Personal Exposure to Particle Concentration in a Busy Street

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Abstract

Humanity has been discussing aspects like environment, sustainable development, public health, leisure and work. Connections between these aspects are growing its importance to decision makers. Urban air quality levels are one of the most important items, concerning public health in urban environment. The knowledge of pollutants influence in human health is a matter of major importance nowadays, and it is known that personal exposure to particle concentration is a key factor in citizen's health. Aspects like street geometry, motorways, pedestrian ways, traffic strategies, time and schedules, can influence air quality levels and consequently human exposure.

This article studies the influence of street geometry, wind direction, daily car traffic, pedestrian trajectories and particle matter concentration (PM_{10}) levels in short-term personal exposure on a busy street of Barreiro City in Portugal. Ansys Fluent was used to simulate particle dispersion in Bocage Street. Buildings high, width, length and geometry, as well as distance between buildings and road width were considered in the simulation work. Different meteorological conditions were simulated, namely, wind direction and wind velocity.

The results show that pollutant concentration is highly dependent of street geometry and wind conditions. The pedestrian trajectories and its time schedules also play a major rule in the short-term personal exposure to PM_{10}. It was notice that when the buildings orientation is the same as the wind, good pollutant dispersion is promoted. Also different size in buildings promotes recirculation that can be positive, rising the wind velocity and promoting pollutant dispersion,

if the wind direction is from North, or negative trapping pollutants when the wind is from South. It is also possible to conclude that pedestrian trajectories that correspond to cross the road in the centre of street results in the highest values in terms of short-term personal exposure to PM_{10}.

Keywords: PM_{10}, Personal exposure, Street Canyon, Buildings Configuration, Fluent

1 Introduction

The importance of achieving good air quality is a key factor in urban planning nowadays. Aspects like traffic, street configuration and buildings geometry, green spaces and gardens and the pedestrian ways are growing its importance to decision makers. When speaking about urban air quality, particle concentration is one major issue and modern studies have dedicated particular attention to the influence of street canyon design in the dispersion of pollutants in general and PM_{10} in particular. Numerical tools like Computational Fluid Dynamics (CFD) models have been highly developed, and are now a very reliable tool for simulating pollutant concentrations in urban areas. Very satisfactory modelling accuracy is now possible, mainly due to the continuous important development of very powerful numerical codes, parallel to fantastic increases in hardware performances. Complementary with this computational tools measurement campaigns are also very important, because they contribute to validate de simulations and help understanding the accuracy rate of computational results. In the range of air pollutants, particular attention was dedicated to 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 have focused 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. This article studies the influence of personal exposure to PM_{10} in a particular street in Barreiro city in Portugal in particular considering different pedestrian ways in that particular street.

2 The Street

The street that is considered in this study is part of Avenida do Bocage which is located in Barreiro city. Barreiro is a medium size city located 40km south of Lisbon (Figure 1). This is a small city, over $34km^2$ and 80000 inhabitants, with industry near the centre and typical city traffic. Barreiro is almost flat, with the highest point at approximately 10 meters 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 highway from the capital of Portugal, Lisbon. So the traffic flux is very important especially in rough hours, representing the main source of pollution in the street. The importance of this street is also connected with the fact that has inside a primary school (Escola Básica nº5) and with the fact that represent an important pedestrian way to people who goes to the river or to the fluvial station.

Figure 1 – Location of Avenida do Bocage the studied street

3 The CFD Simulation

The CFD simulation was carried out with Ansys Fluent 12.0 software, which is a multi-purpose commercial software, widely used in this kind of application and constantly validated through comparison of results with other validated models (Di Sabatino, et al, 2008) or through wind tunnel experiences (Awasthi, et al, 2009). To fulfil the aim of this study, the spatial discretisation of the computational domain a tetrahedral grid was used, 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. A 3D flow simulation with a Lagrangian approach was used, assuming steady state conditions, and for the turbulence, the k–epsilon turbulence model was used, more precisely the RNG k–epsilon turbulence mode 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. The 2-way street PM_{10} car emission rate was introduced, using the ADMS-Urban model, and considering the traffic that crosses the street. No chemical reactions were considered for PM_{10} 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), at the top a symmetry boundary was considered, assuming a zero flux of all quantities across the horizontal plane. For this study the simulation domain considered was a $715x300m^2$ centred in the Av Bocage with approximately 160200 cells.

The characterization of the traffic emissions in the domain was made by the implementation of a traffic counting campaign in the street. The counting was carried in periods of one hour and the vehicle characterization was aggregated according to its typical vehicle categories (light duty, heavy duty, buses and motorcycles). PM_{10} emissions were then calculated by the model ADMS Urban, considering traffic as line sources and considering the mean traffic number of vehicles in rough hours as the baseline scenario for traffic emissions. The other emissions considered in the domain, were introduced as background concentrations in the model, and summed to the Fluent results. The value for background concentrations was collected from the Portuguese Air Quality Stations system. The Fidalguinhos Air Quality station data for PM_{10} was used, as this station is classified as urban background station. The model validation was made using real measurements of PM_{10} concentrations made in the street (Garcia 2011).

4 The four scenarios considered

Four scenarios to the configuration of Avenida do Bocage were considered, concerning building disposition. One corresponding to the real actual geometry of the street with the actual architectural layout, disposition and volumetric configuration of buildings (Disposition A). Three other virtual dispositions for the street buildings were simulated, considering the alteration of the buildings configurations, with the objective of trying to improve the air quality in this street. The first new virtual configuration, designed as Disposition B, considers a new gap of 4m between the buildings along the street. The scenario designed as Disposition C was also tried, considering gaps of 6m between the buildings along the street. Finally the scenario designed as Disposition D, considerer the same volume as actual real disposition for the buildings along the street, but considers the same high and width for all buildings along the street without gap between buildings. The four building disposition scenarios are shown if figure 2.

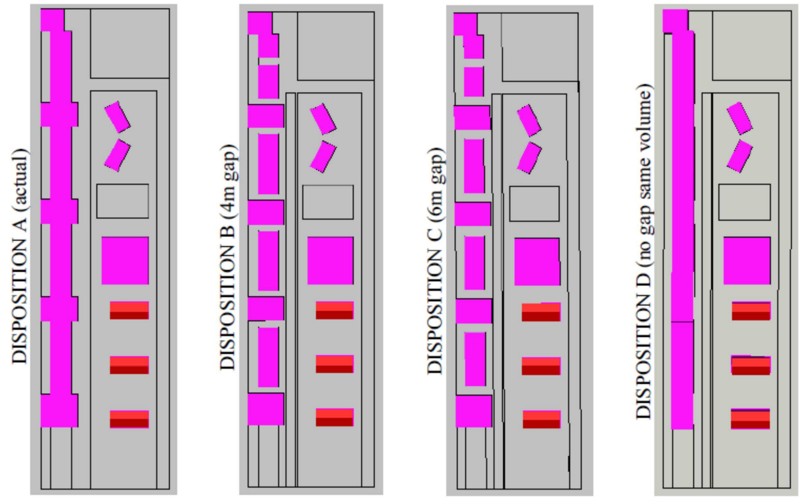

Figure 2 - The four building disposition scenarios considered

5 The PM_{10} concentration results

The concentration results obtained for PM_{10} simulations for horizontal concentrations fields to the actual (real) configuration (Disposition A) of the street, considering the four wind directions, are presented in figure 3. This figure shows contours of PM_{10} concentrations at 1,5m high (considered the medium typical human nose level and used in frequent exposure studies) considering only traffic emissions (no background concentrations).

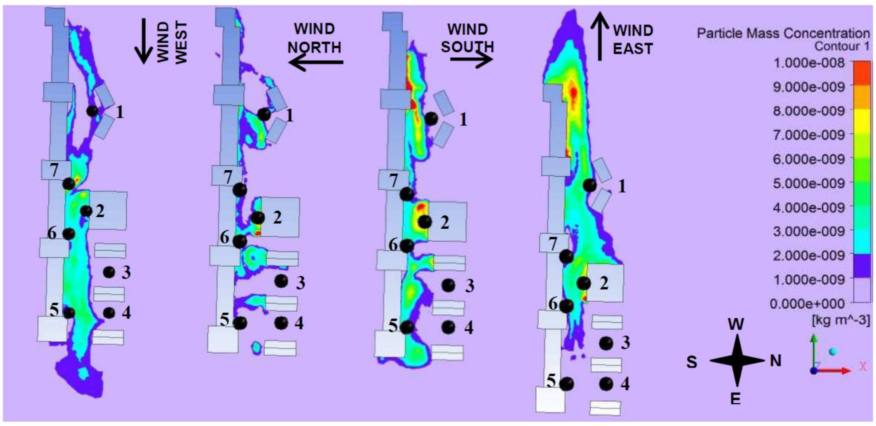

Figure 3 - Contour plots of PM_{10} concentrations at 1.5m level for the actual street configuration (Disposition A) for the main four wind directions

In table 1 are shown the values of PM_{10} simulated concentrations at 1,5m high considering all the emissions (traffic + background) for the actual (real) configuration of the street (Disposition A). These concentrations are shown for seven strategic points located in the street. Additionally it is also shown the mean concentration value for a plane located 1,5m high and also for the mean concentration at 1,5m high weighted by the wind frequency, this value is designed by CW (Weighted Concentration).

$$CW = C\ PM_{10} \times fi$$

Where $C\ PM_{10}$ is the concentration of PM_{10} ($\mu g/m^3$) and fi is the wind direction frequency.

Table 1- PM_{10} concentrations at 1,5m high for disposition A (actual real configuration)

Designation	Location	PM_{10} Conc. ($\mu g/m^3$) West wind	PM_{10} Conc. ($\mu g/m^3$) North wind	PM_{10} Conc. ($\mu g/m^3$) South wind	PM_{10} Conc. ($\mu g/m^3$) East wind	CW (µg/m3)
Point 1	School	21.6	21.2	20.7	22.3	21.3
Point 2	Bingo	23.0	28.6	27.1	27.0	25.4
Point 3	Car park(border)	20.1	20.0	20.1	20.0	20.1
Point 4	Car park (middle)	20.4	20.0	20.1	20.0	20.2
Point 5	High building corner	20.5	20.6	22.7	20.0	20.9
Point 6	Residential building (east)	22.2	21.5	21.9	21.0	21.7
Point 7	Resid. building (west)	25.0	20.9	22.5	20.7	22.8
Mean value	1,5m plane (all domain)	20.8	20.5	21.0	21.1	----
CW	1,5m plane (all domain)	20.3	20.1	20.1	20.1	----

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 $\mu g/m^3$ for North wind conditions. But if we consider the mean value of concentrations at 1,5m high plane for the entire domain, the highest value is achieved for east wind conditions with a mean value of 21,1$\mu g/m^3$.

Results obtained for the simulations with the new configurations are shown in figures 4, 5 e 6 and in table 2, 3 e 4. Figure 4 shows the results obtained for the simulations for PM_{10} concentrations horizontal fields for Disposition B, which corresponds to have a gap of 4m between the buildings along the street. Figure 5 shows the results obtained for the simulations for PM_{10} concentrations horizontal fields for Disposition C, which corresponds to have a gap of 6m between the buildings along the street. Figure 6 shows the results obtained for the simulations for PM_{10} concentrations horizontal fields for Disposition D, which corresponds to no gap between buildings but considering same high and width for all buildings. In these figures, contours of PM_{10} concentrations at 1,5m high, considering only traffic emissions (no background concentrations), are shown for the four main wind directions studied. Tables 2, 3 and 4 shows the values of PM_{10} simulated concentrations at 1,5m high considering all the emissions (traffic + background) for the four scenarios considered, Dispositions A, B, C and D.

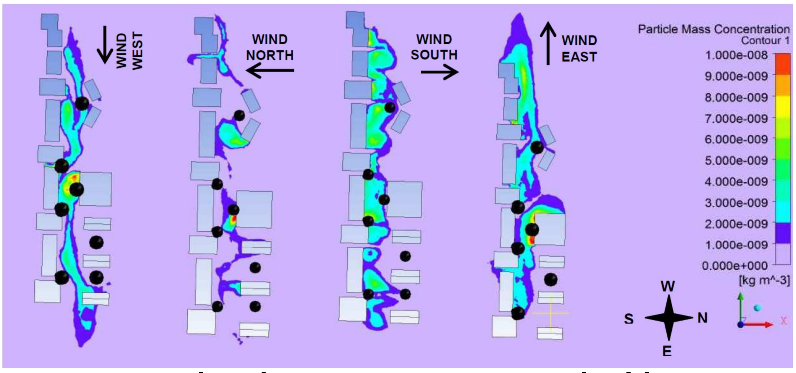

Figure 4 - Contour plots of PM_{10} concentrations at 1.5m level for Disposition B (4m gap) for the main four wind directions

Table 2- PM_{10} concentrations at 1,5m high for disposition B (4m gap)

Designation	Location	PM_{10} Conc. (µg/m^3) West wind	PM_{10} Conc. (µg/m^3) North wind	PM_{10} Conc. (µg/m^3) South wind	PM_{10} Conc. (µg/m^3) East wind	CW (µg/m3)
Point 1	School	22.3	20.8	22.7	22.2	21.8
Point 2	Bingo	25.7	23.2	21.8	27.6	24.1
Point 3	Car park(border)	20.0	20.0	20.0	20.0	20.0
Point 4	Car park (middle)	20.0	20.0	20.7	20.0	20.1
Point 5	High building corner	20.0	20.0	20.4	21.2	20.2
Point 6	Residential building (east)	21.0	20.1	23.9	20.7	21.2
Point 7	Resid. building (west)	23.3	20.0	21.2	20.0	21.6
Mean value	1,5m plane (all domain)	20.5	20.3	20.6	20.8	----
CW	1,5m plane (all domain)	20.2	20.0	20.1	20.0	----

By the analysis of figure 4 and table 2, it is visible that the implementation of a 4m gap between buildings, generically decrease significantly the concentrations of PM_{10} in the street. This is due to the fact that these gaps between the buildings reduce the effects of creation of vortex inside the street since there is no barrier to the wind, resulting in a better capacity of pollutants dispersion along the street decreasing the PM_{10} concentrations.

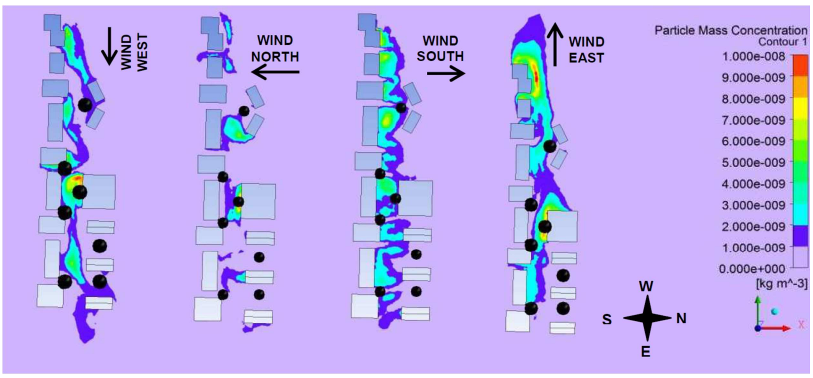

Figure 5 - Contour plots of PM_{10} concentrations at 1.5m level for Disposition C (6m gap) for the main four wind directions

Table 3- PM_{10} concentrations at 1,5m high for disposition C (6m gap)

Designation	Location	PM_{10} Conc. (μg/m^3) West wind	PM_{10} Conc. (μg/m^3) North wind	PM_{10} Conc. (μg/m^3) South wind	PM_{10} Conc. (μg/m^3) East wind	CW (μg/m3)
Point 1	School	20.9	20.8	21.0	21.2	20.8
Point 2	Bingo	25.9	26.8	21.1	26.8	24.9
Point 3	Car park(border)	20.0	20.0	20.3	20.0	20.1
Point 4	Car park (middle)	20.4	20.0	20.5	20.0	20.3
Point 5	High building corner	20.0	20.0	20.1	20.1	20.1
Point 6	Residential building (east)	20.1	20.1	20.2	20.5	21.2
Point 7	Resid. building (west)	22.9	22.9	20.0	20.1	21.2
Mean value	1,5m plane (all domain)	20.6	20.6	20.6	20.9	----
CW	1,5m plane (all domain)	20.3	20.2	20.1	20.1	----

The results of figure 5 and table 3 shows that with the implementation of a 6m gap between buildings (disposition C) comparing to the scenario of having 4m gap between buildings (disposition B) doesn't represent a visible decrease in PM_{10} concentrations along the street, concluding that increasing gaps length doesn't bring significant improvements in the street air quality.

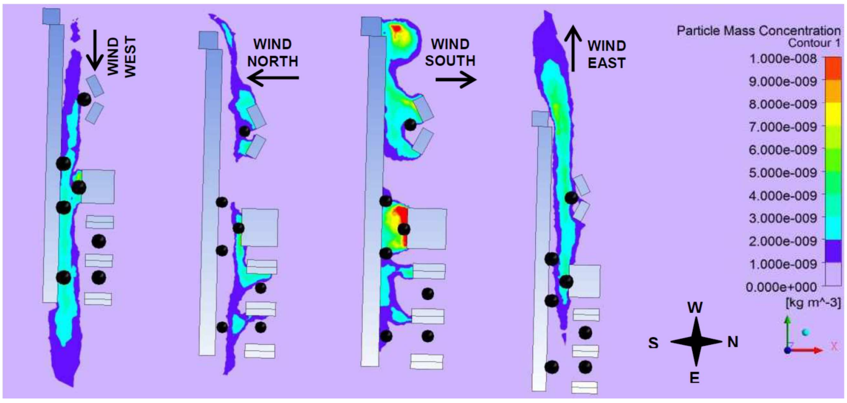

Figure 6 - Contour plots of PM_{10} concentrations at 1.5m level for Disposition D (no gap same volume) for the main four wind directions

Table 4- PM_{10} concentrations at 1,5m high for disposition D (no gap same volume)

Designation	Location	PM_{10} Conc. (μg/m^3) West wind	PM_{10} Conc. (μg/m^3) North wind	PM_{10} Conc. (μg/m^3) South wind	PM_{10} Conc. (μg/m^3) East wind	CW (μg/m3)
Point 1	School	20.0	21.3	21.5	22.0	20.8
Point 2	Bingo	24.1	22.8	30.7	23.0	24.7
Point 3	Car park(border)	20.0	20.1	20.0	20.0	20.0
Point 4	Car park (middle)	20.0	20.2	20.6	20.0	20.0
Point 5	High building corner	23.2	20.4	21.1	20.1	21.6
Point 6	Residential building (east)	23.3	20.0	21.9	20.4	21.8
Point 7	Resid. building (west)	22.2	22.2	21.4	20.7	21.3
Mean value	1,5m plane (all domain)	20.3	20.4	20.8	20.6	----
CW	1,5m plane (all domain)	20.1	20.1	20.2	20.0	----

The results of figure 6 and table 4 shows the solution of considering the buildings with no gap but with the same volume represent a good solution that promotes good pollutant dispersion visible in the 1,5m high mean concentration results obtained for this configuration.

6 The short-term personal exposure results

With the objective of studying the influence of the four different scenarios (A, B, C and D) in short-term personal exposure to PM_{10}, four pedestrian trajectories were considered for people crossing the street in direction of the fluvial station. The four pedestrian trajectories are shown in figure 7 and the characterization is made in table 5.

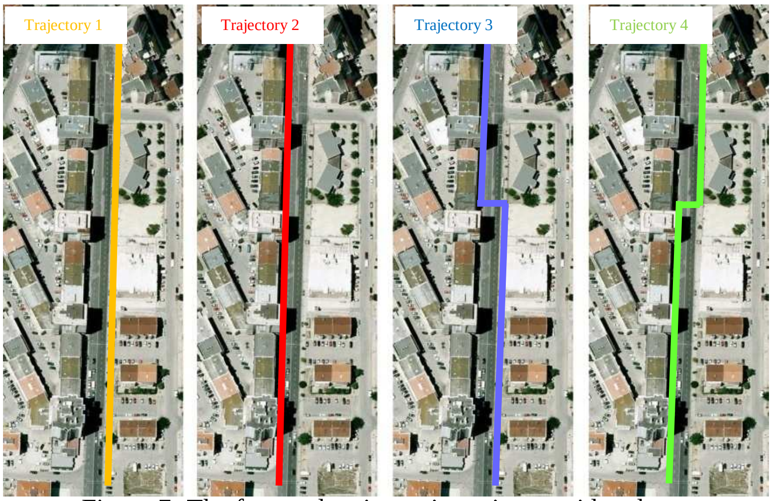

Figure 7- The four pedestrian trajectories considered

Table 5 - Characterization of the four pedestrian trajectories

Pedestrian trajectory	Description of trajectory	Total walking distance (m)	Walking mean velocity (m/s)	Total time (s)
1	Only north side	300	1.0	300
2	Only south side	300	1.0	300
3	North to south	310	1.0	310
4	South to north	310	1.0	310

Short term personal exposure E(t) in a period of time t can be expressed as:

$$E(\Delta t) = \int_0^t C(t)dt \cong C_i t_i$$

Where C(t) is the pollutant concentration in a particular time t in µg/m^3, C_i is the discrete concentration in cellule i in µg/m^3 and t_i is time of expose in cellule i in seconds.

In order to calculate the total exposure related with each of the pedestrian trajectories, the computational domain was discretized in a grid with 240 cellules and 279 nodes, each one correspondent to 10s time walk trajectory. The short-term personal exposure (E) was calculated in the nodes corresponding to the four pedestrian trajectories considered. This discrete grid is shown in figure 8.

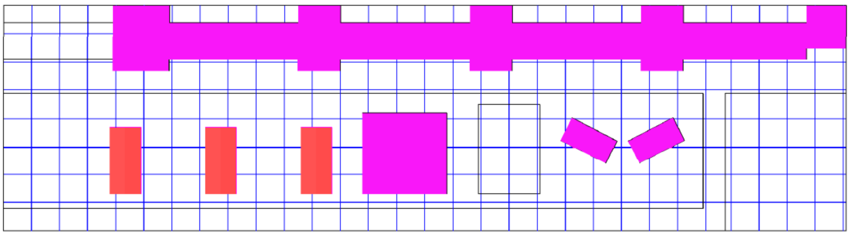

Figure 8- The discrete grid used in short-time exposure calculations

The results obtained to this short-time personal exposure to PM_{10} for the four scenarios (A, B, C and D), under the four main wind directions and to the four pedestrian trajectories considered (1, 2, 3 and 4) are shown in table 6.

Table 6 - Short-term personal exposure to PM_{10} for the four trajectories considered

Pedestrian	Scenario A				Scenario B				Scenario C				Scenario D			
trajectory	W wind	N wind	S wind	E wind	W wind	N wind	S wind	E wind	W wind	N wind	S wind	E wind	W wind	N wind	S wind	E wind
1	6059	6033	6119	6189	6045	6021	6002	6059	6020	6019	6013	6059	6009	6000	6045	6007
2	6066	6036	6138	6175	6049	6016	6015	6068	6045	6012	6011	6064	6057	6030	6089	6045
3	6274	6244	6341	6370	6185	6125	6213	6279	6183	6121	6209	6271	6211	6215	6220	6227
4	6263	6228	6337	6361	6172	6115	6201	6264	6170	6114	6260	6265	6248	6248	6223	6229

All values in $\mu g.s/m^3$

By the analysis of the results it is possible to verify that the lowest value for short-term personal exposure is obtained for pedestrian trajectory 1 in scenario D under North wind conditions. The highest value for short-term exposure is obtained for pedestrian trajectory 3 in scenario D under East wind conditions. It is visible that pedestrian trajectories 3 and 4 are always worst than trajectories 1 and 2. That is related with the fact that trajectories 3 and 4 correspond to crossing the street in an area were the PM_{10} concentration are higher.

7 Conclusions

CFD software Ansys Fluent 12 was used to simulate and study the particle concentrations (PM_{10}) and correspondent short-term personal exposure in a busy street with high road traffic, in Barreiro city in Portugal. Four different configurations for the street, considering various building dimensions and gaps between buildings were simulated. Looking to the results obtained, it is possible to conclude that the street configuration and building geometry have important influence in the results for PM_{10} concentration in the street. The results also show that PM_{10} concentration is strongly dependent of the predominant wind direction. The results for PM_{10} mean concentration at 1,5m high, for west wind and east wind directions show that the better concentrations levels are obtained with configuration D (no gaps between buildings but same volume) because this geometry promotes the dispersion of pollutants as the wind is oriented with buildings. For north wind and south wind directions, configuration B is the one that results in lower concentrations. For these wind directions there are no visible improvements in having higher gaps (6m) between buildings instead of 4m gaps. So the best configuration for this street considering the wind direction and the frequencies of occurrence is configuration B. For theses PM_{10} obtained concentrations, the level of short-term personal exposure in dependent of the pedestrian trajectory considered in the street. The best short-term exposure values are obtained for scenario D (when buildings have the same volume) for trajectory 1 (walking only on the south side of street) and under North wind conditions. The worst short-term exposure is obtained for pedestrian trajectory 3 in scenario A under East wind conditions. We can also conclude that pedestrian trajectories 3 and 4 (crossing the street in the centre of street) are always worst for personal exposure than trajectories 1 and 2.

8 References

Awasthi S., Chaudhry, K.K., (2009) "Numerical simulation and wind tunnel studies of pollution dispersion in an isolated street Canyon", International Journal of Environment and Waste Management, Volume 4, 1-2, 243-255.

Amorim, J.H., Lopes, M., Borrego, C., Tavares, R., Miranda, A.I., (2010) "Air quality modelling as a tool for sustainable urban traffic management", Ecology and the Environment, volume 136.

Di Sabatino, S. Buccolieri, Pulvirenti B, Britter (2008), "Flow and Pollutant Dispersion in Street Canyons using FLUENT and ADMS-Urban", Environ Model Assess, 13:pp.369–381.

FLUENT (2009) Manual, Chapter 4. Turbulence ANSYS, Inc. January

Garcia, J., Coelho, L.,Gouveia C.,, Cerdeira, R.,Louro, C., Ferreira, T.,Baptista M. (2010), "Analyses of human exposure to urban air quality in a children population", International Journal of Environment and Pollution, 1/2/3, 40:pp94-108.

Garcia, J., Cerdeira, R., Tavares, N, Coelho, L. M. R., Kumar, P. (2011), "Comparative study of measured and modeled PM10 concentrations in different building configurations of a urban street canyon", Atmospheric Environment journal (under reviewing)

Kumar, P., Ketzel M., Vardoulakis S., Pirjola L., Britter R., (2011), "Dynamics and dispersion modeling of nanoparticles from road traffic in the urban atmospheric environment – a review", Journal of Aerosol Science, 42, pp.580-603.

Martins, A., Cerqueira M., Ferreira F., Borrego C.,Amorim J. H. (2009), "Lisbon air quality: evaluating traffic hot-spots", International Journal Environment and Pollution, Volume 39, 374, pp.306-320