \( \theta_{ref} \) it is evident that wind direction has an influence (Fig. 8). Large errors occur in the ratios as these are now combined across the two methods. For the single-sided case, the ratio is generally below 1, suggesting that the pressure-based method overestimates ventilation rate. For the isolated single-sided cube, \( Q_{nt}/Q_{np} \) is around 1 for \( \theta_{ref} = -100° -145° \) and \( \theta_{ref} = 150° \), suggesting that better agreement occurs between the methods when the flow is not impacting on the front face of the cube (opening side). For the isolated single-sided cube, as \( \theta_{ref} \) decreases from 150° towards 0°, \( Q_{nt}/Q_{np} \) tends towards 0.5, although for \( \theta_{ref} = 60° -70° \) a range of \( Q_{nt}/Q_{np} \) of 0.4 - 0.7 is measured.

Other factors, such as wind speed fluctuations in separated flow around the opening (causing mixing at the opening) may have an effect alongside wind direction. It also might suggest that the thermal component of the ventilation tends to act against the wind driven component for flows perpendicular to the opening, leading to a lower ventilation rate measured by the tracer gas. For the present study, internal-external temperature differences were mostly less than 5°C, meaning that the stack effect is small and is very rarely dominant for both single-sided and cross ventilated configurations. It is unknown how representative the internal-external temperature difference is compared to the across opening difference. For both the single-sided and cross-ventilated isolated cubes there are a few points with ratios > 2, i.e. \( Q_{nt} > Q_{np} \). For the single-sided case this occurs when the wind is impacting the cube back and is twice the ratio of measurements for similar wind directions (Fig. 8a). For the cross ventilated cube, there are insufficient data to determine the cause (Fig. 8b).

The cross ventilated isolated cube in general has higher values of \( Q_{nt}/Q_{np} \) than those measured for the single-sided case. For the cross ventilated isolated cube, when \( \theta_{ref} \) was perpendicular to the front opening (\( \theta_{ref} = 0° \)), \( Q_{nt}/Q_{np} \) was approximately 0.6, increasing to 1 to 1.5 when \( \theta_{ref} \) = 45°, suggesting that it is important to note wind direction when concluding whether the pressure difference method overestimates \( Q_{nt}/Q_{np} = 0.6 \) or underestimates \( Q_{nt}/Q_{np} = 1.5 \) the ventilation rate.

This may be influenced by the internal mixing state of the cube. CFD simulations of the cube's internal flow [32,33]: a jet was present for \( \sim 45° < \theta_{ref} < 45° \) for the isolated cube; and for the array case internal flow was too unsteady for a jet to be sustained. For similar wind directions (e.g. \( \theta_{ref} = 0° \)) the jet was also seen via smoke visualisation for
both single sided and cross ventilated cases but was often disrupted by fluctuations in wind direction. There may be better agreement between the ventilation methods when there is not a strong internal jet, and instead unsteady mixing dominates, though more data are required to confirm this. Another possible reason is the variation of $C_d$ with wind direction, which is given one of two values in this study.

For the isolated case, $\theta_{\text{ref}}$ is similar to $\theta_{\text{local}}$ (Fig. 1) and little difference in relation with wind direction can be seen when Figs. 8 and 9 are compared. Except when the reference flow is coming from behind the cube ($\theta_{\text{ref}} = 180^\circ$) and $\theta_{\text{local}}$ is $45^\circ$–$135^\circ$ and $-45^\circ$ to $-135^\circ$, indicating that the local mast is in the recirculation region in front of the cube. This is related to the non-linear relation between $\theta_{\text{ref}}$ and $\theta_{\text{local}}$ (for detail see [17]). Fig. 9a shows that the wide range of $\theta_{\text{ref}}$ for the single sided array corresponds to a narrow range in $\theta_{\text{local}} = 0^\circ$–$45^\circ$, suggesting that the array “channels” the flow for these reference wind directions. $Q_{NT}/Q_{NP}$ is approximately 0.3, suggesting for when flow is not quite perpendicular to the opening, the pressure difference method consistently overestimates the ventilation rate. For the cross ventilated array case there is a wider range of $\theta_{\text{local}}$ than $\theta_{\text{ref}}$, suggesting that the local mast is located within overlapping wakes from neighbouring cubes, and the wide spread in $Q_{NT}/Q_{NP}$ is visible across the range in $\theta_{\text{local}}$. Some of this spread, such as for $\theta_{\text{local}} = 90^\circ$, could be associated with the flow across the opening being caused by turbulent effects. Fig. 9b indicates that local wind direction alone is not enough to explain the difference in the two methods. Determining which parameters have the largest effect on the ratio between the two methods is difficult, although it is shown to be dependent on wind direction for all cases.

5. Conclusions

The large data set measured during the REFRESH Cube Campaign has enabled a detailed evaluation of two ventilation rate measurement methods (tracer gas decay, pressure-based) for a simplified building across a wide range of conditions: wind speed and direction, single-sided and cross-ventilated configurations, and isolated and staggered building array. This provides a substantial contribution to the understanding of the relative performance of the two methods under realistic meteorological conditions for a simplified built environment.

Errors in the tracer gas measurements are carefully considered. Results demonstrated that a single sensor does not necessarily give a ventilation rate representative of the whole space, and that some wind conditions led to more spatial variability and thus higher errors. Maximum and minimum fits of a decay curve to concentration data within margins of measurement error are used to estimate the error for
the ventilation rate at each measurement location; then all estimates are averaged across all three sensors.

Assessment of pressure method averaging times, suggests 10 min or greater is needed to obtain a reliable measure of the average ventilation rate within the cube. Shorter periods are too variable compared to tracer gas results. However, shorter timescales show the variability with external conditions. Agreement between the two normalised ventilation rates (tracer gas \(Q_{\text{vg}}\) and pressure methods \(Q_{\text{pp}}\)) for the four configurations (single-sided and cross ventilated, isolated and array) is poor. The pressure difference method does not capture similar ventilation rates to the tracer gas methodology.

Both ventilation rate methods have their shortcomings: tracer gas - requiring a well-mixed internal environment and minimal infiltration; and pressure difference - needing knowledge of \(C_0\) and how it changes with wind direction alongside several assumptions which are unlikely to always hold in realistic outdoor flow.

The ratio \(Q_{\text{vg}}/Q_{\text{pp}}\) changes with reference wind direction. For single-sided ventilation it approached 1 when the opening was on the leeward side of the cube in the wake, and otherwise was small for windward flows, suggesting that the pressure method was an overestimate. For cross ventilation, the ratio was closer to 1 although there was more scatter. There was a slight trend for the ratio to approach 1 when the flow was not directly perpendicular to the front face for the isolated case. There may be better agreement when the internal mixing state is less dominated by a single jet, i.e. for oblique wind directions for the isolated case, and in general for the array case where external flows are highly unsteady. Sheltering may also reduce the flushing rate of the tracer gas from the cube relative to internal mixing rate.

The work could be extended by comparing the methods within controlled environments where the true ventilation rate is known, e.g. wind tunnel experiments. CFD modelling of the internal flow and tracer gas dispersion would aid sensor positioning and allow either stagnant or jet areas to be avoided or actively focused on. Whilst some of the differences between methods may be explained by changing wind directions, more work is required to explore simultaneous thermal effects, effects of sensor positioning and variations in the internal flow.

Declaration: All authors have approved the final version of the manuscript, which is submitted. This article is the authors' original work, has not received prior publication and is not under consideration for publication elsewhere. There are no known conflicts of interest.

Acknowledgements

This work was funded by the University of Reading and EPSRC REFRESH project (EP/K021893/1). Thanks to Solutions for Research and John Lally for assistance with the full-scale observations. Support from EPSRC LoHCool (EP/N009797/1) is also acknowledged. Datasets can be found at DOI: http://dx.doi.org/10.17864/1947.137.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2018.03.055.

References


