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EXPERIMENTAL STUDY OF FLOW AND DISPERSION IN REGULAR ARRAYS OF RECTANGULAR BUILDINGS

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Abstract: Wind tunnel experiments on regular arrays of buildings were conducted in the environmental wind tunnel in the EnFlo laboratory at the University of Surrey. The results have shown that the canopy has obstacles sufficiently long compared with their heights to yield extensive flow channelling along streets. This supports the suggestion that the streets are long enough to be representative for street network modelling approaches. The wind tunnel data, along with LES and DNS simulations, are being used to understand the behaviour of flow and dispersion within regular array with a more realistic geometry than the usual cuboids. This integrated methodology will help developing parametrisations for improved street network dispersion models.

Key words: *Wind tunnel, building arrays, urban canopy, pollutant dispersion.*

INTRODUCTION

The accidental or deliberate release of hazardous airborne materials in densely populated areas is a contemporary threat that poses new scientific and modelling challenges. The dispersion modelling community is faced with the task of providing first responders with models that allow for a fast but accurate prediction of plume pathways, enabling to make informed decisions for evacuation and sheltering procedures. DIPLOS (Dispersion of Localised Releases in a Street Network, http://www.diplos.org) is a collaborative project between institutions in the UK and France that aims to develop and improve dispersion parameterizations in emergency response tools like the street-network based dispersion model SIRANE (Soulhac et al., 2011). The work presented here concentrates on the EnFlo wind tunnel experiments.

METHODOLOGY

All experiments were conducted in the environmental wind tunnel in the EnFlo laboratory at the University of Surrey. This is an open-circuit tunnel with a working section that is 20 m long and 3.5 × 1.5 m in cross-section. The model canopy comprised a square array of 294 (14 × 21) h×2h×h rectangular blocks with height h = 70 mm, mounted on a turntable whose axis of rotation was 14 m downstream of the test-section entrance. The origin of the rectangular coordinate system was set at the turntable (and model) centre, with x in the streamwise direction and z upwards. Figure 1 shows the arrangement for the orientation defined as θ=0° - i.e. with the oncoming flow perpendicular to the longer sides of the array obstacles. The array was curtailed at its corners in order to fit the turntable and thus allow ease of rotation to any desired angle. Note that the boundary layer upstream of the array was initiated by a set of five Irwin spires, 1.26 m in height, and developed over surface roughness comprising a staggered array of relatively sparsely distributed thin plates 80 mm × 20 mm (width and height, respectively), with spacing 240 mm in both x and y. The boundary layer at the start of the urban array (x = −2 m) was thus about 14h in depth and was found to be reasonably homogeneous across the span with no systematic spanwise variations. Measured velocities were within ±5% of the spanwise mean. An internal boundary layer grew from the leading edge of the array, but conditions within the canopy, assessed for example by measurements along a spanwise street for the θ=0° orientation, were essentially independent (i.e. within the experimental uncertainty) of the particular street downwind of the fifth street from the start of the array. Two reference ultrasonic anemometers mounted downstream of the array in the tunnel exit ducts were used to ensure that all the experiments were undertaken at the same freestream velocity in the approach flow (2 ms^{-1}). The Reynolds number based on obstacle height and the velocity at that height in the upstream boundary layer was about 7400, or about 830 when based on the friction velocity u_τ (i.e. $Re_\tau = h\, u_\tau / \nu$, where ν is the kinematic viscosity). The boundary layer was thus well within the fully-rough-wall regime. Velocity and turbulence measurements were made using a two-component Dantec laser Doppler anemometer (LDA) system with a FibreFlow probe of outside diameter 27 mm and focal length 160 mm. This provided a measuring volume with a diameter of 0.074 mm and a length of 1.57 mm. Measurements in the local U-W plane within the street network (i.e. in planes aligned with the streets) were obtained by use of a small mirror set at 45° beneath a downward pointing probe. The flow was seeded with micron sized sugar particles at a sufficient level to attain data rates around 150 Hz. In general, data collection times were 2.5 min, selected to control the standard error in the results. This led to a typical standard error in U of 2%, in u^2 of 10% and in w^2 of 5%, and corresponds to an averaging time of about 200T , where T is defined as an eddy turnover time, $T = h/u_\tau$. Our confidence is based on use of this LDA system over a long period of time, with a range or orientations and geometries (with or without the mirror system). There were many instances of the same variables being measured in different ways, without (for example) probe blockage problems becoming apparent. However, a potential source of significant error in the measurements was due to positioning uncertainty relative to the local buildings and tunnel co-ordinates. For example, an orientation error of 0.1° in the array alignment to the wind-tunnel axis would result in a positioning error of about 2.5 mm relative to the buildings over a 1.5 m lateral traverse (i.e. in the y-direction), assuming the traverse itself to be perfectly aligned with the tunnel co-ordinates. There are inevitable imperfections in any wind tunnel and traverse installation and these had particular significance in this case because of the large volume over which results were required. In broad terms, the positional error in any horizontal plane was typically 2 mm. The implications obviously depend on the gradients of flow properties at any given location and resulting uncertainties were greatest in the thin shear layers downstream of the block surfaces (i.e. the side-walls and roof). The consequences of small errors in height relative to the local building roof level were obvious in initial experiments. This particular issue was resolved by use of a small ultrasonic height gauge attached to the traversing arm – in this way local height uncertainties (i.e. relative to the adjacent block) were reduced to about ±0.5 mm.

Figure 1. Looking upstream in the wind tunnel. The array is in the $\theta = 0°$ orientation

Further practical issues directly affecting the flow were the accuracy of rotation of the array and its alignment relative to the approach flow. The 0° orientation proved by far the most demanding in these respects as any, albeit small, departure from the ideal set-up generated a small cross-flow in the street network. Dispersion measurements would then show a plume axis that drifted to one side, as indeed was observed in preliminary experiments that became the motivation for technique and hardware improvements. Ultimately, these resulted in plume-axis drift that was less than 1°; it is hard to see that anything substantially better can be achieved. Finally, it is worth noting that the 45° array orientation case was far less sensitive to these matters, or rather that any consequent effects were far less obvious. Tracer concentration measurements were performed by releasing a neutrally buoyant gas ‘tracer’ into the flow and measuring its concentration using air sampling at selected points downstream. The tracer used was a gas mixture of propane in air and the emission was released from a round source with a 20 mm internal diameter. The instrument used for concentration measurements was a Cambustion fast flame ionisation detector (FFID), a fast response instrument that is capable of measuring hydrocarbon concentration fluctuations with a frequency response of 200 Hz. Scalar fluxes were measured using the LDA and FFID at the same time on a common measurement volume. This setup was originally described by Carpentieri et al. (2012) and is capable of measuring the turbulent part of the flux along with the mean part at locations within the urban model.

FLOW AND CONCENTRATION MEASUREMENTS

The major focus within the DIPLOS project is the canopy region itself (i.e. flow, turbulence and dispersion in and just above the $z \leq h$ region) but it is of interest first to consider the flows above the canopy and for various wind directions. A drag increase was observed for the oblique wind directions (especially 15° and 30°), where the frontal area density of the model is highest and, more importantly no long streets aligned with the prevailing wind direction are present. Further interesting insights on the flow in and above the canopy are reported by Castro et al. (2017), using these wind tunnel experiments in combination with LES and DNS simulations.

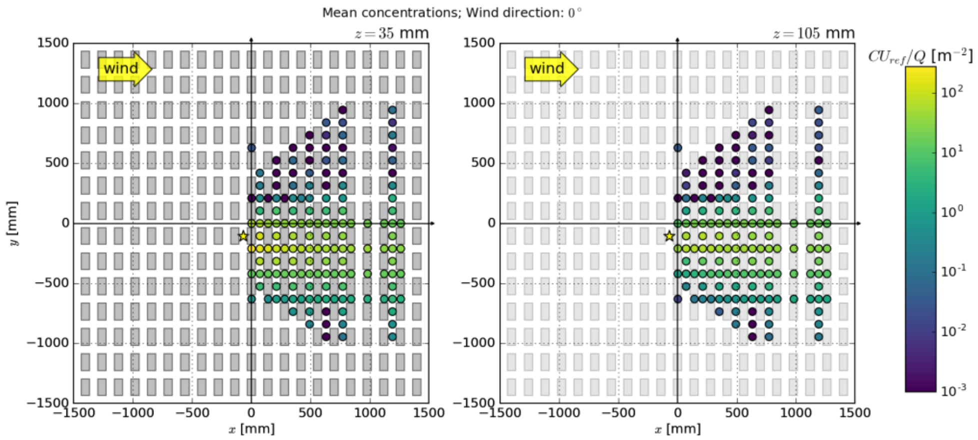

Figure 2. Non dimensional concentrations within (left) and above (right) the canopy for the 0° case

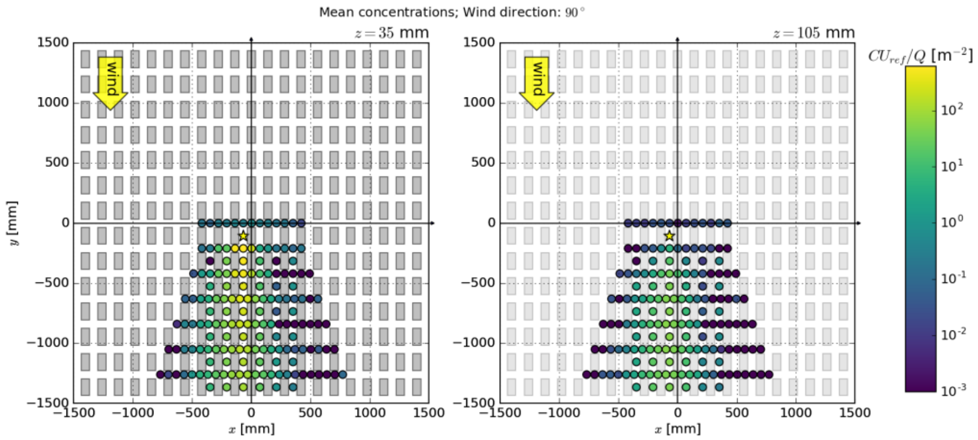

Figure 3. Non dimensional concentrations within (left) and above (right) the canopy for the 90° case

Concentration maps within and above the canopy (z/h = 0.5 and 1.5, respectively) are presented in Figures 2-4 for three wind directions: 0, 90 and 45°. The strong channelling effect is already visible by comparing Figure 2 with Figure 3. The plume in the 0° case is considerably wider than the plume in the 90° because of the streets orientation, deviating already from the classic cube array. This phenomenon is further evidenced in Figure 4 where, despite a 45° model orientation, we can observe a plume centre line (defined as the line of the maximum spanwise concentration value) within the canopy almost aligned with the long streets and the y axis. Of course the channelling effect is not as strong above the canopy, but a significant deviation from 45° can be seen nevertheless, especially close to the source location.

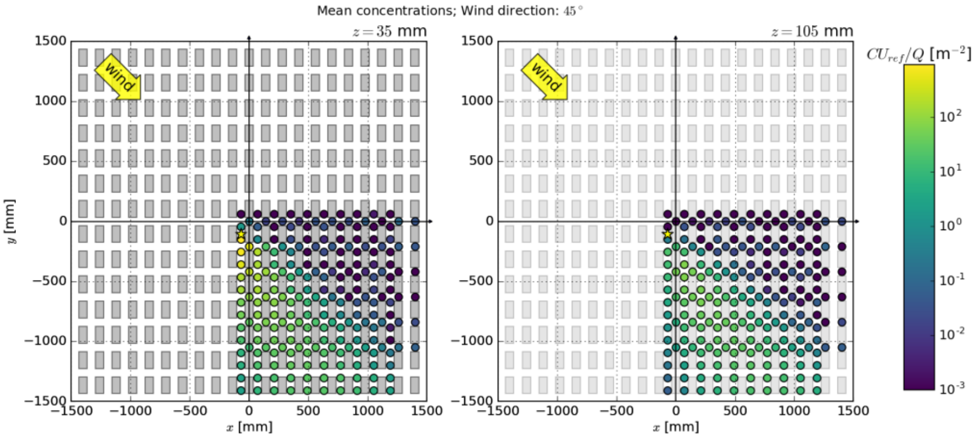

Figure 4. Non dimensional concentrations within (left) and above (right) the canopy for the 45° case

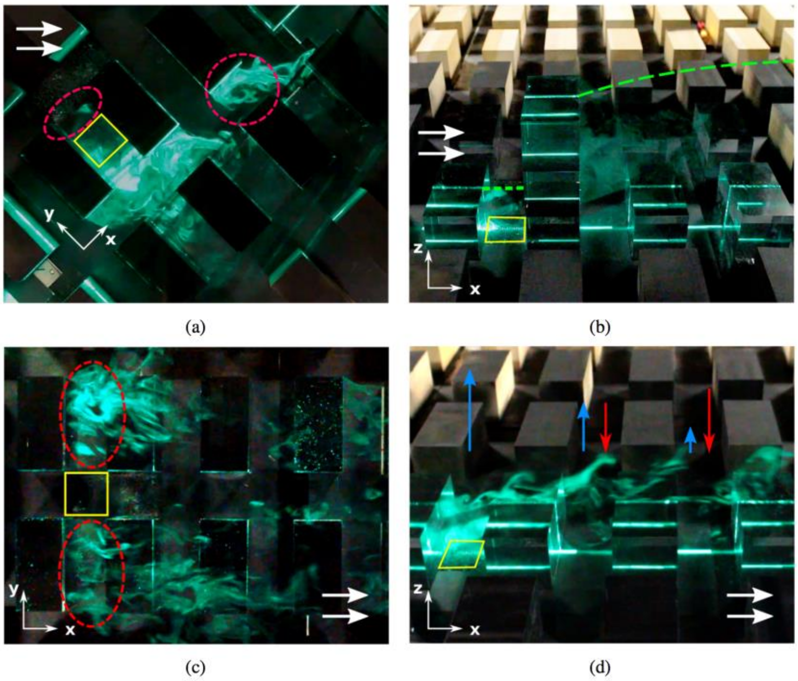

Figure 5. Wind-tunnel flow visualisation within a uniform array of cuboidal buildings. White arrows show the approach flow wind direction, squares indicate the ground-level smoke-release area

Other interesting characteristics of the dispersion behaviour can be better appreciated by looking at some flow visualisation experiments: smoke was released upstream of the area of interest and the flow pattern illuminated by a laser sheet to highlight a particular slice of the flow. Some interesting features, presented as stills taken from the videos, are shown in Figure 5.

Figure 5(a) shows wake-source formation and upstream transport in a horizontal cross-section (x–y) at z/h = 0.5. Wake sources modify the source emission scenario, introduce additional local retention time scales that affect local exposure levels to pollutants in the near-field of the primary source and influence dispersion pathways. This effect is particularly evident in Figure 5(b), where a taller (3h) building has been added to the array, showing in the vertical cross-section (x-z) a chimney effect on the leeward side of the tall building. These wake sources, for example, can enhance initial detrainment of material out of the urban canopy as shown in Figure 5(c), where two large detrainment areas in a horizontal cross-section (x-y) just above roof level (z/h = 1.07) are shown. Some of the material detrained above the buildings can be re-entrained back into the canopy after a few building blocks as shown in Figure 5(d), where the vertical (x–z) plane illustrates detrainment (upward blue arrows) and re-entrainment (downward red arrows) from/into street canyons. The length of the arrows indicates the relative importance of either effect with distance from the source.

EFFECT OF AN ISOLATED TALL BUILDING

In modern cities one can often find buildings which surmount the surrounding canopy. These tall buildings can be isolated or form a group, typically in modern city centres. Heist et al. (2009) examined experimentally and numerically the flow around an isolated building in a regular neighbourhood of buildings forming streets and closed courtyards. They noted large velocities in the spanwise direction which were caused by the presence of the tall building and vertical velocities downwind of the tall building reaching 25% of the freestream wind velocity. Brixey et al. (2009) used the same building configuration as Heist et al. (2009) for wind-tunnel and numerical simulations of scalar dispersion from line sources. They found that the vertical dispersion and the vertical extent of the plume in the wake of the tall building is greatly enhanced. The spanwise flow towards the tower also increased the width of plumes from sources further away from the tall building laterally. This is the reason why, as shown in Figure 5(b), some experiments were carried out in a modified array configuration, with one of the building substituted with a taller version (2h or 3h). Tests were conducted in the 0° configuration and some preliminary results were analysed and reported by Fuka et al. (2017), along with extensive LES simulations.

CONCLUSION AND FURTHER WORK

Wind tunnel measurements of flow and concentrations in an urban-like array were performed in the framework of the DIPLOS project. Results are available for different wind directions, within and above the regular building canopy. The experimental database includes three components of mean velocity and turbulence, as well as concentrations, concentration fluctuations and concentration fluxes. The extensive array and the small scale of the model posed challenging problems for reaching the desired high accuracy needed to validate the numerical simulations. The wind tunnel data, along with LES and DNS simulations, are being used to understand the behaviour of flow and dispersion within regular array with a more realistic geometry than the usual cuboids. This integrated methodology will help developing parametrisations for improved street network dispersion models. When a tall building is placed into the regular array, the flow changes significantly. Larger vertical velocities allow significant advective vertical scalar fluxes. Scalar from ground level sources in front of the tall building is transported mainly sideways around the building. The experimental data-base also include experiments executed for short duration releases (“puffs”) and two-point concentration measurements used to quantify spatial correlations. These data are currently being analysed and results will be available in the near future.

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