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MIXING AND TRANSPORT WITHIN REAL STREET INTERSECTIONS: THE CASE OF MARYLEBONE STREET, LONDON (UK)

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Abstract: In recent years, airflow dynamics and pollutant dispersion within street canyons and arrays of buildings have been intensively studied, both in idealized geometries and in real cases. However, a full comprehension of how turbulent mixing and mean flow transport control dispersion of pollutants through network of streets has been far less achieved. This paper adopts a computational fluid dynamics (CFD) approach to investigate airflow dynamics and particles dispersion in real network of streets i.e. the neighborhood around Marylebone (London, UK) for which extensive data set are available. Particle dispersion within individual street canyons will be studied by means of the publicly available CFD code OpenFOAM, using a large-eddy-simulations (LES) approach to model turbulence within the canyon and an Eulerian method to model particle dispersion. We consider mixing and transport in long streets, such as Marylebone Road, street intersections and the network of streets connected by this intersection. The evaluation of mean scalar flux allows to easily evaluate street ventilation at several positions of the street canyon by using the concentration field calculated from LES directly.

Key words: *LES model, OpenFOAM, mixing and transport, neighbourhood-scale dispersion.*

INTRODUCTION

The majority of urban dispersion studies using computational fluid dynamics (CFD) has been using Reynolds-averaged Navier-Stokes (RANS) models and therefore focusing on time-averaged variables. However, near the roads, the existence of high spatial and temporal variability of pollutants has been documented by measurements from several urban field experiments. A typical case is pollutant concentration within a street canyon, where emissions from vehicles are not easily ventilated out of the canyon so that pollutant concentration is high and has significant spatial gradients. RANS method has the disadvantage of being unable to predict the unsteadiness and intermittency of flow and dispersion. In addition, most RANS models assume gradient transport, which may not be the case for pollutant removal/re-entry at the roof level of a street. Capturing small scale features may be important to assess people’s exposure in cities as well as to plan mitigation strategies. Recently, many studies, including field observations, wind tunnel experiments, and numerical simulations, have been carried out to investigate the effects of buildings morphology along the streets, wind conditions, and vehicle-induced turbulence on pollutant concentrations in a street canyon and more complex group of buildings or neighborhoods (see Di Sabatino et al. for a review). Dispersion of pollutants depends on the dynamics of the background flow (Belcher, 2005). There is persuasive evidence that local flow fields at a neighbourood scale are essentially unsteady with fluctuations that are several times the mean (Louka et al., 2000). Despite the use of RANS models it remains unclear whether or not dispersion can be adequately represented by models based on both mean flow and turbulence and the latter being parameterised as only diffusive. Hargreaves and Baker (1997) developed a model based on the dispersion of a series of pollutant-emissions from a number of individual vehicles moving along a street canyon. These puffs of pollutant are carried along the canyon by an assumed flow field. Such a model requires information about intermittent fluctuations. One powerful numerical tool that can provide such information is large-eddy simulation (LES). LES has typically been applied to atmospheric processes of the scale of the boundary layer (Shi and Yeo, 2016). For an urbanlike geometry made of cube arrays, Kanda (2006) conducted a series of LES simulations of the flow. Liu and Barth (2002) reported a careful LES study of street canyon flow and dispersion of pollutants from road emissions. Their results were compared with wind-tunnel experiments conducted by Meroney et al. (1996), and Pavageau and Schatzmann (1999). Liu et al. (2004, 2005) examined turbulent flow inside a street canyon with three aspect ratios and the exchange rate of pollutants at roof level. Salim et al. (2011) have reported about the superiority of LES dispersion simulations in street canyon of RANS models.

This study adopts an LES model based on a one-equation subgrid-scale (SGS) model. The model is applied to study the turbulent pollutant dispersion within a real urban geometry at a neighborhood scale. The source is located within Marylebone street in the inner-city area of central London (UK), a well-documented real field case for which both meterological and concentration measurement are available (Jeanjean, 2017). A recent work Profiles of spatial-and-temporal-mean scalar-flux-at-the-roof-level (SFRL) are obtained and related to the flow regimes within the street.

MODELLING SETUP

Description of the geometry

Marylebone is an affluent inner-city area of central London (UK), located within the City of Westminster. It is characterised by major streets on a grid pattern such as Marylebone Rd, one of the busiest roads of central London, with smaller alleys between the major streets. Marylebone Rd is characterised by a street canyon configuration with an aspect ratio (height H over width W) near unity (Nikolova et al., 2016). It is one of the most polluted sites in the UK, with an average NO_2 concentration of 94 g m^{-3} in 2014, according to the AURN measurements, located near University of Westminster. An overview of the study area is shown in Figure 1 (left panel).

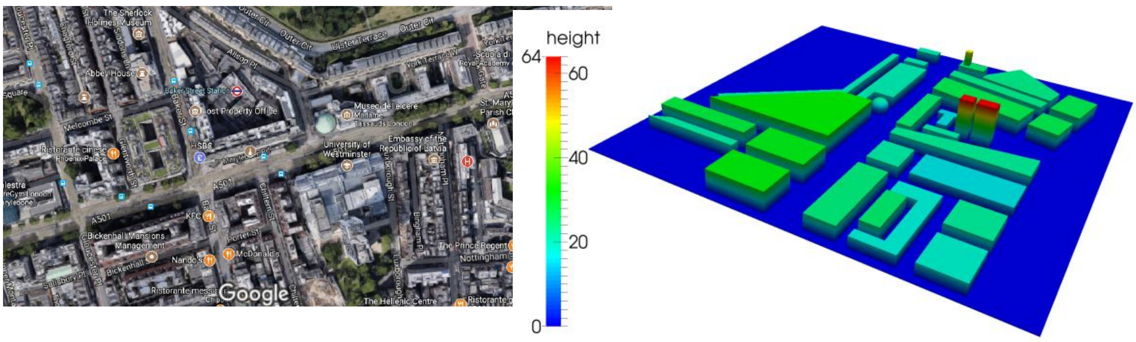

Figure 1. Overview of Marylebone Rd and surrounding area (left). Schematic of the area used for computation (right). The colour scheme indicates the building heights in meters. The image is taken from Municchi (2014).

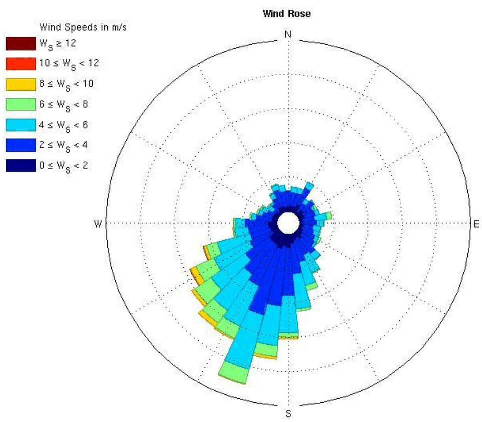

Figure 2. Typical wind rose for Marylebone Road using 2014 hourly data.

Wind data for the year 2014 were retrieved from the London City Airport weather station (EGLC, available at https://www.wunderground.com), every 30 min with a wind direction accuracy of 10°. The station is located around 15 km west of the monitoring site. In 2014, the recorded average wind speed was 4.3 m/s and the prevalent wind direction was South-West (Figure 2).

Numerical approach and grid

In direct numerical simulation (DNS) the Navier-Stokes equations are solved as such using fine spatial and time resolution. In LES, the resolution is coarser and Navier-Stokes equations (NS) are solved for the spatially filtered variables pressure and velocity, with additional subgrid scale (SGS) terms appearing as source terms in the equations. In this work we used OpenFOAM solver with LES extension. The LES equations take the form NS (u, p)=τ_{sgs}, where τ_{sgs} requires modeling. Here, we choose the one-equation eddy-viscosity SGS approach by Yoshizawa (1993) where an additional transport equation for the SGS turbulent kinetic energy is solved:

$$\frac{\partial k_{sgs}}{\partial t} + \frac{\partial}{\partial x_j}(u_j k_{sgs}) = \frac{\partial}{\partial x_j}\left[(\nu + \nu_{sgs})\frac{\partial k_{sgs}}{\partial x_j}\right] + P_{k_{sgs}} - C_\epsilon \frac{k_{sgs}^{3/2}}{\Delta} \tag{1}$$

where P_{ksgs} is the resolved rate of strain tensor and V is the volume of the computational cell. The filtered LES equations can then be closed by setting τ_{sgs}. The spatial discretization utilizes the second order accurate finite volume method. Basically, the one-equation SGS model allows to overcome the deficiency of local balance assumption between the SGS energy production and dissipation adopted in algebraic eddy viscosity models. Such a phenomenon may occur in high Reynolds number flows and/or in the cases of coarse grid resolution. Best practice guidelines were followed to build the computational domain (COST Action 732, 2005). Given that maximum reported height in the domain is a building height (H) of 63 m, the computational domain was built with its boundaries placed more than 15H away from the modelled area. The top of the computational domain was set to 505 m, which corresponds to 8H. The dimensions of outer domain gives an appropriate mesh size for the required flow detail and run time. The computational domain has been built using structured elements with a finer resolution close to the ground and the walls within the neighborhood scale. Several tests have been performed to verify grid size independence with increasing mesh numbers. The final number of the computational cells used is about 10 million cells. The smallest dimension of the elements, in the region near the heated walls, is 0.25 m in the direction normal to the wall and 0.5 m in the other directions. Figure 3 shows the computational domain (left) and some details of the wesh (right).

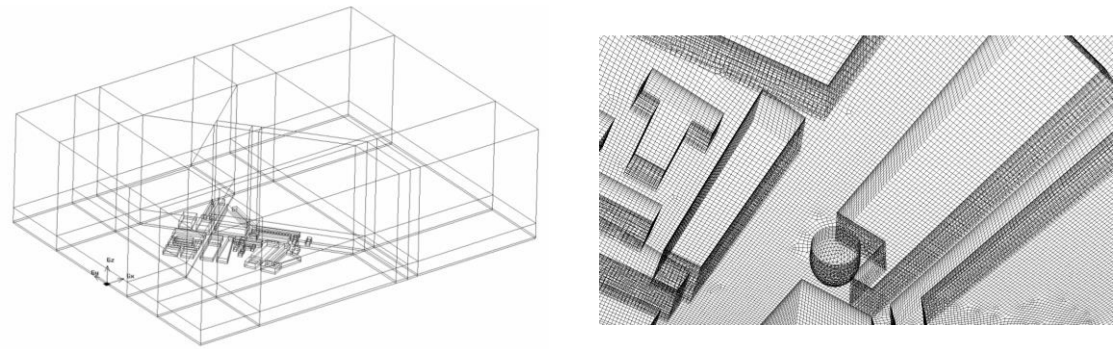

Figure 3. Computational domain (left) and some details of the structured mesh (right).

RESULTS

The turnover time of the primary circulation, tc, in the canyon is of the order of tc=(W+H)/U=20 s. The simulation is conducted from zero wind inside the canyon without emissions for 300 s, long enough for turbulent dynamics to be settled to a quasi-equilibrium state. Starting from this time (called t_0), the model runs with emissions (rate is denoted by q in units of g m^{-1} s^{-1}) inserted during the period [t_0, t_1=t_0+600 s].

It has been ensured that concentration fields and flux at the roof level have reached a quasi-equilibrium state for the second half of the period [t_0, t_1]. The results of the last 150 s, with a frequency of 200 Hz are analysed and presented here. Figure 4 depicts the instantaneous streamlines at the Gloucester road intersection (left) and at the AURN monitoring station location. The flow field is strongly affected by the geometry of the street, i.e. channelling in secondary streets or recirculation is observed near intersections.

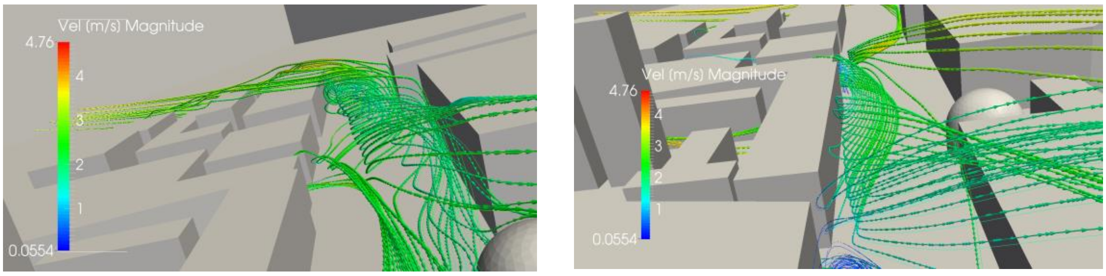

Figure 4. Instantaneous streamlines of the velocity field at the intersection (left) and in the middle of the canyon (right).

Mean concentration and second-moment resolved-scale concentration fluctuations have been calculated from LES results by averaging over the time, in the interval [t_0,t_1]. Carbon monoxide has been used as a tracer pollutant for all simulations using emissions rates estimated from the traffic in Marylebone Rd. The mean SFRL (M-SFRL) is the average of the mean concentration over the street surface at roof level. This flux includes both transport of scalar by mean wind and dispersion of scalar by resolved-scale turbulence, then it can be written as a concentration times a velocity. Here the concentration is taken to be the concentration difference between the surface and the ambient concentration, which is zero because no background has been included. The velocity then becomes the transfer velocity defined in Barlow and Belcher 2002. Figure 5 shows profiles of time-averaged dimensionless c/C_0 as a function of x and z, at the locations 1-7 along the street axis (right). The locations are shown by Figure 5 (left). The concentration scale used for normalization is $C_0=q/(U_{ref}\ H)$, where q is the line emission rate per unit length (in our case $q=0.03$ mg m^{-1} s^{-1}). Figure 5 shows that the lowest values of concentration c/C_0 are found on sections 1-2-4-7, i.e. near intersections.

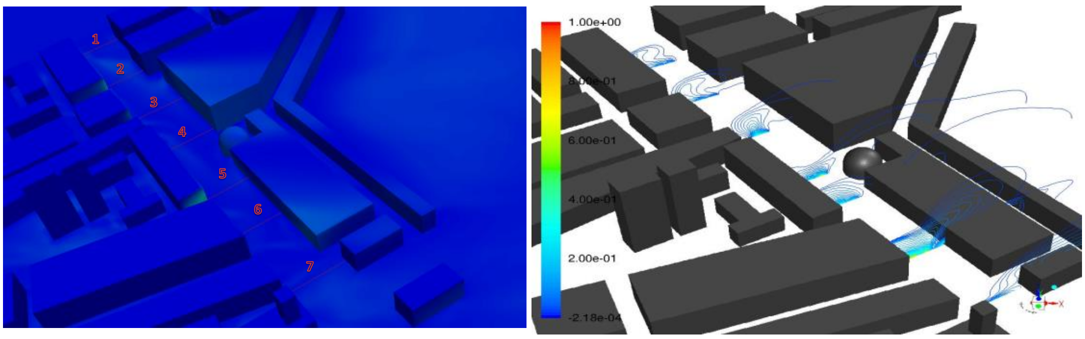

Figure 5. Time-averaged c/C_0 profiles along the street (right); specific locations within the canyon used to evaluate fluxes (left).

Table 1. Values of M-SFRL (normalised with (U_{ref} C_0)) at locations 1-7 of Figure 5.

	1	2	3	4	5	6	7
M- SFRL	0.001	0.001	0.004	0.003	0.004	0.004	0.002

Table 1 shows that near the intersections, lower values of M-SFRL than those within the canyon are obtained. Near the intersections is then necessary to introduce a new definition of mean scalar-flux, which considers the cross sections of the lateral streets. In fact, by evaluating the average of the mean concentration over the cross section of the lateral street surface at location 1, the M-SF is 0.003.

CONCLUSIONS

This study shows a LES model of the transport and dispersion of passive scalars in a real street canyon. The results of spatial distribution of mean concentration demonstrate the promising capability of LES to capture the main features of transport and dispersion processes in a real urban configuration. The LES results show that M-SFRL is very sensitive to the geometry of the buildings within the street, with a fixed approach flow direction. The lowest concentration in the street and the lowest scalar flux from the source has been obtained near the intersections. We observed spreading of pollution mostly to the transverse streets down the wind. Near the intersections, lower values of M-SFRL than those within the canyon are obtained. Near the intersections is then necessary to introduce a new definition of mean scalar-flux, which considers the cross sections of the lateral streets.

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