

Three-dimensional numerical modelling of air flow in a finite array of square buildings

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1 Introduction

In the past decades, one of the issues that have attracted increased attention is the degradation of air quality in urban, and therefore, densely populated areas. Especially in areas of insufficient ventilation, pollutant concentration reach levels much higher than the limits set by the World Health Organisation, the EU or the local government. The dispersion of pollutants in urban environments is dominated by the wind flow around complex building structures. Down-wash phenomena and increased local turbulence strongly influence not only the mean flow field but also the diffusion parameters. A typical configuration is the so-called street canyon, formed along a street in a densely built urban area. At the bottom of a street canyon, the vehicles emit gaseous pollutants in the form of buoyant plumes. Under certain conditions, e.g. for non-zero wind component perpendicular to the street, higher concentration levels are observed on the leeward than on the windward side of the street canyon, assuming the street canyon is infinitely long. In reality not all street canyons are two-dimensional in the sense that they are not infinitely long. In most urban areas a main street is intersected at regular intervals with other smaller or bigger streets, thus giving rise to more complex wind field patterns than the ones met when a flow is considered to be two-dimensional. Due to their rather coarse resolution, mesoscale models can not predict these influences accurately and, therefore, in the recent years microscale models have been developed which explicitly take into account the building structure and provide a much more detailed insight into urban dispersion. Nevertheless, atmospheric flow and pollutant dispersion over urban areas is affected by phenomena belonging to different scales. Regional transport and the flow in the upper part of the planetary boundary layer are mainly determined by mesoscale phenomena. Hence, multiscale model systems are being developed, starting at local-to-regional scale and going down to the microscale. An example of such a model system is ZEUS, which is currently under development at the Aristotle University of Thessaloniki, based on the mesoscale model MEMO¹ and the microscale model MIMO². Within that frame the microscale model MIMO, was employed in order to study the three-dimensional characteristics of wind flow in a finite array of square rings of buildings. The case was studied experimentally³, and MIMO was validated against the available experimental data. Furthermore, the wind flow pattern developed at several locations away from an intersection is studied.

2 Microscale Model Description

The microscale model MIMO is a three-dimensional model for simulating microscale wind flow and dispersion of pollutants in built-up areas. It solves the Reynolds averaged conservation equations for mass, momentum, energy and other scalar quantities such as the humidity or the concentration of pollutants. The conservation equation of mass is formulated in terms of the pressure, yielding an

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elliptic differential equation. The discrete form of the elliptic equation is solved using a preconditioned conjugate gradient (CG) method. The standard k - ϵ two-equation turbulence model is used for this particular study. For the numerical treatment of advective transport a three-dimensional second-order flux-corrected transport scheme (FCT) is applied. Within MIMO a finite volume discretisation procedure is adopted for solving the governing equations on a staggered grid arrangement. Coordinate transformation is applied to allow non-equidistant mesh size in all three dimensions in order to achieve a high resolution near the ground and near obstacles. In the model MIMO there exist several possibilities for initialisation: measured inflow data, theoretical inflow profiles.

3 Inflow profiles and boundary conditions

The experimental set-up suggested a computational domain including 4 rows of 14 buildings each, with size $0.25 \times 0.25 \times 0.06$ m and thus a grid of $270 \times 110 \times 40$ cells approximately. This would not be feasible for application. Only a few buildings upstream would be necessary, to achieve a stable internal boundary layer and to be far enough from the inlet boundary. Thus, the computational domain constructed included two rows of six buildings each, keeping a distance of $5H$ away from the inlet boundary, a distance of $13H$ away from the outlet boundary and a distance of $5H$ away from the lateral boundaries, where $H=0.06$ m. The computational domain consists of $180 \times 72 \times 38$ grid cells (Figure 1).

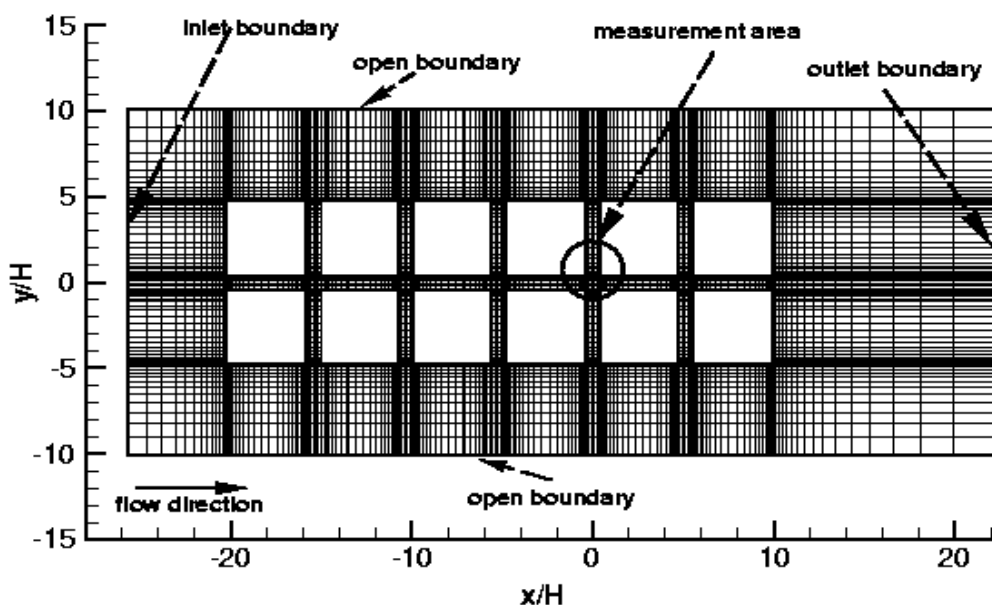


Figure 1 Plan view of the computational domain.

The main street extends along the x -axis, intersected regularly by side streets, which extend along the y -axis. Both the main street and the side streets have the same width, i.e., 0.06 m. The friction velocity $u^*=0.37772$ m/s, the roughness $z_0=0.0004$ m and the profile exponent $\alpha=0.22$, which were derived from the experiment were used for determination of the inflow profiles. The velocity was computed using the power law, $u=U_{ref} (z/z_{ref})^\alpha$, where $U_{ref}=5.37$ m/s, and $z_{ref}=0.4$ m. The turbulent kinetic energy was given a uniform inflow profile, $k=u^{*2}/C_\mu^{0.5}$, where, $C_\mu=0.09$. The dissipation was calculated as, $\epsilon=u^{*3}/\kappa z$, where $\kappa=0.41$ is von Karman's constant. At the inlet, Dirichlet boundary conditions were implemented, whereas Neumann boundary conditions were implemented at the outlet. The top of the computational domain is considered to be a symmetry boundary. At solid walls the no-

slip condition is employed and the wall function employed for the representation of the flow is Sondak and Pletcher⁴. The lateral boundaries are open.

4 Discussion of results and conclusions

The microscale model MIMO was applied in order firstly to validate its performance against a complex computational domain and secondly to study the three-dimensional characteristics of wind flow close and far away from an intersection, inside a street canyon. Variables x , y , and z were made dimensionless by dividing by the building height (H), and the velocity u by dividing by U_{ref} . Thus, in Figure 2, a comparison is given between the measured dimensionless horizontal velocity profile at location $x/H=0, y/H=1$ and the dimensionless horizontal velocity profile as computed by MIMO. The agreement between measured and computed velocity is very good. The measurement area is located near the street intersection, where the wind field established is quite complicated (Figure 3). The flow is parallel to the axis of the main-street and perpendicular to the axis of the side-street. The flow seems steady away from the intersection, but at the intersection it is disturbed by a recirculation vortex-like structured flow emerging from the side-street and oriented towards the leeward corner of the side-street. The flow is symmetric as the same pattern occurs from both sides of the main-street. Moving from location A to location B along the side-street, the wind gradually rotates and blows from the windward to the leeward wall of the side-street, at approximately $y/H=1.4$, changing direction again and blowing at an angle from the windward to the leeward wall, tending to become parallel to the axis of the street. It thus flows in a corkscrew-like manner. In Figures 4 and 5 a side view of the wind field developed at locations A and B respectively is given. At location A, a main vortex is established, whose centre is tilted towards the lower windward corner, obviously affected by the presence of the intersection. However, at location B, the main vortex established is centred and is identical to the wind field evolved for a two-dimensional street canyon. Thus, the distance from the intersection is large enough to affect the wind field.

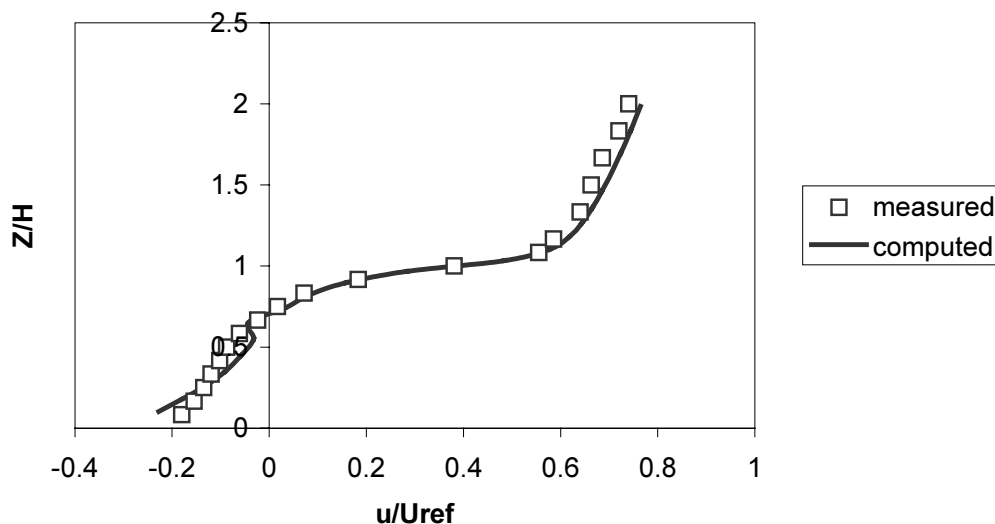


Figure 2 Comparison of measured dimensionless horizontal velocity to computed for location ($x/H=0, y/H=1$).

Concluding, it is important to note that MIMO performed very well even after the simplifications made. The three-dimensional nature of a street canyon produces corkscrew-like vortices and thus a more complicated wind field. It is essential to alter the wind direction in order to study the effects on the wind filed patterns. Furthermore, the concept of the two-dimensional street-canyon is true as long as its length is 3 to four times larger than its width.

5 References

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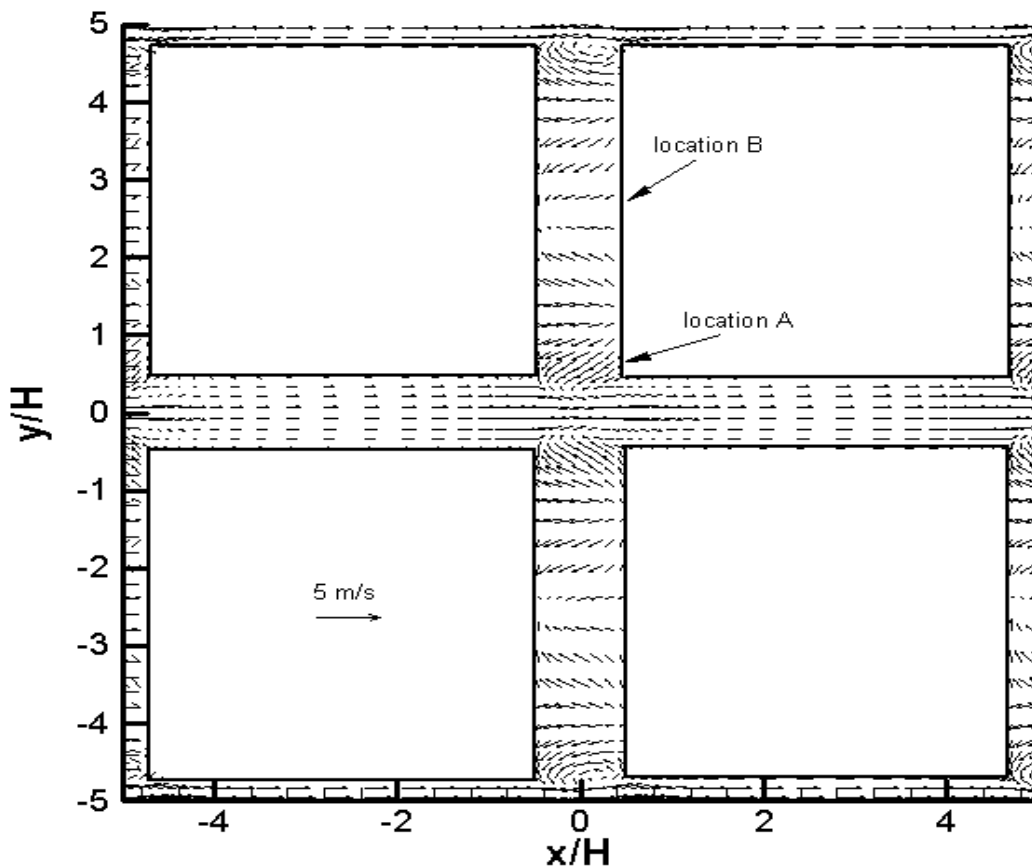


Figure 3 Wind field established at the measurement area at height $z/H=0$.

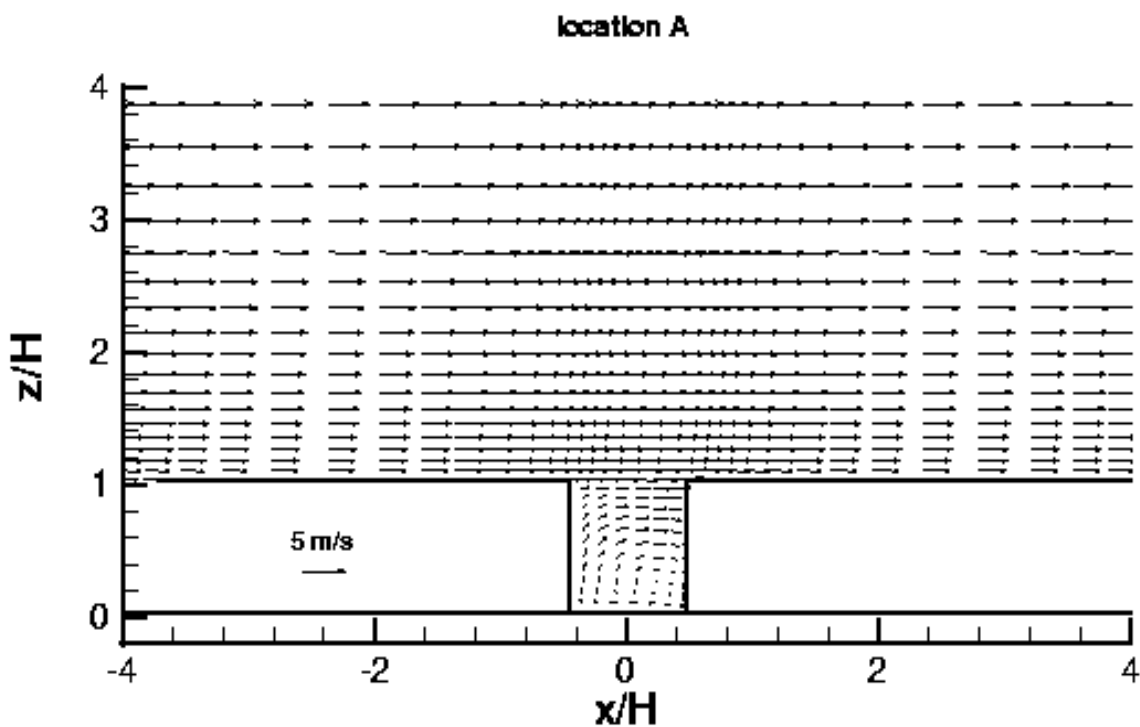


Figure 4 Side view of wind field developed at location A.

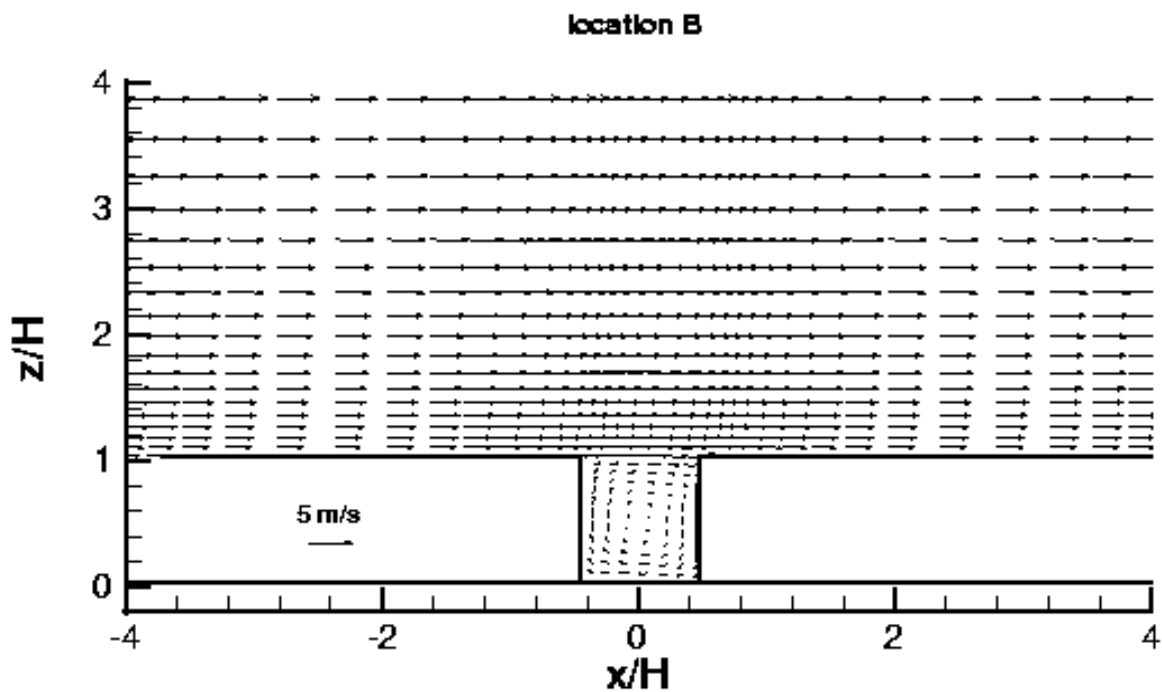


Figure 5 Side view of wind field developed at location B.