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# A FORMULATION FOR THE STREET CANYON RECIRCULATION ZONE BASED ON PARAMETRIC ANALYSIS OF LARGE EDDY SIMULATIONS

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**Abstract**: Poor air quality continues to be a common problem for the bigger cities. Urban air quality models operate in the street scale and are capable of calculating the concentrations of pollutants for each street. These models are relatively easy and cheap to use, so they can be an excellent tool for many tasks, such as city planning and moderation of the traffic. To be efficient, they rely heavily on simple mathematical formulas that model the various flow phenomena between buildings and the atmosphere, to calculate the dispersion as a function of geometry and meteorological conditions. The sum of recirculating vortices that control the pollutant dispersion, has been collectively named as the recirculation zone. Current models use semi-empirical parameterisations of the recirculation zone, which are backed up by numerous field and wind tunnel experiments. In this paper, a strategy is discussed and applied, to possibly find an objective description of the recirculation zone, as a function of the street canyon geometry and the flow and dispersion characteristics. Specifically, the quadrant analysis of turbulence is applied on the results of wind flow and pollution dispersion, obtained from a Large Eddy Simulation (LES) in a wide street canyon with building height to street width ratio equal to 1/3. The quadrant analysis implemented here uses the fluctuations of the vertical velocity and the concentration. The two of the four events that clean the air in a street canyon, are added to create a parameter named as Cleaning Effect. The possibility of using this value to define different regions in the street canyon and thus the recirculation zone is discussed, in a preliminary use of this method.

***Key words:*** *Street canyon, dispersion, recirculation zone, quadrant analysis*

## INTRODUCTION

The population of Earth continues to increase and alongside increases the percentage of people living in big cities. Air pollution is a well-documented problem of modern cities and although pollutant control technologies are being improved, their transfer to everyday life activities is delayed and it is not guaranteed to solve the problem. The need to study air pollution remains important and air dispersion modelling is a fast and economic approach, to quantify the effect of pollutant sources, located in the urban fabric. Small scale air quality models (AQMs) are used to calculate the pollutant concentrations in a street canyon and they must account for the series of specific transport phenomena, which are caused by the wind flow between buildings.

The effect of the countless recirculating vortices that control the dispersion patterns is characterised with the collective term recirculation zone. Currently, AQMs use empirical numerical schemes that are validated with data from experiments and field measurements to predict the dispersion patterns. For example, SREET-SR (Johnson *et al.*, 1973) and CPBM (Yamartino and Wiegand, 1986) assume a normal street canyon (aspect ratio around 1) and use empirical data to form equations that give different concentrations for the upwind and downwind sides of the road. OSPM (Berkowicz, 2000) covers wider street canyons, using a trapezoid box model, to connect the contribution of recirculation with the street canyon geometry. The length of the trapezoid is twice the upwind building height. Thus, depending on the aspect ratio (hereafter AR), the downwind side receives either the contribution of recirculation (narrow canyons), or the only amount of pollutants that comes out of the box model (wide canyons). Furthermore, SIRANE (Soulhac *et al.*, 2011) defines that road segments with AR larger than 1/3 are treated as street canyons, thus containing recirculating flow regions, while wider canyons are treated as open terrain. SIRANE also assumes that the street canyon area will be well-mixed with a uniform pollutant concentration.

The existence of these formulations indicates two special characteristics of the street canyon scale AQMs: a) they usually calculate more than one concentrations for the road and b) they need a limit to distinguish the AR, from which the pollutant dispersion in wider street canyons is not affected by recirculation. This limit comes from either empirical observations or mathematical analysis, combined with corrections from data sets of field experiments. Our goal is to study the flow field and pollutant dispersion for ideal street canyon geometries, to find the properties of the flow that determine the characteristics of the recirculation zone. Any possibility of developing a specific description of the recirculation zone, could possibly expand the applicability of these simple models for more complex geometries.

Ideally, this new definition should indicate a geometrical area, in which the pollutants are further delayed from dispersion to the upper atmosphere by the recirculating flow inside the street canyon. The limits of this area would be designated by the change of one or more flow properties at the limit locations. In our previous presentation (Chatzimichailidis *et al.*, 2016), we tried some classic vortex visualization criteria (Kolář, 2007), such as vorticity, and Q and $\lambda_2$ criteria. These criteria were applied on the average velocity fields and they only succeeded in highlighting the existence of the stronger vortices, while they failed to give any information for the weaker ones. In this presentation, the dispersion of pollutants is simulated and the quadrant analysis of turbulence is applied in the street canyon area. In the next section, the technical setup of the simulations and the theory of quadrant analysis are briefly discussed.

## METHODOLOGY

### Configuration setup

The study is conducted with Large Eddy Simulation (LES) simulations, carried out using the open-source CFD toolbox OpenFOAM v2.3.1 (Weller, 2010). The advantage of LES is that the transient numerical solution of the Navier-Stokes equations allows 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 standard PISO solver (pisoFoam in OpenFOAM). The convection – diffusion equation was added to the transient solver, to simulate the dispersion of a passive scalar. The standard Smagorinsky model (Smagorinsky, 1963) is used for the subgrid turbulence. The model's constant Cs is set to 0.1 and the van Driest dumping function is applied for the cells along the wall boundaries, following the common suggestion for the Smagorinsky model. The studied geometry is rather simplistic, but it is studied to possibly develop criteria, which later will be used in more realistic geometries.

The setup of our simulations is a modified version of the strategy, employed with success initially by Li *et al.* (2008) and later by more researchers, e.g. Bright *et al.* (2013). Following the standard practice for atmospheric LES, the boundary conditions at the inflow patch have 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 AR. 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 pollution source is modelled by a group of cells, the typical emission factor of which was taken by Zhong *et al.* (2015).

**Validation**
The validation of the velocity results have been presented in (Chatzimichailidis *et al.*, 2016), while the passive pollutant dispersion was validated by comparison again the wind tunnel results by Pavageau (1996) and Meroney *et al.* (1996). The comparison with the LES by Li *et al.* (2008) is also presented, as it has similar technical characteristics to our own.

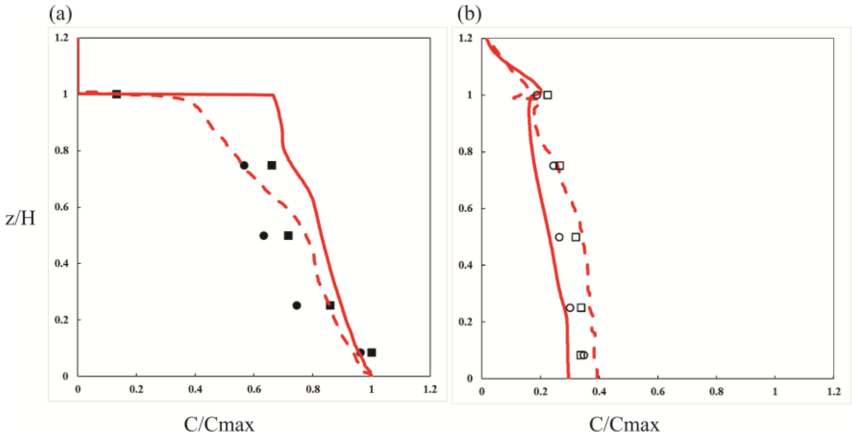


**Figure 1.** Simulated normalised concentration profiles at the (a) upwind and (b) downwind building walls for a street canyon with AR = 1. Current LES is presented by the continuous red line, the LES by Li et al. (2008) by the dashed line. the wind tunnel data by Pavageau (1996) are presented with squares and by Meroney et al. (1996) with circles. z/H is the non-dimensional height, where H is the building height.

The results are presented in Figure 1, where concentrations are normalised with the maximum concentration observed at the upwind wall, following the example by Koutsourakis *et al.* (2012). The simulation results are found to be in good agreement with the wind tunnel data.

**Quadrant analysis**
The quadrant analysis is a tool developed initially by Willmarth (1975) and is used to study the turbulence motions. The sign of the components of velocity fluctuations is quantified into four type of motions (also known as events). Depending on the combination of their signs, the four events are defined as Q1 (u'>0, w'>0) or outward interaction, Q2 (u'<0, w'>0) or ejection, Q3 (u'<0, w'<0) or inward interaction and Q4 (u'>0, w'<0) or sweep. Quadrant analysis is expanded by Nosek *et al.* (2016), by studying the combination of the signs of the dimensionless concentration fluctuation and the vertical velocity. The new events are named as: C1 (c'>0, w'>0) or venting of polluted air, C2 (c'>0, w'<0) or re-entrainment of polluted air, C3 (c'<0, w'<0) or entrainment of clean air and C4 (c'<0, w'>0) or venting of clean air. This implementation allows to determine the effect of vertical velocity to the pollutant dispersion out of the street. Quadrant analysis was used by Kellnerová *et al.* (2012), to determine the duration and thus the percentages of the events, at the roof-top level of the studied street canyon. Moreover, Nosek *et al.* (2016) used the previously mentioned types of quadrant analysis in wind tunnel experiments, to find that sweeps and ejections were correlated with the entrainment of clean air and the venting of polluted air, respectively. Finally, Li *et al.* (2016) used quadrant analysis, to visualise how the distribution of events changes with the change of temperature for a street canyon with AR = 1.

In the next sections, some preliminary results are presented using the data from the simulated velocity field and pollutant dispersion, interpreted with the use of quadrant analysis. The applicability of the method to the derivation of conclusions is studied and discussed.

**RESULTS**
For narrow street canyons, with AR close to 1, the recirculation zone covers the whole street area, so our study focuses on the wider cases. The presented results come from the post-processing of LES for an ideal street canyon with AR = 1/3. Quadrant analysis is used in an effort to find parts of the street canyon

that can be associated with the regions in which the pollutants tend to be gathered. The quadrant analysis presented by Nosek *et al.* (2016) was firstly carried out, using the fluctuations of the vertical velocity and dimensionless concentrations. This analysis was performed on the time series of velocity and dimensionless concentration, at 172 probes covering the whole street canyon. The time-series of each probe is analysed, to find the percentages of each event. The gathered information is grouped in the Cleaning Effect, defined as the sum of the two events that "clean" the street canyon, i.e. the venting of polluted air and the entrainment of clean air. The result is presented in Figure 2(b), where each probe location is assigned the value of the Cleaning Effect in percentage (%) units. The values are interpolated to create the contours. Finally, the black line is created automatically, in the areas where the Cleaning Effect value is 50%. This value is selected after testing all the spectrum from 10 to 90% and finally presented, as it seems to designate the area in which the pollutants are gathered.

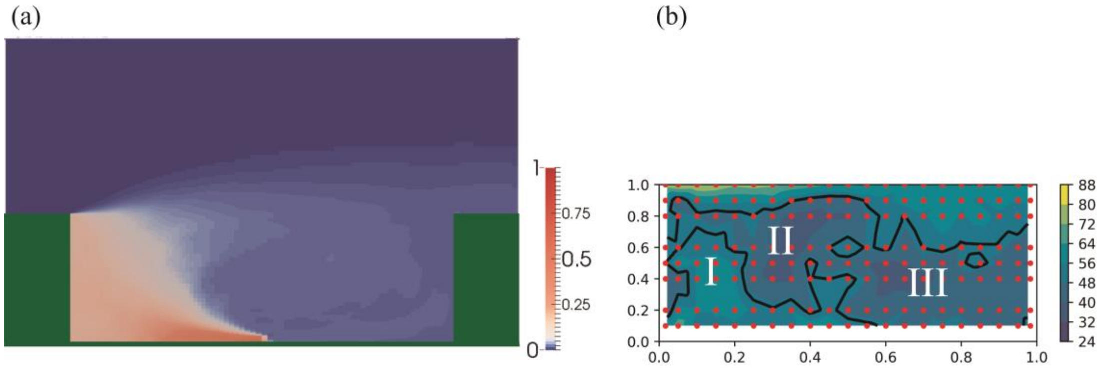


**Figure 2.** (a) Simulated normalised concentration field (C/Cmax) and (b) scatterplot of the Cleaning Effect values, the thick black line designates the 50%

The resulting black lines divide the street canyon in three amorphous regions. The Cleaning Effect in Regions II and III, is smaller than 50%, meaning that the flow there prevents the pollutant removal to the upper atmosphere. Comparing the diagram to the velocity flow field presented in (Chatzimichailidis *et al.*, 2016), Region III is the lower part of the main vortex that dominates the flow in a street canyon with AR = 1/3, resulting in the pushing of pollutants to the upwind side. Region II, represents the area with unspecified velocity created by the crash of the external atmospheric flow, with the counter flow from the large vortex. Region I is an area dominated by a lot of weak recirculating vortices, which do not have the power to push the pollutants out the canyon. The relatively higher values of Cleaning Effect can be attributed to the fact the pollutants are eventually pushed out through Region I. Finally, the weird shape of the regions may be attributed to the relatively small observation time of 450 seconds of transient LES. More seconds of transient simulations will be conducted to extract further conclusions.

## CONCLUSIONS

Our final goal is to arrive to a definition of the recirculation zone, as a function of one or more flow properties. To achieve this, the quadrant analysis on the flow and dispersion results of an LES is used. The two events that contribute to the cleaning of a street canyon were added to a parameter named as the Cleaning Effect. The visualisation of this parameter was presented and a lot of cutoff values were tested, to observe any possible division of the street canyon in regions, which would ultimately define the recirculation zone. The selected and presented cutoff value is the 50%, which was found to divide the street canyon in One of the defined regions shows a first resemblance, with the area in which the pollutants are gathered.

This practice is yet unknown, if it has any practical use and before using it in more complex geometries, we need to apply it in similar ideal setups, e.g. wider street canyons with AR = 1/4 and AR = 1/5, to further test its validity.

A drawback of the method, is that quadrant analysis uses only the sign of the velocities to group the flow and dispersion motions into events, while the strength of these motions is ignored. Currently, we test a series of flow properties, so that the new variation will incorporate the strength of each event.


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