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Studying the effect of wind direction on cross-ventilation turbulent flows

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SUMMARY
Natural ventilation depends upon the characteristics of the approaching flow (e.g. wind direction, turbulence) and the building's openings (e.g. number, position, geometry). This study aims to examine the less understood turbulent aspects of the incoming flows for varying angles of the incident flow, under cross ventilation scenarios. Measurements that were taken during the period October 2014 – July 2015 at Silsoe, UK in the frame of the REFRESH project are used. One metal cube was equipped with two Gill R3 sonic anemometers, whilst the flows around the metal cube and upstream were measured by five sonic anemometers. Cross ventilation was established with openings of area 0.4 m^2. Results show that for flows perpendicular, diagonal and parallel to the openings, velocity power spectra indoors appear flattened, implying an enhancement of the importance of small eddies indoors. When the flow is parallel to the openings, unsteady phenomena are dominant and pulsation flows develop. CFD (Openfoam) simulations facilitate the understanding of the flow development under different wind directions.

KEYWORDS
wind direction, turbulence, Silsoe, sonics, CFD

1 INTRODUCTION
Natural ventilation, one of the main controls of occupant's comfort, primarily depends upon the characteristics of the approaching flow (e.g. wind direction, turbulence) and the building's openings (e.g. number, position, geometry). In cross ventilation, when the ventilation openings are placed in opposite walls and under winds perpendicular to the openings, a jet penetrates the indoor environment (Tominaga and Blocken, 2015). On the other hand when the flow is parallel to the openings, an unsteady flow develops and fluctuations become the main source of momentum for air exchange (Hu et al., 2008). Features of this kind of flows are by far less well understood. This study aims to examine the less understood turbulent aspects of the incoming flows for varying angles of the incident flow, namely when the flow is perpendicular, diagonal and parallel to the openings, under cross ventilation scenarios.

2 MATERIALS/METHODS

Measurements were conducted during the period October 2014 – July 2015 at Silsoe, UK, a rural experimental facility used in wind engineering studies in the frame of the REFRESH project (Refresh: Remodelling Building Design Sustainability from a Human Centred Approach, www.refresh-project.org.uk). One metal cube represented a ventilated indoor space and a staggered array of 6 m high cubes, represented idealised buildings. The metal cube was equipped with 32 pressure taps and two Gill R3 sonic anemometers, whilst the flows around the metal cube and upstream were measured by five sonic anemometers operating at 10 Hz. Two sonics situated 3 m away of the cube (3.5 m above ground level) and two sonics 0.5 m away of the openings were measuring the flows around and inside the cube respectively. Background flows were measured by two sonics placed at 10 m and 6 m respectively on a 10 m meteorological mast 14 m away of the cube. Different ventilation modes were examined, namely single sided ventilation, cross ventilation and conditions when the cube was sealed. Cross ventilation was established with openings of area 0.4 m^2 and we focus on the period May - July 2015 when the array was removed. Three cases were selected and further studied in the following: 1. Approaching flow perpendicular to the openings on 2-6-2015 between 09:00 and 09:30 UTC 2. Approaching flow diagonal to the openings on 1-6-2015 between 23:00 and 24:00 UTC and 3. Approaching flow parallel to the openings on 4-6-2015 between 11:00 and 11:30 UTC.

Cross-flow ventilation configurations are compared with computational fluid dynamics simulations conducted in OpenFoam (v2.3.1 OpenCFD Ltd) using the transient k-ω sheer stress transition scale adaptive simulation turbulence model, which is a hybrid large eddy simulation model on a fine unstructured hexahedral mesh. A domain was modelled with approximately three building heights upstream and five downstream. The atmospheric boundary layer was recreated at the inlet and the vortex method was used to induce fluctuations (King et al., 2017).

3 RESULTS AND DISCUSSION

In Figure 1a OpenFoam's snapshots of normalised velocity magnitude contours for background flows perpendicular to the openings are presented (King et al., 20017). A jet can be seen indoors, and the two main features of the plane jet can be observed i.e. downwind the jet decays and spreads (Pope,2000).

The flow patterns and turbulence intensities as measured by the sonics around and inside the cube are presented in Figure 1b. Turbulence is higher close to and inside the cube. A flow reversal is observed at the lee side of the building, associated with higher turbulence. The jet predicted by the model is also apparent.

When the flow approaches the cube at 45° relative to the openings (Figure 2a), the entering flow has the characteristics of an impinging jet. It can be seen that part of the incoming flow flows along the sidewall before penetrating the cube, in agreement with the results found in the wind tunnel study of Ohba et al. (2011). The general characteristics of the incoming and exiting flows seen in the LES simulation are confirmed from the sonic measurements (Figure 2b). The sonic at the back of the cube lies within the wake and Figure 2b indicates enhanced turbulence, related with unsteadiness and vortices that develop at the wake of the cube. Turbulent intensities are higher into the cube and at the back of the building.

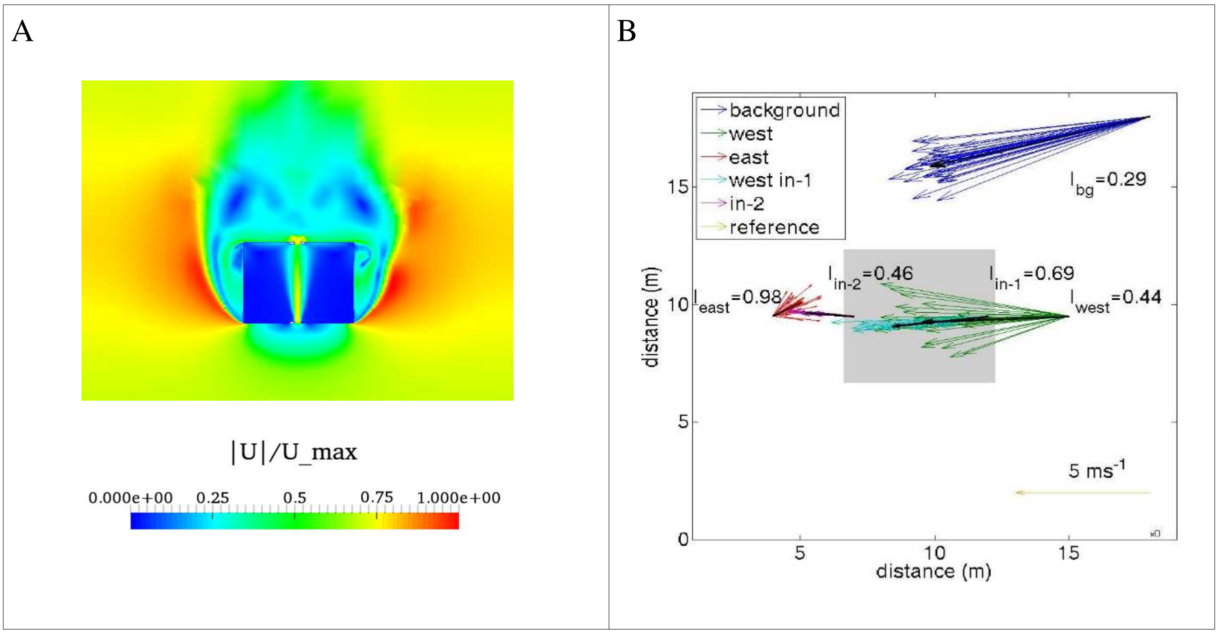

Figure 1. Normalised instantaneous velocity magnitude ($|u|/u_{ref}$) on a horizontal plane at window height 3.5m for flow perpendicular to the opening (King et al., 2017. Note that the flow enters the domain from the lower side of the picture (a). Flow conditions under perpendicular background flow (wind directions 90^o) at 2-6-2015, 09:00-09:30 UTC. Sonic anemometer data are shown as 1-minute mean wind vectors and half hourly mean vectors (black lines). Turbulence intensities are also shown for every anemometer (b).

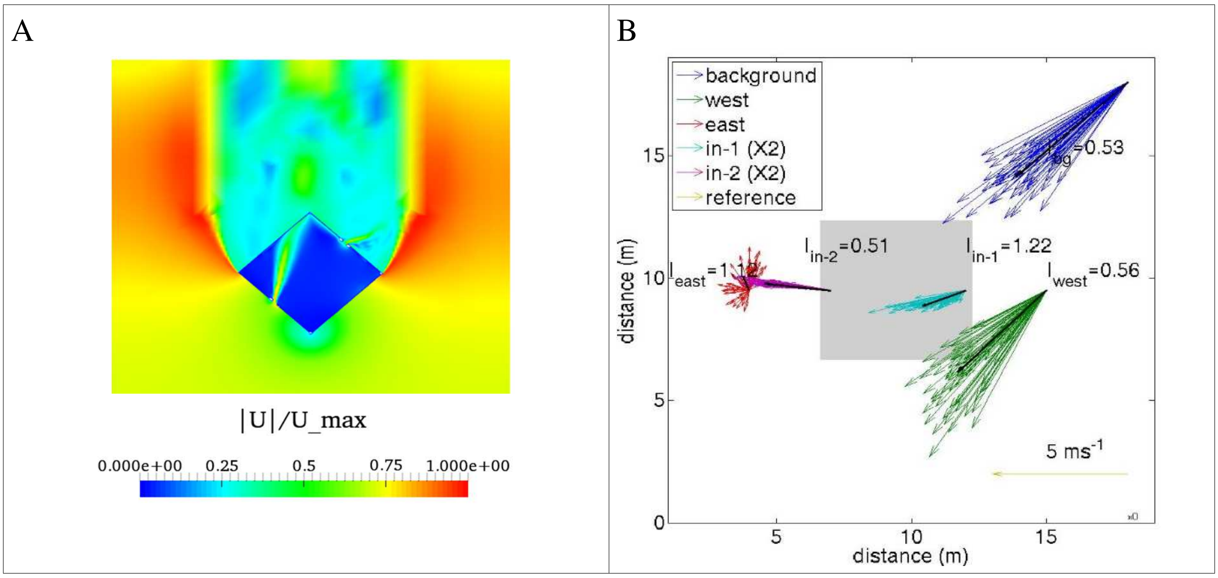

Figure 2. Normalised instantaneous velocity magnitude ($|u|/u_{ref}$) on a horizontal plane at window height 3.5m for wind directions 45^o (King et al., 2017- a). Flow conditions under background flow at wind directions 45^o at 1-6-2015, 23:00-24:00 UTC. Sonic anemometer data are shown as 1-minute mean wind vectors. Turbulence intensities are also shown for every anemometer (b).

Under parallel background flow the two openings are in the wake of the cube (Figure 3a). It is expected therefore that in this case unsteady phenomena will be dominant. Looking at the 1-minute vectors measured by the sonics it is apparent that the flow is very weak and unsteady with a pulsating mode at both openings. Mean half hourly vectors show that flow exits the cube at both openings. The mean half hourly vectors reveal indoor flows similar at both openings with the flow obtained from the model. It is worth noting that the high turbulence levels indoor indicate the predominance of the unsteadiness.

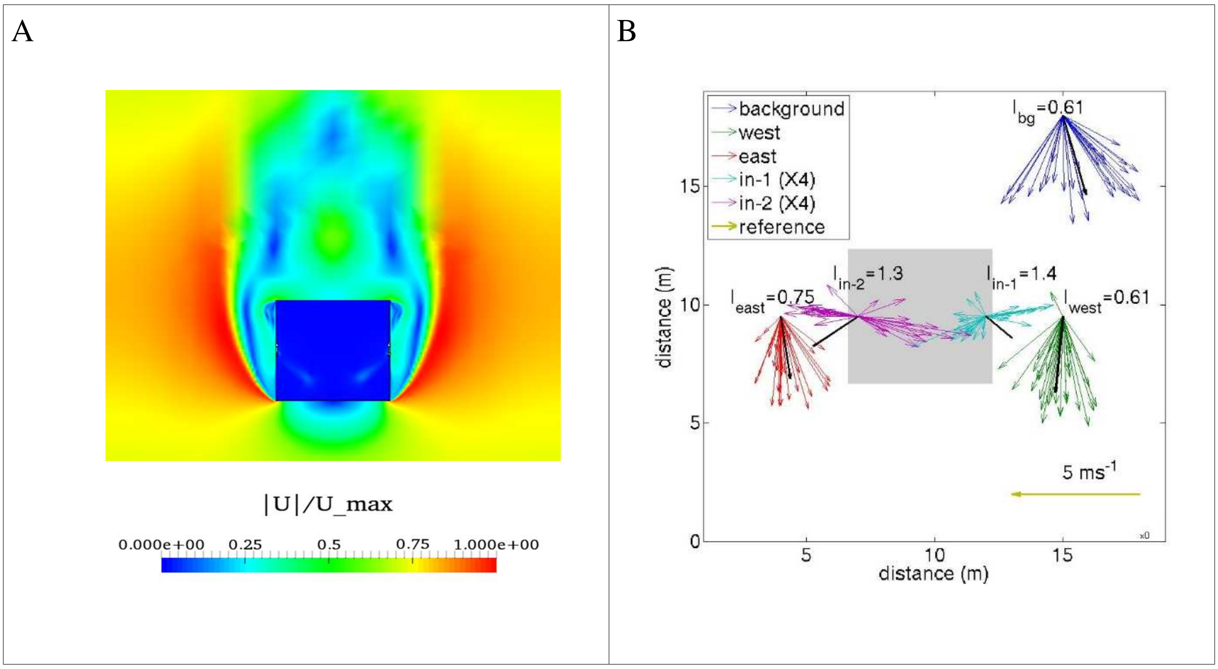

Figure 3. Normalised instantaneous velocity magnitude ($|u|/u_{ref}$) on a horizontal plane at window height 3.5m for parallel flow (wind directions 0^o King et al., 2017 - a). Flow conditions under parallel background flow at 4-6-2015, 11:00-11:30 UTC. Sonic anemometer data are shown as 1-minute mean wind vectors. Turbulence intensities are also shown for every anemometer (b).

The statistical distribution of the instantaneous wind directions measured with the sonics indoors when the flow is perpendicular to the openings (Figure 4a, b) clearly show that close to the openings the indoor flow mainly depends on the dominant impinging outdoor wind direction. Different patterns are observed for the indoor small-scale flows under parallel flow (Figure 4e, f). Wind direction distributions at the east-ward opening show a small-scale pulsating pattern changing between entering and exiting the cube (Figure 4f). On the other hand at the west-ward opening the dominant pattern implies that at the small scale the flow mainly exits the cube (Figure 4e), consistent with the vector analysis of Figure 4b. Observed discrepancies between the small scale and mean 1-min patterns need further examination. For the diagonal case (Figure 3c,d) a very broad range of the wind direction distributions centered at ~ 208^o is observed for the entering flow, indicating some contribution from directions other than the impinging diagonal flow. The very narrow range observed at Figure 3d points to the alignment of the exiting flow with the geometry of the opening.

Figure 5 shows spectral analysis of the wind speed vector measured away, around and inside the cube. The spectrum measured outside the west-ward opening of the cube show that a distinct clear maximum can be also observed at ~0.005 Hz, associated with relatively slow time scales ~200 sec. At the back of the building, a spectral peak at large scales ~10^{-1} (associated time scale ~10sec) apparently associated with a reversal of the flow observed there. Inside the cube high spectral energy is evident, higher for the entering and lower for the exiting flow, onsistent with the turbulence Intensities presented at Figure 3b. The intense maximum at 0.005 Hz is also observed indoors, but there is also increased spectral energy at higher frequencies for the entering flow.

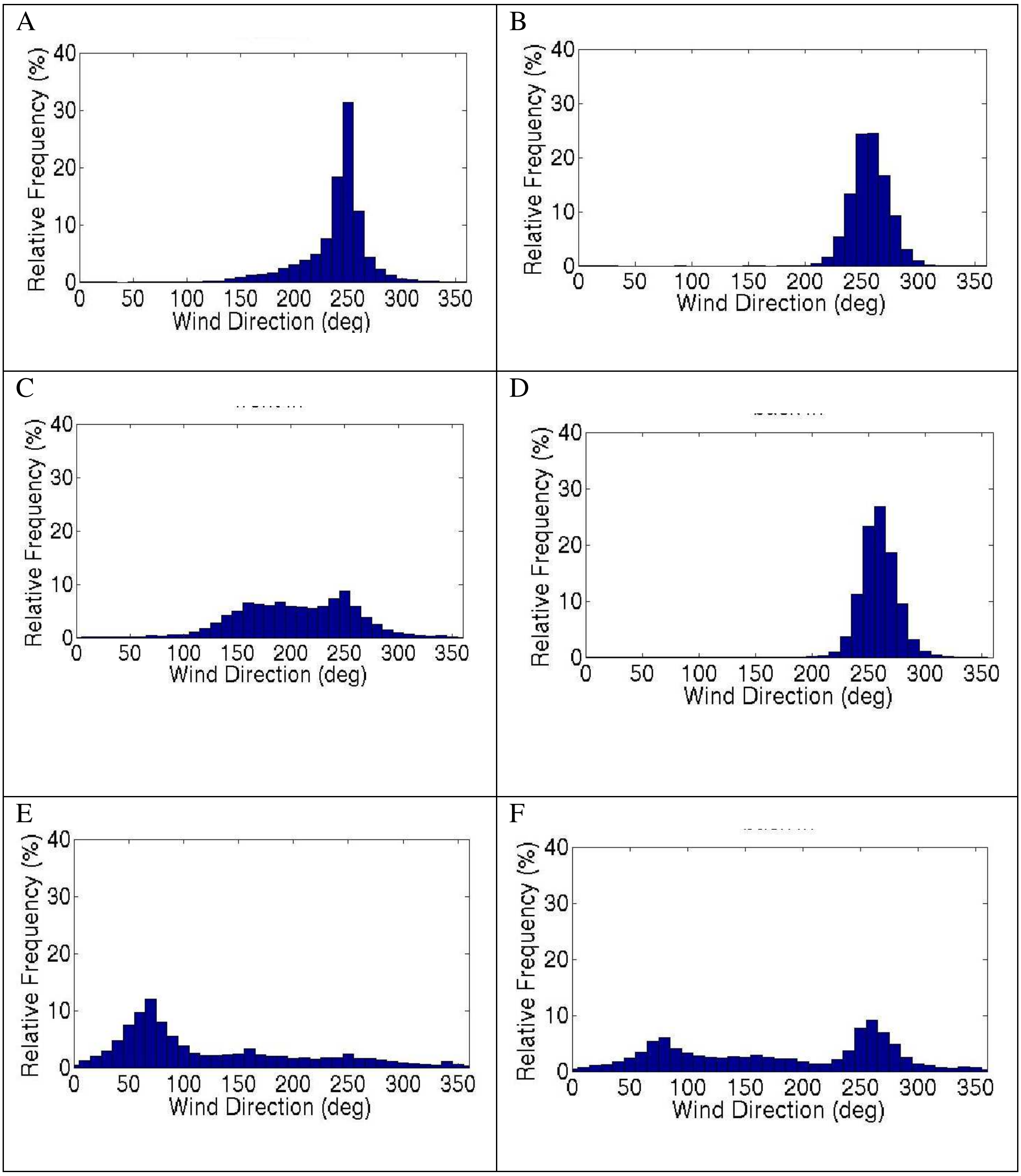

Figure 4. Statistical distributions of the instantaneous wind directions measured inside the cubes at the west-ward (a, c, e) and east-ward (b, d, f) openings (positions in-1 and in-2 respectively, notation of the sonic is the same as in Figure 2a) for flow perpendicular (a,b) diagonal (c,d) and parallel (e,f) to the openings.

Under parallel flow (Figure 5C) enhanced spectral energy closer to and inside the cube is observed. Increased spectral energy is observed indoors at low and high frequencies, and therefore indoor spectra are more flattened and the inertial subrange which can be seen at the outdoor spectra is not observable indoors. When the flow impinges on the cube at 45^{o}, the spectra indoors look similar to the spectra measured under perpendicular flow, with enhanced spectral energy experienced at the west-ward sonic.

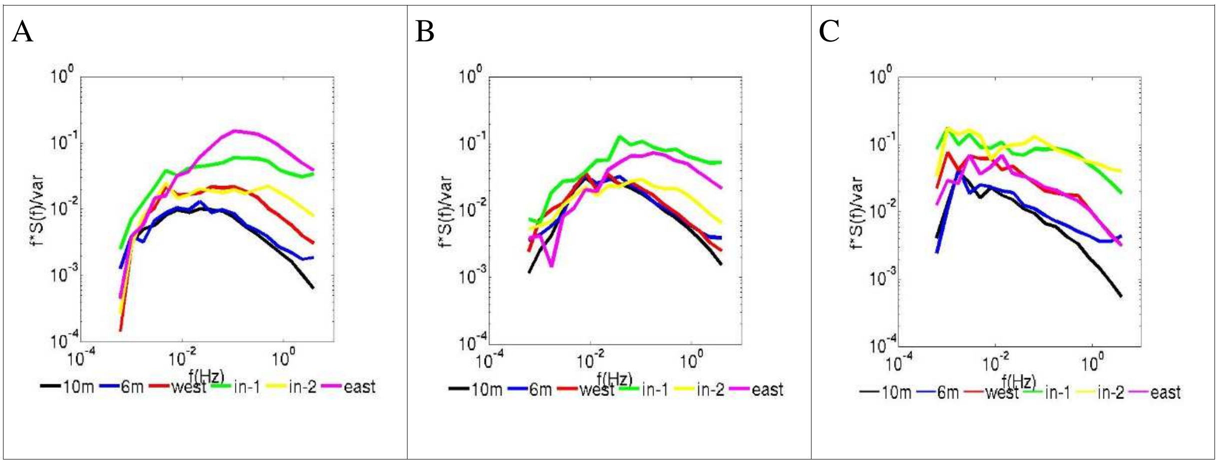

Figure 5. Frequency spectra of the wind speed under perpendicular (a) diagonal (b) and parallel (c) flow measured on 2-6-2015, 09:00-10:00 UTC, 1/6/2015 23:00 – 24:00 UTC and 4-6-2015, 11:00-12:00 UTC respectively.

5 CONCLUSIONS

In this study, results obtained at the Silsoe experimental cube during a 10 month field campaign are reported, focusing on three case studies when the flow was perpendicular, diagonal and parallel to the openings of a cube under cross ventilation scenario. CFD simulations facilitated the understanding of the flow field around and inside the cube and were confirmed by the experimental results. Spectral analysis highlighted the significance of the small scale fluctuations indoors. Our results reveal the dependence of the fine structure of the indoor flows from the wind direction of the approaching flow under cross ventilation scenarios.

6 ACKNOWLEDGEMENT

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7 REFERENCES

Hu C.-H., Ohba M., , Yoshie R., (2008). CFD modelling of unsteady cross ventilation flows using LES. *Journal of Wind Engineering and Industrial Aerodynamics*, 96 (10-11), 1692-1706.

King M.-F., Gough H.L., Halios C.H., Barlow J.F., Robertson A., Hoxey R. and NoakesC.J. 2007. Investigating the influence of neighbouring structures on natural ventilation potential of a full-scale cubical building using CFD. *Under preparation.*

Ohba M., Irie K. and Kurabuchi T., 2001. Study on airflow characteristics inside and outside a cross-ventilation model, and ventilation flow rates using wind tunnel experiments. *Journal of Wind Engineering and Industrial Aerodynamics,* 89, 1513–1524.

Tominaga Y. and Blocken B., 2015. Wind tunnel experiments on cross-ventilation flow of a generic building with contaminant dispersion in unsheltered and sheltered conditions. *Building and Environment,* 92, 452-461.

Pope S., 2000. Turbulent Flows. Cambridge University Press.