Measuring a Pollutant Plume over a 3D printed City Model

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SUMMARY:
The modelling of urban air pollution requires an understanding of the turbulent processes involved. This projects aims to provide direct measurements of turbulent dispersion over urban terrain with a high-fidelity experimental study. An investigation into scalar dispersion over a 3D-printed model of the City of Southampton, which is a medium-size coastal city in the south of England, was carried out. This 1000:1 scale model was created to represent 1 km^2 of Southampton's city centre experiencing an onshore south-south-westerly wind. Experimentally measuring turbulent scalar fluxes is challenging as it requires both concentration and velocity measurements in the same place, and at the same time. Particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF) were used to measure full fields of these turbulent scalar fluxes. Measurements were carried out in streamwise-vertical and wall-parallel planes to create a detailed map of concentration and velocity data for a case in which a plume from an offshore point source was introduced upstream of this model.

Keywords: Urban wind climate, Building aerodynamics, Pollutant dispersion

1. INTRODUCTION

The risk to public health posed by air pollution is significant (Dziubanek et al., 2017), and living in an urban environment is a risk factor that increases exposure. The world's population is still growing and is also gravitating more towards these urban environments. This means that a larger proportion of this population will be directly exposed to urban air pollution (United Nations Department of Economic and Social Affairs, 2018). Due to this, there is an increasing need for more accurate predictions of urban air pollution. Computational models for urban air flow and air pollution are popular because of their speed and convenience. However, realistic data remains crucial for the development and calibration of the mathematical models required for simulations. Acquiring realistic data for this purpose can only be done through either sensor data in real world scenarios, or through scaled experiments in wind or water tunnels.

Experimentally measuring pollutant dispersion can be done through several methods, both intrusive and non-intrusive. In wind tunnels, the most common methods are to use a fast flame ionisation detector (FFID) (Carpentieri et al., 2012) or photo-ionisation detector (PID) (Talluru et al., 2018). These measurement techniques acquire concentration data at a single location at the head of a probe. Doing experiments in a water flume allows for the use of the planar laser induced fluorescence (PLIF) technique. This technique is a non-intrusive technique that quantitatively measures the fluorescence response of a dye in planar slices and calibrates this response to known dye concentration values.

There is a very limited amount of existing experimental data that includes both concentration and velocity measurements over realistic city models. The majority of existing experimental studies use either idealized urban roughness or fully randomized roughness (Fuka et al., 2018). While idealized roughness can prove somewhat representative in highly ordered cities, such as Barcelona; most cities are built in a pseudo random form with neighbourhood scale order. Out of the existing aerodynamic studies into realistic city models, most are carried out in wind tunnels, in which acquiring full fields of concentration data is much more difficult than it is in water (Lim et al., 2022; Nironi et al., 2015). We aim to fill this gap by collecting full fields of concentration and velocity data above a realistic city, in order to characterise the spatial distribution of pollutant dispersive fluxes.

2. METHODOLOGY

Experimental measurements were made in the University of Southampton's Recirculating Water Tunnel. The city model is submerged in the water tunnel during the experimental campaign. This model was created to represent 1 km^2 of Southampton's city centre and the full to model scale is 1000:1. In this model, both terrain elevation and building height are represented, and the flow direction corresponds to the predominant wind direction of an onshore south-south-westerly.

The incoming flow was conditioned to have a boundary layer depth of approximately 300 mm and a free-stream flow velocity of 0.6 m/s. Using the maximum building height of 45 mm as the length-scale, the Reynolds number was 27,000. Using the mean building height across the central section of the model of 20 mm gives a Reynolds number of 12,000. All data in this paper has been made dimensionless using a characteristic building height of $H = 20$ mm. In order to experimentally simulate an onshore pollutant plume from the docks, a scalar source was introduced 50 mm upstream of the model. The scalar used was Rhodamine 6G fluorescent dye, which was illuminated using a Nd-YAG laser with an emission wavelength of 532 nm. This scalar was introduced with a low enough velocity that it did not measurably affect the velocity field, and was introduced at ground level through the use of a non-intrusive tube underneath the experimental setup.

3. RESULTS

Figure 1 presents a map of the upper limit of the plume as defined as the isocontour of 0.002 percent of the source concentration. This plot was generated through the use of the seven streamwise-vertical slices. The isocontour heights were then extrapolated and interpolated in the cross-stream direction between the seven points assuming a Gaussian. This avoided any assumption of the streamwise development but did result in cross-stream bands in the image. Using the peaks of the plume height, it was calculated that the plume deflects from the mean flow direction by 4.2 degrees. This deflection can be attributed to the influence of the mean street canyon orientation being aligned towards the left side of the model.

The vertical advective and turbulent fluxes are displayed in figures 2 and 3 respectively. We focus on the vertical fluxes as these are the most relevant for weather and pollution modelling. This data is taken from the centre plane of the flow. The turbulent flux field has a constant upwards direction at nearly all points in the flow, as is shown by the predominant red colour visible in figure 3. The sign of the advective flux field varies across the city model. As the scalar field has a constant

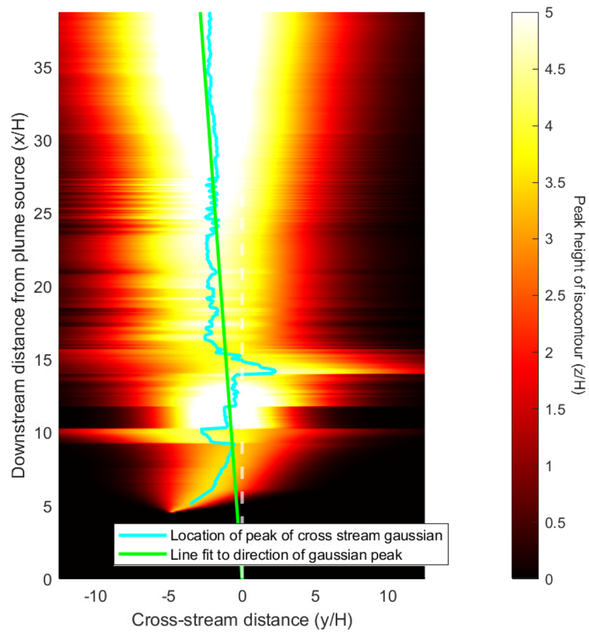

Figure 1. A map of the upper limit of the plume as defined as the isocontour of 0.002 percent of the source concentration. The displacement of the centre of the mean plume is shown in blue. The best-fit line in green shows the centre follows a mean direction of 4.2 degrees to the left of the mean flow direction.

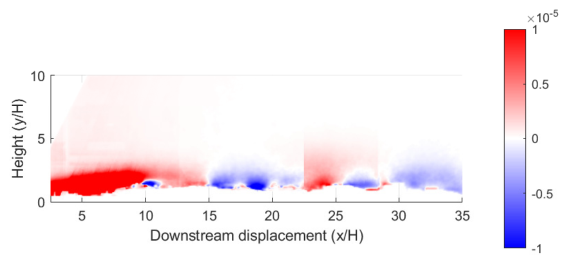

Figure 2. The vertical advective scalar flux ($\frac{CV}{C_s U_\infty}$) measured along the centreline of the city model.

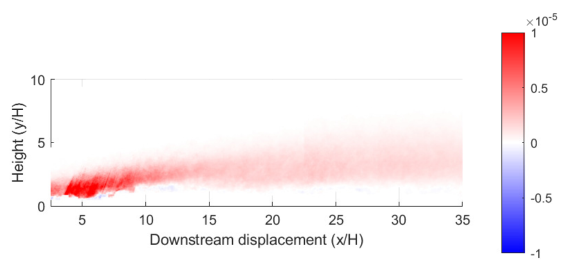

Figure 3. The vertical turbulent scalar flux ($\frac{\overline{c'v'}}{C_s U_\infty}$) measured along the centreline of the city model.

positive sign, this is reflecting the varying sign of the vertical velocity component. This is most visible at $x/H = 22.5$ in figure 2 where the sign change happens close to a camera stitch line. It is noteworthy that both components of vertical transport are of similar average magnitudes.

4. CONCLUSION

This study has shown that across most areas of an urban flow, the magnitude of the vertical turbulent flux is very similar to the magnitude of the vertical advective flux. The vertical turbulent and advective fluxes also share no correlation in sign or strength, making the prediction of one using the other impossible. This demonstrates the difficulty in modelling the turbulent fluxes accurately, while also showing the importance of this modelling to simulating accurate results of scalar dispersion. This study is one of very few to measure full fields of simultaneous concentration and velocity data over a realistic city model.

The mean concentration data and plume shape indicate that the buildings are strongly influencing the shape of the plume away from what you would expect over regular or random roughness. Instead, the plume still seems mostly Gaussian, but is diverted from its expected direction. The current hypothesis is that the plume is being influenced to follow the mean street canyon direction of the large street canyons.

The conclusion that can be drawn from these measurements is that in most areas the city is acting as uniform roughness increasing the general turbulent mixing. The key exceptions to this rule are the neighbourhood scale order that is created due to street canyon alignment and the few particularly large buildings.

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