Studying street geometry influence in PM_{10} concentration

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Abstract: This paper intends to show the influence of street geometry in particle concentration emitted from traffic source, on a busy street of Barreiro City, Portugal. FLUENT software was used to simulate particle dispersion, air flow and turbulence in the street. Buildings and road characteristics were considered, as well as winter and summer most predominant meteorological conditions. Also, particle concentrations were measured. The results show that when street orientation is equal to wind orientation, a good dispersion is promoted and low particle concentrations are achieved. Concerning the effect of building height, some recirculation is noticed affecting mainly the residents. In this street geometry north wind direction promotes some positive recirculation raising wind velocity and pollutant dispersion, while the effect of south winds is negative since the wind speed is lower, trapping particles. Considering some differences in the geometries it was possible to conclude that some gaps between buildings could help pollutants' dispersion.

Keywords: particle concentration; simulation; street canyon; traffic source; buildings; street geometry; PM_{10}; FLUENT software.

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1 Introduction

Urban planning is a matter of major importance concerning development and public health. It is essential to have a sustainable development that allows progress and at the same time quality of life, being one of the most important items the health safety, where urban air quality levels assume an important relevance (Borrego et al., 2003). In this matter particle concentration in streets is one major issue. Topography and urban obstructions such as buildings and other construction have great influence in the atmospheric flow and consequently on the pollutants' dispersion. This effect changes the pollutant dispersion, particularly vehicle exhaust pollutants, which cannot be carried away by the wind, due to buildings which act as barriers, avoiding the wind circulation. Dispersion cannot occur since air and consequently air pollutants, are trapped within the street canyon, raising the concentration of the contaminants. So, for decision makers it is important to know the influence of building volume and street geometry on air quality.

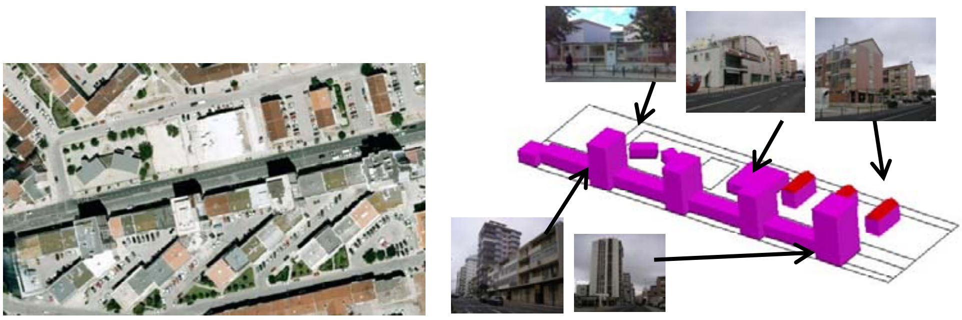
Nowadays, numerical tools like computational fluid dynamics (CFD) models have been highly developed and are a very reliable tool for simulating wind and dispersion fields in urban areas which are characterised to have complex geometries. These tools can also model the complex effect of meteorology. Very satisfactory modelling accuracy is now possible, mainly due to the continuous improvement of very powerful numerical codes and increase in hardware and software performances. In order to complement and to validate the results of these models pollutants motorisation campaigns are also very important.

Particular attention has being dedicated to pollutant particulate matter (PM) considering both PM_{10} and $PM_{2,5}$ (Martins et al., 2009; Amorim et al., 2010) and more recently nanoparticle (Kumar et al., 2011). Most epidemiological studies focus on PM_{10} and $PM_{2,5}$ and there is a certain evidence that short term exposure to high concentrations of PM_{10} can aggravate pulmonary diseases and have influence in paediatric asthma (Garcia et al., 2010) and long term exposure to high concentrations on PM_{10} may increase the risk of cardiovascular disease and pulmonary disease.

2 Domain in study

The studied domain is Avenida do Bocage which is a busy street located in Barreiro City about 40 km south from Lisbon (Figure 1). This is a small city, over 34 km^2 and 80,000 inhabitants, with industry near the centre and typical city traffic. Barreiro is almost flat, with the highest point at approximately 10 m above sea level. The weather is temperate, with no severe seasons. Avenida do Bocage is an important strategic key point in the city, because connects the city centre of Barreiro with an important motorway to the Portuguese capital, Lisbon. Traffic flux is very important especially in rush hours, representing the main source of pollution.

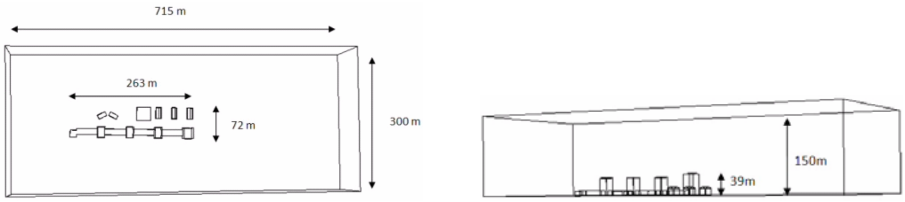
Figure 1 Bocage Avenue (domain) (see online version for colours)



3 CFD model

The CFD model used in this study was ANSYS FLUENT 12.0 software. This multi-purpose commercial software has been widely used in this kind of application and constantly validated through comparison with other validated models (Di Sabatino et al., 2008) or through wind tunnel experiences (Awasthi and Chaudhry, 2009). To fulfil the aim of this study, the spatial discretisation of the computational domain was a tetrahedral grid, refined near the buildings. The geometry of the street is showed in Figure 2 and also the domain regarding wind from west. As different wind directions were studied, different domains were used, to assure sufficient distance between the buildings and the domain boundaries in the simulation.

Figure 2 Street geometry and domain to wind from west conditions



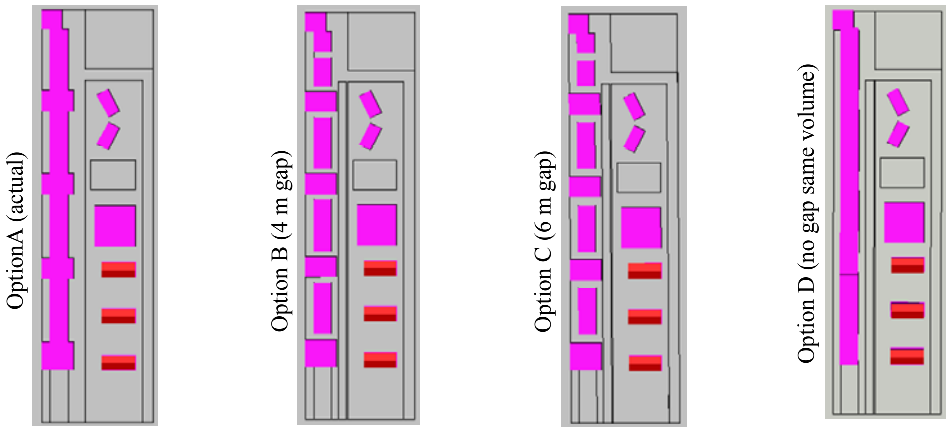
A 3D flow simulation with a Lagrangian approach was used, assuming steady state conditions and the model k-epsilon as turbulence model (RNG k-epsilon turbulence sub-model) providing an analytical formula for turbulent Prandtl numbers and an analytically-derived differential formula for effective viscosity that accounts for low-Reynolds-number effects (FLUENT, 2009). A wind profile, turbulent kinetic energy and turbulence dissipation rate was introduced as a user defined function (UDF) considering a power-law vertical wind profile. PM_{10} car emission rate used in FLUENT was calculated through ADMS-Urban software, considering traffic flows, velocity and type of fuel. No chemical reactions were considered for pollutants emissions. In terms of boundary conditions, a no-slip condition was imposed at all solid surfaces (the flow in the near-wall region was represented by the law-of-the-wall for mean velocity), a symmetry boundary was considered at the top and lateral boundaries, assuming a zero flux of all quantities across the horizontal plane.

For this study the simulation domain considered was a 715 × 300 m^2centred in the Av Bocage with approximately 160,200 cells.

4 Building geometry scenarios

With the purpose of studying possible air quality improvements the in this street, four building arrangements scenarios were considered. One corresponding to the real geometry of the street, with the actual architectural layout, disposition and volumetric configuration, is designated as option A. Another virtual configuration, called as option B, considers gaps of 4 m between buildings, option C considers gaps of 6 m between buildings, and finally option D considers the same height for all the buildings without gaps between them. The four building scenarios are shown in Figure 3.

Figure 3 The four building disposition scenarios considered, the actual (real) and three others (see online version for colours)



5 Emissions characterisation

Rua do Bocage is one of the most important road connections from Barreiro to Lisbon, being the main traffic emission source in the considered domain. For traffic emissions characterisation in this road, a traffic counting campaign was carried out in periods of one hour and vehicle types were registered: light duty, heavy duty, buses and motorcycles. This information was used as input in ADMS-Urban software, as well as fuel type, vehicles' velocity and road type, considering traffic as a line source, to calculate PM_{10} emissions rate. The mean value of background concentration measured by the background stations from the Portuguese Air Quality Acquisition system was also considered and introduced in ADMS-Urban and summed to FLUENT results, to account for pollutants not emitted in the studied street. Background emissions are important to achieve the real pollutant concentration, allowing the comparison with measured values, since it is not possible to measure only the pollutants emitted in the street. In this way it is possible to validate the results of calculated values. However, to study pollutant dispersion inside the street and compare different canyon configurations, the background is not relevant. For this reason, in this study, background emissions are only used to compare the measured and calculated values and to give a more realistic concentration value.

6 Results

PM_{10} concentration results from FLUENT are presented in Figure 4. The results are shown in a horizontal surface with 1.5 m (considered the medium typical human nose level and used frequently in exposure studies) for the first scenarios, actual (real) configuration (option A), considering four wind directions (W, N, S and E) and traffic emissions as source (without background concentrations).

Figure 4 Contours of PM_{10} concentrations at 1.5 m high for four wind directions for option A (actual configuration) (see online version for colours)

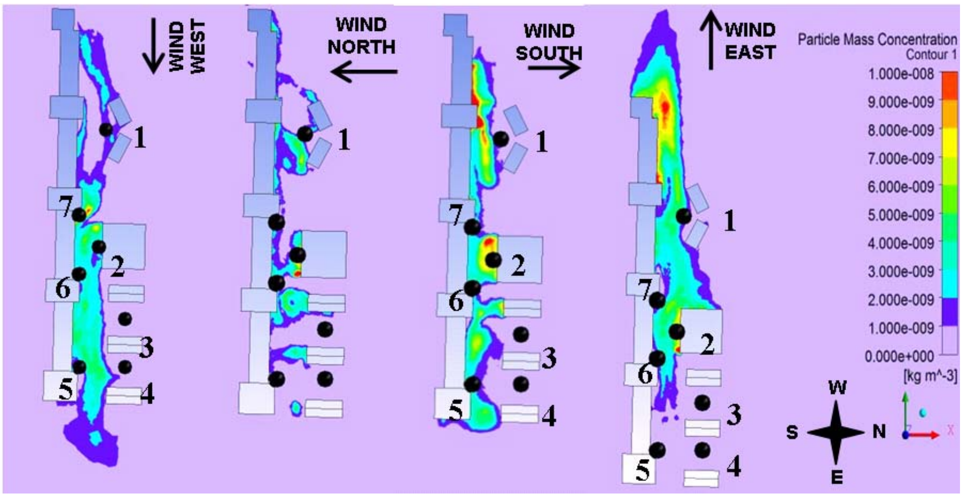


Figure 4 shows that highest values of PM_{10} concentrations are achieved for south wind and east wind, with hot-spots respectively at the centre and at the end of the street. In the case of south wind the hot spots result from the transversal vortex induced by the highest buildings located on the south part of the street. The wind from south passes through the buildings trapping pollutants in the street. In the case of east wind the hot-spot is a result of the difficulty in the dissipation of pollutant, due to a large building on the north part of the street that acts as a barrier causing recirculations.

Table 1 PM_{10} concentrations at 1.5 m high for option A (actual configuration)

Designation	*Location*	*PM_{10} conc. (μg/m^3)*				
		Calculated for west wind	*Calculated for north wind*	*Calculated for south wind*	*Calculated for east wind*	*Measured for west wind*
Point 1	School	21.6	21.2	20.7	22.3	33.0
Point 2	Bingo	23.0	28.6	27.1	27.0	31.0
Point 3	Car park (border)	20.1	20.0	20.1	20.0	29.0
Point 4	Car park (middle)	20.4	20.0	20.1	20.0	29.0
Point 5	High building corner	20.5	20.6	22.7	20.0	27.0
Point 6	Residential building (east)	22.2	21.5	21.9	21.0	28.0
Point 7	Residential building (west)	25.0	20.9	22.5	20.7	28.0
Mean value	1.5 m plane (all domain)	20.8	20.5	21.0	21.1	-
AQ index	1.5 m plane (all domain)	20.3	20.1	20.1	20.1	-

In Table 1 are shown the values of PM_{10} concentrations at 1.5 m high considering all the emissions (traffic + background) for the actual street configuration (option A) compared with PM_{10} concentrations measurements made on seven strategic points along the street, on both sides of the road. Additionally the table shows the mean concentration value for the 1.5 m plane and also for the mean concentration weighted by the wind frequency, considered the air quality index (AQ index), for the same plane.

The simulation results shown that the highest value of PM_{10} concentration is achieved in point 2 (Bingo building) with a value of 28.6 $\mu g/m^3$ in north wind conditions. But if we consider the mean value at 1.5 m high for all the domain, the highest value is achieved for east wind conditions with 21.1 $\mu g/m^3$.

Results from the simulations at 1.5 m horizontal surface, with the new configurations are shown in Figures 5, 6 and 7. Figure 5 shows the results of PM_{10} concentrations for option B, which corresponds to the 4 m gaps between buildings. Figure 6 shows the results of PM_{10} concentrations for option C, which corresponds to the 6 m gaps between buildings and Figure 7 shows the results of PM_{10} concentrations for option D, which corresponds to all buildings at the same height and width. In these figures only traffic emissions are considered (no background concentrations) for all wind directions studied.

Figure 5 Contours of PM_{10} concentrations at 1.5 m high for the main four wind directions (option B) (see online version for colours)

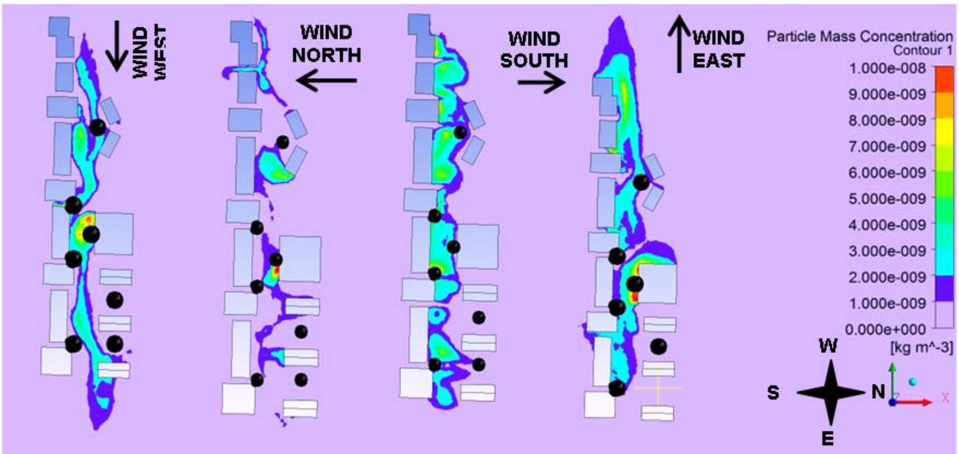


Figure 5 shows that the implementation of a 4 m gap between buildings, generically, decreases the concentrations of PM_{10} in the street. This is due to the fact that these gaps between buildings reduce vortex inside the street and promote wind circulation, resulting in a better capacity of pollutants dispersion along the street decreasing the PM_{10} concentrations.

Figure 6 Contours of PM_{10} concentrations at 1.5 m high for the main four wind directions (option C) (see online version for colours)

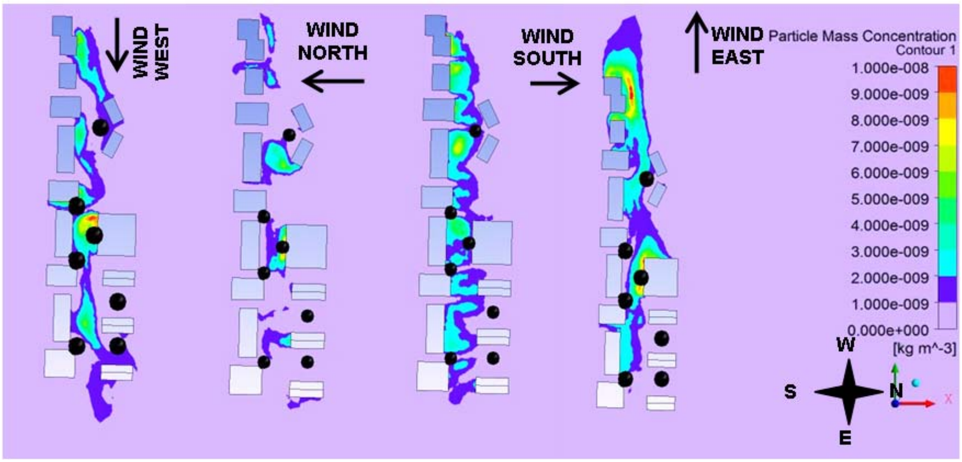
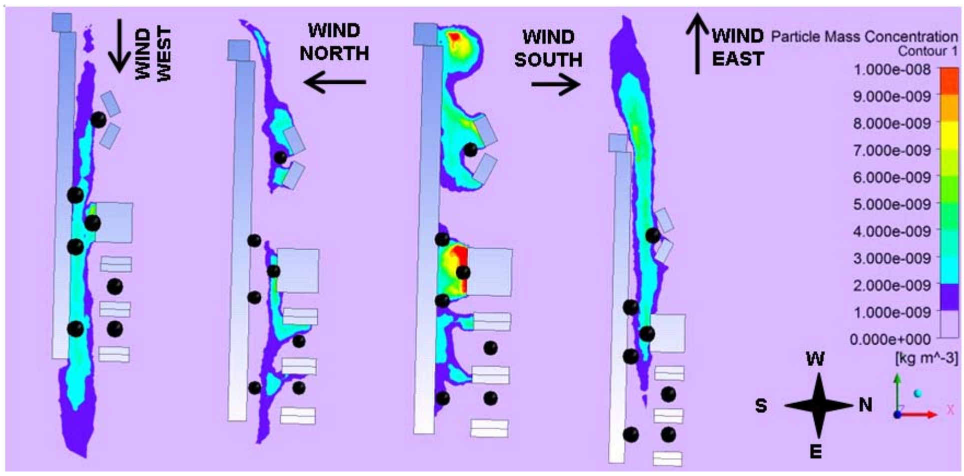


Figure 6 shows that with the implementation of a 6 m gap between buildings (option C) in comparison to option B (4 m gaps between buildings) does not represent a visible decrease in PM_{10} concentrations, concluding that increasing gap length does not bring any improvements in the street air quality.

Figure 7 Contours of PM_{10} concentrations at 1.5 m high for the main four wind directions (option D) (see online version for colours)



Considering option D, it is possible to see that, in general, pollutant dispersion is promoted when all buildings have the same dimensions, since there is less recirculation caused by different geometries, allowing a good wind circulation except for wind from south.

Table 2 shows the results of PM_{10} mean concentrations for a surface located at 1.5 m high, considering all the emissions (traffic + background) and for the four different options considered and different wind directions. It is possible to observe that the lower concentrations values are obtained for configuration D when considering west and north wind direction, and also configuration B and C for north wind direction.

Table 2 PM_{10} mean concentrations for a 1.5 m high surface for the different options and four wind directions

	PM_{10} *concentration* ($\mu g/m^3$)	
West wind	Option A	20.8
	Option B	20.6
	Option C	20.6
	Option D	20.4
North wind	Option A	20.5
	Option B	20.4
	Option C	20.4
	Option D	20.4
South wind	Option A	21.0
	Option B	20.6
	Option C	20.6
	Option D	20.8
East wind	Option A	21.1
	Option B	20.9
	Option C	20.9
	Option D	20.6

7 Conclusions

The CFD commercial software ANSYS FLUENT was used to simulate and study particle concentrations (PM_{10}) in a busy street with abundant road traffic, in Barreiro City in Portugal. Four different street configurations were tested to see the influence of street geometry in pollutant dispersion. The concentration values calculated for the different street configurations don't show significant differences since the small traffic flow, however it is still possible to have an idea of the influence of street configuration in the dispersion of pollutants. From the results it is possible to conclude that street configuration and building geometry have influence in the particle dispersion and concentration inside the street. It was shown that it is possible to reduce PM_{10} concentrations, improving air quality after some alterations in street geometry, considering the strong dependence of pollutant dispersion from predominant wind velocity and direction. In general, the best average concentrations levels were observed for Option D (no gaps and equal volume for all buildings) because this geometry avoids the formation of vortex, promoting the dispersion of pollutants, for different wind directions. The exception is for south wind direction where having gaps between buildings is more favourable (options B and C) since the wind is perpendicular to the street side with buildings with equal volume, making the wind pass over the street trapping the pollutants emitted locally. Interestingly, there are no visible improvements in having higher gaps (6 m – option C) between buildings instead of 4 m gaps (option B).

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