Comparison of computed and measured wind fields within street canyons

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ABSTRACT

Natural ventilation is one of the most efficient passive cooling techniques for buildings. Knowledge of the wind speed in street canyons is the necessary condition for the application of such a technique in dense urban configurations. Thus, prediction techniques to evaluate the microclimate and dispersion parameters in street canyons, has become a subject of intense scientific research. In most cases, wind flow and pollutant dispersion characteristics have been studied numerically and experimentally. The microscale model MIMO was employed in order to perform a three-dimensional modelling of the wind field within three typical deep street canyons, located in the centre of Athens. Computational results were compared to field data collected during consecutive three-day experimental campaigns that took place in the summer period. Results from the computations have shown that the wind field in urban areas is quite complex, presenting areas of very low wind speeds and convergence of vortices. The model underestimated the measured wind speed intensities, which may be partly explained by the uncertainty of specific input parameters, the necessary simplifications for the application of such models and finally the geometrical complexity of the area modelled. Finally, computations were performed for a reference velocity of 2.5 m/s, which is considered to be a threshold value. The wind field developed departed from the one observed in the previous cases.

1. INTRODUCTION

Natural ventilation is one of the most efficient passive cooling techniques, Santamouris and Assimakopoulos, (1997). Design of naturally ventilated urban buildings requires knowledge of the wind speed characteristics in street canyons, (Santamouris, 2001). Prediction of microclimate and dispersion parameters in street canyons has become a subject of intense scientific research in recent years. Wind and temperature characteristics in dense urban environments are strongly different than those of rural or semi urban areas. Previous studies have shown that the use of non appropriate wind and temperature data in the design of urban buildings may result in important errors regarding the air flow in urban buildings (Geros et al., 1999).

In recent years wind flow and pollutant dispersion characteristics have been studied numerically and experimentally with a view to provide an insight in urban dispersion. Very few field experiments exist regarding the study of the airflow and temperature characteristics in urban street canyons, such as work reported by DePaul and Sheih, (1986), Nakamura and Oke, (1988), Santamouris et al., (1999), and Georgakis and Santamouris, (2004). However, most existing field experiments concern pollution studies such as the one by Vakeva et al., (1999) and Michallef et al, (1998).

For the study of the airflow characteristics in urban areas CFD models based on k-ε two-equation turbulence models, were developed, able to represent successfully the wind flow and pollution dispersion characteristics round single buildings or clusters of obstacles, (Sini et al., 1996; Ehrhard et al., 2000; Jeong and Andrews, 2002). They are the most commonly used models for various types of flow due to their computational robustness and expected efficiency.

Within that frame, the microscale model MIMO was employed in order to perform a three-dimensional modelling of the wind field within three typical street canyons, located in the centre of Athens. Computational results were compared to field data collected during consecutive three-day experimental campaigns that took place in the summer period. The purpose of the present work is to compare the model to the experimental data but most importantly to identify and if possible explain discrepancies between theoretical results and real time data.

2. EXPERIMENTAL METHODOLOGY

The Urbvent research project of the European Commision, (Allard and Ghiaus, 2004), aimed to produce all necessary knowledge to promote the use of natural ventilation in urban buildings. In the frame of project, field experiments were performed during the summer of 2001 in three pedestrian deep street canyons, referred to as Streets A, B and C from here on, in the centre of Athens. On this respect specific experiments have been carried out in street canyons to understand the wind and temperature distribution. The geometrical characteristics of the street canyons are summarised in Table 1. The experimental campaigns, which took place in each of the three canyons, included the following measurements: a) Wind speed and direction (30sec intervals) in the centre of the canyon with pulse output and Porton wind wane anemometers, respectively, placed on a 15.5 m telescopic mast at four different heights (3.5 – 7.5 – 11.5 – 15.5 m). b) Wind speed measurements on three orthogonal axes near both the canyon facades with two three-axis anemometers mounted on the exterior façades of two buildings facing the canyon at a distance from the walls. c) Wind speed and direction at the top of the canyon with a cup anemometer placed at a height of 6 m above the rooftop of the canyon building (see also Fig. 1). The experimental data gathered were subsequently divided in reference velocity groups. More details regarding the experimental campaign may be found in Ghiaus et al., (2005).

Table 1: Description of the experimental site and definition of the in-canyon measurement points.

Geometrical Features	Street A	Street B	Street C
Canyon Width (W) (m)	8	8	9
Building Length (L) (m)	55	70	100
Building Height (H) (m)	23	28	30
W/H Ratio	0.35	0.29	0.3
L/W Ratio	6.88	8.75	11.11
Measurement Points			
1, 2, 3, 4 Wind speed and direction- meteorological mast	middle of street, 20m from north intersection, 3.5, 7.5, 11.5, 15.5 m from ground		
5 Three-axis anemometer, left facade of canyon	1.5m from wall, 5m from northern intersection and 10m from ground		
6 Three-axis anemometer, right facade of canyon	1.5m from wall, 8m from northern intersection and 20m from ground		

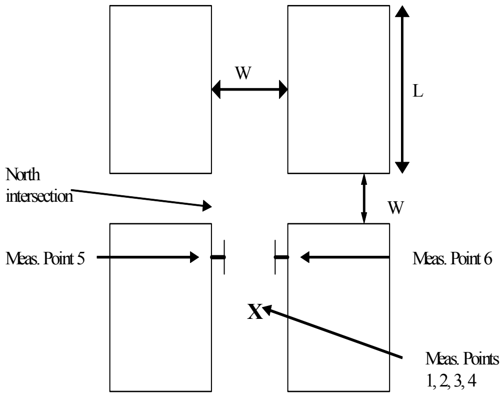

Figure 1: Plan view of the measurement locations inside the three canyons, (drawings not to scale).

3. NUMERICAL CALCULATIONS

3.1 Microscale Model description

The microscale model MIMO (Ehrhard et al., 2000), was initially developed at the Institut fur Technische Thermodynamik, University of Karlsruhe. MIMO solves the Reynolds averaged conservation equations for mass, momentum, energy and scalar quantities such as the humidity or the concentration of pollutants. The *turbulence model* applied is based on the eddy viscosity hypothesis of Boussinesq. The standard k-ε turbulence model has been used. The governing equation described previously is solved numerically on a staggered grid by using a finite volume (FV) discretisation procedure. The conservation equation of mass is formulated in terms of the pressure yielding an elliptic differential equation. The discrete form of the elliptic equation is solved using a preconditioned conjugate gradient (CG) method. For the numerical treatment of advective transport a three-dimensional second order total variation diminishing scheme is implemented. Diffusion terms are treated by a second order central difference scheme. The following boundary equations are needed, which are grouped with respect to the physical behaviour of the flow: Lateral inflow and outflow (Dirichlet and Neumann conditions respectively, except for the pressure, which must be of Neumann type), Solid walls (no-slip condition) and Planes of symmetry.

3.2 Description of the boundary and initial conditions

The central urban complex of Athens consists of multi-storey buildings of approximately the same size with vertical and parallel streets intersecting regularly, presenting thus a quite 'homogeneous' roughness terrain. From the modelling point of view only a few buildings upstream and downstream would be necessary, to achieve a stable internal boundary layer with an urban background profile. In all cases the streets were of similar geometry, the building heights not exceeding 30 m and the street width not exceeding 10 m. All streets are considered deep as their W/H ratios do not exceed 0.35, but not long as their L/W ratios are not greater than 11. This consists of a very complex geometry which would most probably result to big needs in computational memory and time.

The computational domain constructed included three rows of four buildings each, keeping a distance of 5H, 13H and 5H from the inlet, outlet and lateral boundaries respectively. The computational domain consisted for all cases of 200 x 100 x 38 grid cells (only 600,000 cells). Both the main street and the side streets have the same width and all buildings are considered square and have the same length and height. The wind speed direction was assumed to be either perpendicular or parallel to the main street canyon axis.

The experimental data provided a single value for the free stream horizontal wind velocity above the street canyons. Furthermore, the turbulent kinetic energy, k, the rate of its dissipation, ε and the friction velocity u^* were not measured. Thus, the profile of the inflow velocity was considered constant of magnitude u=2.5 and 5 m/s (different wind speed scenarios were considered), the turbulent kinetic energy and its dissipation were given uniform inflow profiles and were computed by $k=3/2(U_rT_i)^2$ and $\varepsilon=C_\mu^{3/4} k^{3/4}/l$, respectively. T_i represents the turbulence intensity and was assumed to be 10% according to theoretical values, U_r is the reference velocity and is set equal to u, the empirical constant $c_\mu=0.09$ and l = 0.07L, where L is a characteristic length; in this case the height of the buildings, H.

4. RESULTS AND DISCUSSION

The flow field developed when the reference velocity is 5 m/s is illustrated in Figure 2 (vertical cut, almost mid-length of the street canyon at the measurement location of the meteorological mast) and in Figure 3 (vertical cut, close to the street intersection at the measurement loca-

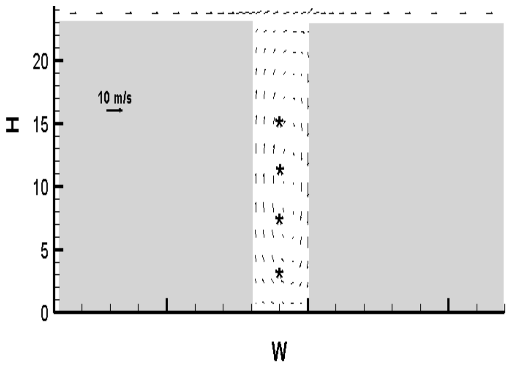

Figure 2: Computed flow field at measurement point of meteorological mast (*: measurement location).

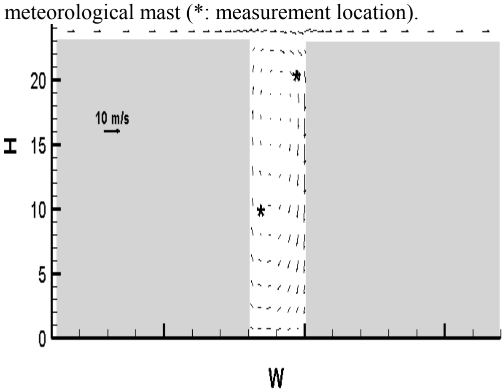

Figure 3: Computed flow field at measurement point of three-axis anemometers (*: measurement location).

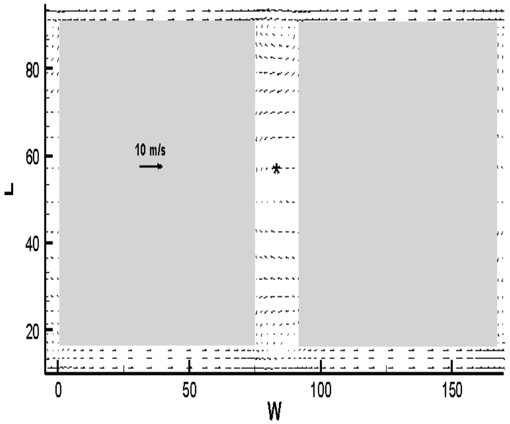

Figure 4: Plan view of computed flow field at a height of 3.5 m (*: measurement location).

tion of the three-axis anemometres). As seen in Figure 2, the flow field developed is characterised by quite small wind speeds inside the canyon and a weak single vortex, its centre being elongated in the vertical direction and leaning towards the right wall of the canyon. The vortex formed departs from the double vortex system observed in two-dimensional deep street canyons (i.e., infinitely long streets), mainly because the street is not long enough thus, enhancing finite canyon effects (from corner vortices) and secondly because it is quite deeper (a typical deep canyon would have a W/H=0.5). As seen in Figure 3, which depicts a vertical section only 10 metres from the north street intersection, the vortex is now lifted its centre reaching the top of the canyon and a weak flow is maintained across the canyon regime, especially at the lower 10 metres of the canyon depth. This may lead to the conclusion that because of the three-dimensional effects the vortex formed moves along the street canyon in a corkscrew-like manner, thus it can not maintain a standard shape, while the vortex centre changes locations according to its motion.

In Figure 4, a plan view of the flow field developed at a height of 3.5 m, is illustrated. The two corner vortices formed at both (north and south) street canyon intersections, are clearly visible. Both vortex centres are close to the right building of the street, they extend along the width of the street covering the distance W completely. Moving along the length L of the street canyon the vortices slowly fade and a weak ‘uniform direction’ flow pattern is evident. The vortices formed weaken at greater heights presenting a more ‘uniform’ flow field.

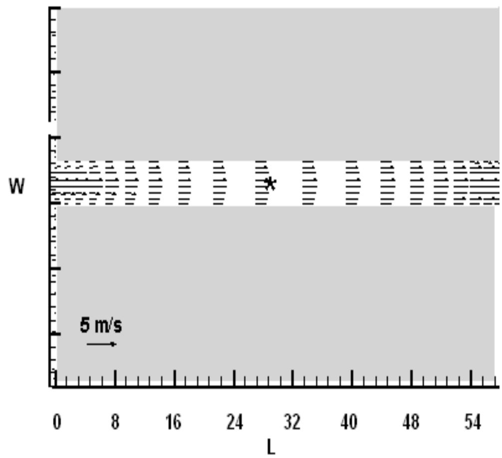

Figure 5: Plan view of the computed flow field at a height of 3.5 m (*: measurement location).

Regarding the parallel flow direction, the wind field established was quite different than the perpendicular case. Plan view of the flow field is given in Figure 5 for a height of 3.5 m (the first measurement point of the mast) the flow field depicted is quite as expected, higher velocities than the perpendicular wind case are developed while the flow is straight, accelerated between the buildings and presents no vortex-like structures. In this case it is important to note that since we assumed the buildings had smooth surfaces, with no balconies extruding from the walls, important features of the real flow are not evident, such as areas of increased local turbulence or small vortices close to the walls, which in reality must be present. The wind speed increases with height.

Simulation results for a reference velocity of 2.5 m/s are given in Figure 6. The flow field developed in this case is quite different from the previous case. This may be attributed to the threshold value given to the reference velocity, which according to current bibliography is the smallest velocity required in order for vortices to form. However, given the deep geometrical configuration of the street it seems that no vortex-like patterns are established. Furthermore, the wind speed inside the canyon is very small, event below 1 m/s. In this case, it would be suggested that thermal effects be taken into account, since they are dominant at very low wind

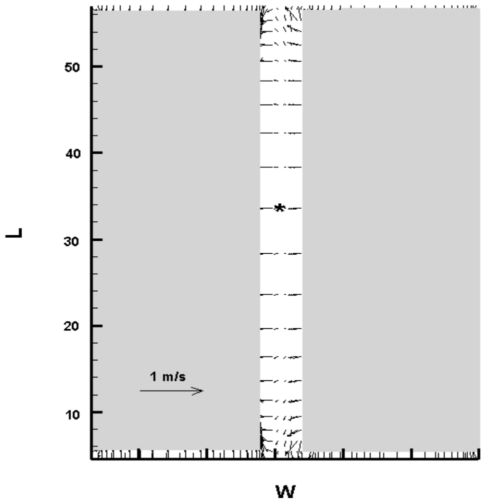

Figure 6: Plan view of the computed flow field at a height of 3.5 m (*: measurement location).

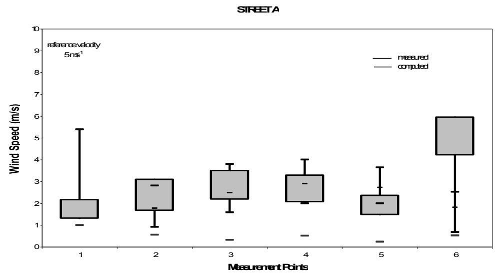

Figure 7: Box plot of computed and measured velocities at different measurement locations, perpendicular wind.

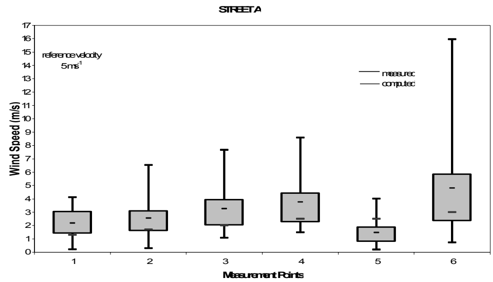

Figure 8: Box plot of computed and measured velocities at different measurement locations, parallel wind.

speeds.

Computations performed for the other streets gave similar wind field patterns while only the wind speed inside the canyon regimes was slightly different. Here again this was expected since the geometrical configuration of all street canyons examined as well as the upstream conditions (spacing of buildings, inlet profiles) are quite similar.

In Figures 7 and 8, box-plot comparisons between measured and computed velocities at all the measurement positions, for all street canyons, for reference velocity of 5m/s and for both the perpendicular and parallel wind directions, are presented. As can be seen the microscale model has underestimated the measured velocities for the perpendicular wind speed case. Interestingly enough, the model has compared well with measured velocities for the parallel wind direction, since in this case the flow is quite simple.

5. CONCLUSIONS

The microscale model MIMO has been compared with data from field experiments performed in three deep urban canyons during the summer period. Results from the computations have shown that:

- The wind field in urban areas is quite complex, presenting areas of very low wind speeds, corner vortices and corkscrew-like flow patterns. No important wind field differences were observed between the three different street canyon cases, which may be explained by their similar geometrical configuration.
- The model underestimated the measured wind speed intensities when the wind was perpendicular to the street canyon axis, while it performed well for the parallel wind direction case.
- Discrepancies between computed and measured velocities may be attributed to modelling simplifications made at initialisation, but most importantly to intermittent vortices of a random character which are present in real field flows but can not be computed by quasi-steady models such as MIMO.
- An additional source of error could also be attributed to thermal effects, which play an important role to the formation of the flow regime especially during the summer, that were not taken into account. Further work should aim at a more detailed modelling of the urban canyons and computation of thermal effects.

REFERENCES

Allard, F. and C. Ghiaus, 2004. Final Report of the URBVENT project, European Commission, Directorate General For Research, Brussels, June.

DePaul, F.T. and C.M. Sheih, 1986. Measurement of wind velocities in a street canyon. Atmospheric Environment 20: 455-459.

Ehrhard, J., I.A. Khatib, C. Winkler, R. Kunz, N. Moussiopoulos and G. Ernst, 2000. The microscale model MIMO: development and assessment. J. of Wind Engineering and Industrial Aerodynamics 85: 163-176.

Georgakis, C. and M. Santamouris, 2004. On the Airflow in Urban Canyons for Ventilation Purposes, The Int. J. Ventilation 3 (1): 53-66.

Geros, V., M. Santamouris, A. Tsangrassoulis and G. Guarracino, 1999. Experimental Evaluation of Night Ventilation Phenomena. Energy and Buildings 29: 141-154.

Ghiaus, C., F. Allard, M. Santamouris, C. Georgakis, C.-A. Roulet, M. Germano, F. Tillenkamp, N. Heijmans, F. Nicol, E. Maldonado, M. Almeida, G. Guaracino, and L. Roche, 2005. Natural Ventilation in Urban Areas -- Results of the European Project URBVENT Part I: Urban Environment, J. Buildings Environment. In Press.

Jeong, S.J. and M.J. Andrews, 2002. Application of the k–ε turbulence model to the high Reynolds number skimming flow field of an urban street canyon. Atmospheric Environment, 36: 1137-1145.

Michallef, A., C.N. Deuchar and J.J. Colls, 1998. Indoor and outdoor measurements of vertical concentration profiles of airborne particulate matter. The Science of the Total Environment 215: 209-216.

Nakamura, Y., and T.R. Oke, 1988. Wind, temperature and stability conditions in an East-West oriented urban canyon. Atmospheric Environment 22 (12): 2691-2700.

Santamouris, M. and D.N. Assimakopoulos, (Editors), 1997. Pasive Cooling of Buildings. London: James and James Science Publishers.

Santamouris, M., (Editor), 2001. Energy and Climate in the Urban Environment. London: James and James Science Publishers.

Santamouris, M., N. Papanikolaou, I. Koronakis, I. Livada and D.N. Asimakopoulos, 1999. Thermal and air flow characteristics in a deep pedestrian canyon under hot weather conditions. Atmospheric Environment 33 (27): 4503-4521.

Sini, J.F., S. Anquetin and P.G. Mestayer, 1996. Pollutant dispersion and thermal effects in urban street canyons. Atmospheric Environment 30 (15): 2659-2677.

Vakeva, M., K. Hameri, M. Kulmala, R. Lahdes, J. Ruuskanen and T. Laitinen, 1999. Street level versus rooftop concentrations of submikron aerosol particles and gaseous pollutants in an urban street canyon. Atmospheric Environment 33 (9): 1385-1397.