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MODELLING THE RECIRCULATION ZONE IN STREET CANYONS WITH DIFFERENT ASPECT RATIOS, USING CFD SIMULATION

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Abstract: Poor air quality in cities was indicated as the cause of seven million deaths, one out of eight globally, only in 2012. Urban streets are the epicentre of the problem, as high concentrations are frequently measured, caused mainly by the traffic and secondly by the general urban background pollution. The flow inside street canyons has some specific characteristics that tend to obstruct the removal of pollutants from the city level. The small scale models that are used to study pollution in streets have to consider about these flow patterns, which many times are referred with the collective term recirculation zone. Our main hypothesis is, that the flow regime in a street canyon governs the recirculation zone and consequently the dispersion. Thus, a quasi-universal expression for the recirculation zone could expand the applicability of these simple models in cases of higher complexity. To understand better the recirculation zone, CFD simulations are validated and used. We use vortex detection methods, namely vorticity, streamlines and the λ_2 and Q criteria, to visualize the vortex structures. The final results are rather inconclusive, although the combined use of the above methods certainly give some insights to the flow structure. In any case more exploratory analysis is necessary in order to validate the further develop the hypothesis of this work.

Key words: *street canyon, recirculation zone, air quality models, Large Eddy Simulation, vortex detection*

INTRODUCTION

Urban streets are a main concern for air quality in cities, as high concentrations are frequently measured, attributed mainly to traffic sources inside the street and secondly to the general urban background pollution. A simple, fast and economical way to study the air pollution is the use of the parameterized air quality models (AQMs), which calculate concentrations of pollutants, using empirical formulations. AQMs have to consider the complexity of the flow inside the streets, as the wind impacts on buildings and creates recirculating vortices, which drastically affect the dispersion of the pollutants inside and above the streets.

The simplest case of flow is the perpendicular, to the building face, wind direction that develops two main vortices, adjacent to the building and the ground (Hanna *et al.*, 1982). Depending on the height to width ratio of the street canyon (aspect ratio), the two vortices inside the canyon intertwine with each other, creating three flow regimes. They have been described (Oke, 1988) as: a) isolated roughness, when the two vortices do not interact, b) wake interference, when the wake behind the leeward building is disturbed by the recirculation created in front of the windward building and c) skimming flow, when the aspect ratio is equal to the unity and one main vortex is formed. Most street canyons are formed by buildings with unequal height and the flow regime for these cases differ significantly (Addepalli and Pardyjak, 2014). Another issue is the solar radiation, as heated facets have been presented to modify the flow and even favour ventilation (Allegrini *et al.*, 2013). Other aspects, such as the roof shape (Kastner-Klein *et al.*, 2004) and the existence of trees at the road sides (Gromke and Ruck, 2009), were indicated to lower the wind speed, reducing the ventilation. Finally, the non-perpendicular wind direction changes the entire flow regime, creating spiral flows (Balogun *et al.*, 2010), which transfer the pollution from one road segment to the other.

Current models haven't incorporated these characteristics yet and rely on empirical parameterizations extensively validated against experiments in real streets. One of the first models, the STREET-SR (Johnson *et al.*, 1973) implicitly defines one single vortex, that covers the width of the canyon and is controlled by the roof level wind velocity. The Canyon Plume Box Model (Yamartino and Wiegand, 1986) uses a single vortex sub-model, for the calculation of the dispersion parameters, the outgoing and incoming fluxes. The Operational Street Pollution Model (Berkowicz *et al.*, 1997), introduced an explicit definition for the recirculation zone as a trapeze, the dimensions of which depend on the upwind building height. On the other hand, SIRANE (Soulhac *et al.*, 2011) assumes that perpendicular wind is a rare situation and most of the time, street canyon segments will be a well-mixed volume with uniform pollutants' concentrations. The fact that these models incorporate the recirculation zone aspect is an advantage for flow regimes that have been defined, but an issue for the rest. On the other hand, the existence of a quasi-universal expression for the recirculation zone could expand the applicability of the typical street canyon models.

Provided that there is convection, the flow regime drives and rules the pollutant concentration levels. In this context, we aim to examine the hypothesis that the recirculation zone can be defined as function of the flow field rather than the geometry. For this reason and to understand better the structure of the recirculation zone, we employ a series of vortex detection methods in various street canyon geometries. These methods analyze the velocity gradient tensor ∇u, giving information on the existence of coherent structures. CFD simulations are used to obtain the flow field and apply the detection methods. The next paragraphs discuss the CFD setup and validation, the vortex detection criteria theory and our preliminary results.

METHODOLOGY

Configuration setup

Computational Fluid Dynamics (CFD) simulations were carried out using the open-source CFD toolbox OpenFOAM v2.3.1. The used CFD method is the Large Eddy Simulation (LES), the advantage of which is the transient numerical solution of the Navier-Stokes equations, allowing the user to observe the real-time advance of the phenomena. LES use the filtered Navier-Stokes equations, which practically means that the vortices larger than the mesh cells are resolved and the small scale turbulence is modelled. The continuity and momentum equations for incompressible flow are solved by the PISO solver (Issa, 1986). The standard Smagorinsky model (Smagorinsky, 1963) is used for the subgrid turbulence. The model's constant C_s is set to 0.1 and the van Driest dumping function is applied for the cells along the wall boundaries, as the common suggestions from the papers in this field.

The setup of our simulations is a modified version of the strategy, employed with success initially by (Li, 2008) and later by more researchers such as (Bright *et al.*, 2013). According to the best practices in LES (Franke and Baklanov, 2007), the boundary at the inflow patch has to be time dependent. In our case it is achieved, by recycling the velocity from the outlet patch to the inlet patch (mapped boundary conditions in OpenFOAM 2.3.1). The pressure and turbulent viscosity are solved in each time step. The spanwise boundaries were set to periodic (cyclic in OpenFOAM), as a neutral boundary that doesn't affect the flow. At the top of the computational domain the slip wall or symmetry boundary condition was used, following again the common practice. This setup implies that the studied domain is a street canyon in an infinite array of street canyons with the same aspect ratio. The street canyon area is discretized with 100 cells for the constant height of the buildings and the proportional quantities where assigned to the other acmes, while the width of the mesh was set to 50 cells. The typical computational domain's structure is shown in Figure 1. The results were validated against experimental data from (Li, 2008) for aspect ratios (H/W) 1, 1/2 and 2 and the agreement varied from fair to excellent. The comparisons for aspect ratio 1/2, are shown in Figure 2 and the agreement is fair.

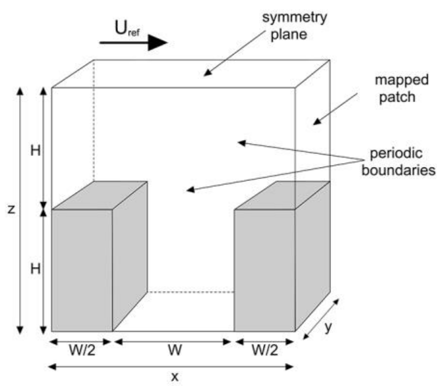

Figure 1. The general geometry, computational domain and patches of the simulations

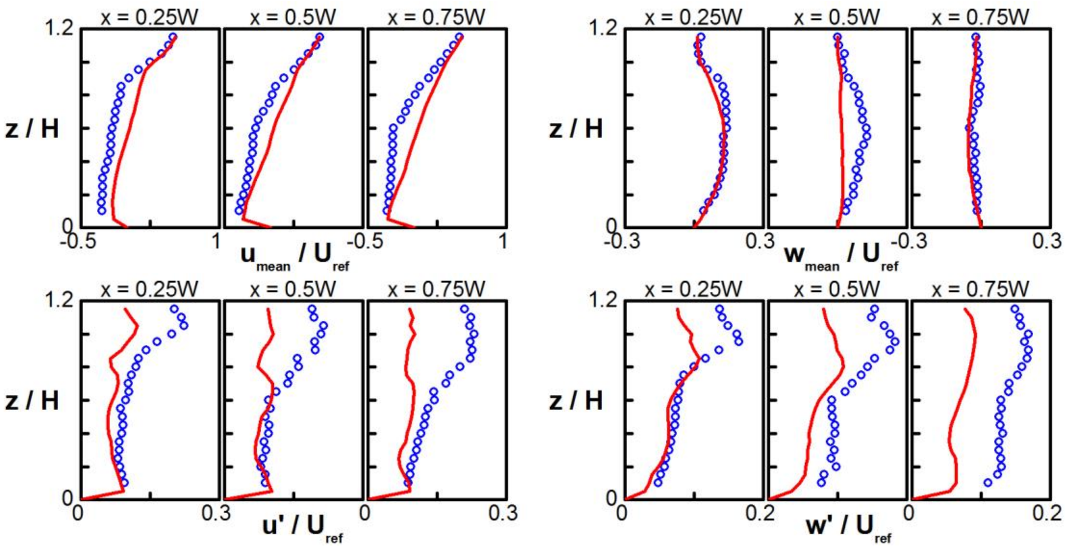

Figure 2. Comparison between averages (top) and fluctuations (bottom) of the velocity components for aspect ratio 1. Current simulations (red line) and experiments from (Li, 2008)

Recirculation zone structure

Any visualization of the instantaneous velocity field is a chaotic picture of vortices. In the case of the average velocity field, the picture becomes clearer, but it is still difficult to distinguish the structure and size of vortices. While there is a lack of a formal and absolute definition of a vortex (Jiang *et al.*, 2005), there are methods – criteria that help to identify and visualize vortices, e.g. vorticity, enstrophy and the Q and λ_2 criteria. They are characterized as local, because they apply a point by point mathematical analysis to the gradient velocity tensor ∇u and based on the result, it is decided whether the point is part of the vortex or not (Chakraborty *et al.*, 2005). On the other hand, the velocity streamlines represent the direction of the velocity in the whole studied area and are characterized as a global method, because they examine many cells instead of one. The λ_2 criterion (Jeong and Hussain, 1995) has been described as one of the most effective methods. λ_2 is the second largest of the three eigenvalues of the gradient velocity tensor $\nabla \mathbf{u} = \mathbf{S}^2 + \mathbf{\Omega}^2$, where $\mathbf{S}$ and $\mathbf{\Omega}$ are the rate-of-strain and vorticity tensors, respectively. Negative λ_2 values indicate that the point belongs to a vortex area, although in practice, such values appear also in areas with highly rotational flow. The Q criterion (Hunt *et al.*, 1988) defines that a vortex exists in the area where $Q = \frac{1}{2}\left[|\mathbf{\Omega}|^2 - |\mathbf{S}|^2\right] > 0$. Vorticity is a typical but rather vaguely defined meter of the local spinning motion of the flow, described by the vector $\vec{\omega} \equiv \nabla \times \vec{u}$, while the streamlines are a number of curves that are tangent to the velocity vector.

RESULTS

Figure 3 presents the application of some of the vortex detection methods to the average flow field of street canyons with aspect ratio 1/3.

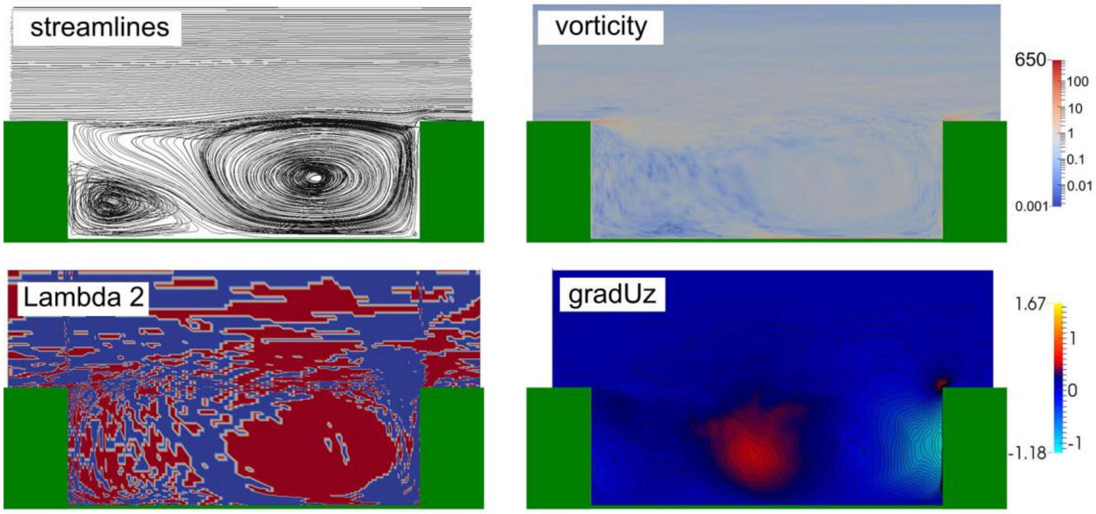

Figure 3. Application of vortex detection methods on the average velocity field of a street canyon with H/W = 1/3

Streamlines capture the formation of the biggest vortex in the downwind side of the street canyon, which is backed up by the large area of negative λ_2 values (red color) in the same area. The picture for the smaller vortex in the upwind side of the road isn't clear in any of the two methods. A drawback of the local vortex detection methods is noticed, that they tend to show results that indicate the existence of vortices in areas with high turbulence. This is caused because the detection criteria are a measure of the rotation of the flow, which is one of the characteristics of turbulent flow. For this reason, the local methods have to be used in conjunction with global methods. The vorticity field has its largest values in the shear layer, just after the upwind building and it proves more sensitive to the small swirls of the flow. This sustains vorticity unsuitable for the detection of big vortices. Finally, the gradient of the vertical velocity component has zero to positive values in the upwind side, indicating a stagnation area, proving the notion of the recirculation zone, that in this part of the street canyon, the removal of pollutants is obstructed. The big values at the centre of the street canyon, show the ending of this area and the negative values at the downwind side show the influx of fresh air, which has been reported by other researchers.

CONCLUSIONS

Main hypothesis of this work is that the flow regime in a street canyon governs the recirculation zone and consequently the dispersion. Thus, a quasi-universal expression for the recirculation zone could expand the applicability of these simple models in cases of higher complexity. To understand better the recirculation zone, CFD simulations were validated and used. We used standard vortex detection methods, namely vorticity, streamlines and the λ_2 and Q criteria, to visualize the vortex structures. The final results are rather inconclusive, although the combined use of the above methods certainly gives an insight to the flow structure. In any case more exploratory analysis is necessary in order to validate the further develop the hypothesis of this work.

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