Influence of Geometry on the Flow and Turbulence Characteristics Within Urban Street Canyons – Intercomparison of Wind Tunnel Experiments and Numerical Simulations

A. Kovar-Panskus[+], P. Louka[++], J-F. Sini[++], E. Savory[+], M. Czech[+], A. Abdelqari[++], P.G. Mestayer[++], N. Toy[+]

[+]University of Surrey, Dept. of Civil Engineering, Guildford GU2 7XH, Surrey, UK
[++]ECN Ecole Centrale de Nantes, Laboratoire de Mecanique des Fluides, 44321 Nantes, France

Introduction

The flow within urban street canyons has been studied for several decades. Georgii et al. (1967), followed by DePaul and Sheih (1986), described the recirculation system that is established in the mean flow within a street canyon exposed to a perpendicular oncoming flow. As this vortex also drives the distribution of pollutants within the canyon, the manner in which the flow and the associated turbulence quantities, governing the dispersion, are dependent on the variation of the aspect ratios also became of major interest. Oke (1987) developed a scheme, still in use, to classify the flows associated with different street canyon aspect ratios (Width(W)/Height(H)). The present investigation has been conducted in a wind tunnel at the University of Surrey where a nominally 2-D street canyon was exposed to perpendicular flow conditions and the aspect ratio varied, according to Oke's scheme, from W/H of 0.3 to 2.0. Pulsed-wire-anemometry was used to measure all 3 mean and unsteady wind-components and also to determine the associated turbulence quantities such as Normal and Reynolds stresses and the 3-D turbulent kinetic energy (TKE). The aim was to gain a deeper knowledge of the flow behaviour inside the canyon and to investigate whether transitions between different flow regimes occur. In parallel to these experiments, the same aspect ratios were numerically simulated at ECN using the numerical code CHENSI, Sini et al. (1996), Louka (2000), in order to validate the model code using the data provided by the wind tunnel.

Methodology

A nominally 2-D cavity of fixed depth, H=106mm, was set up in the neutral boundary layer wind tunnel at the University of Surrey (Fig. 1). The boundary layer was fully developed with a height of δ=737 mm (δ/H=6.95) (Fig. 2), a roughness length z_0=0.26 mm, a displacement height d=8 mm and a friction velocity u_*/U_{ref}=0.051, based on the freestream velocity of U_{ref}=8m/s. The resulting Reynolds number was $5.6\text{x}10^4$, based on the cavity depth. The measurements were conducted with a pulsed-wire anemometer, which gives simultaneous flow speed and direction (Savory (1984) and Castro and Cheun (1982)). The freestream turbulence level, defined as u'/U_{ref}, was approx. 9%. The sampling rate was 50 Hz and a measurement time of 6 minutes per point guaranteed stationary and repeatable values. The measurement data were accurate to within +/-10% for the mean values and +/-15% for the stresses. Reconstruction of the 3 components required 5 sets of measurements at each point, each with a different probe orientation.

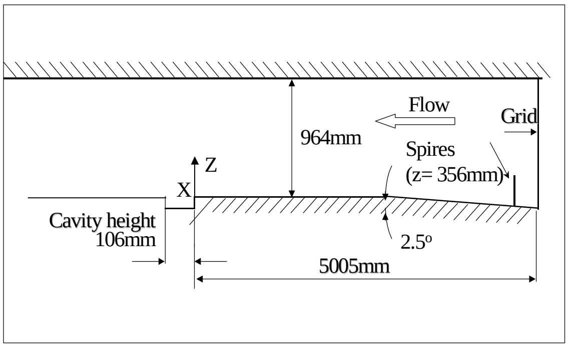


Fig. 1 Diagrammatic representation of the cavity.

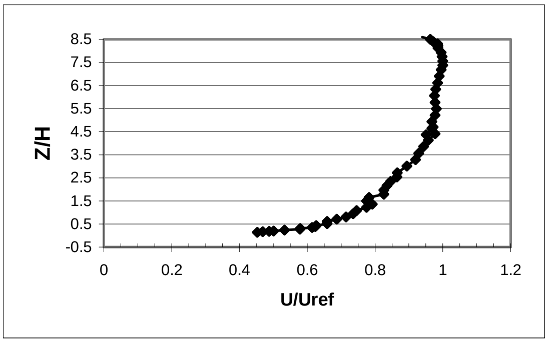


Fig. 2 Oncoming boundary layer velocity profile.

The k-ε numerical model CHENSI, developed at ECN by Sini et al. (1996), has been used for a comparison in order to validate the code. It is based on a staggered Arakawa-c-grid and solution of the incompressible Navier-Stokes-equations. The model has been run in 2-D, providing the mean velocities and the turbulent kinetic energy for the streamwise (X) and vertical (Z) wind components.

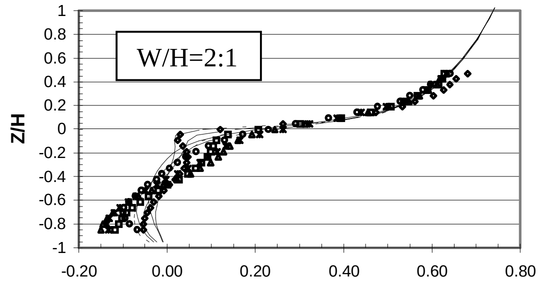
To enable the comparison, the boundary layer profiles for wind speed and turbulence have been used at the inlet of the calculated domain.

Results and Discussion

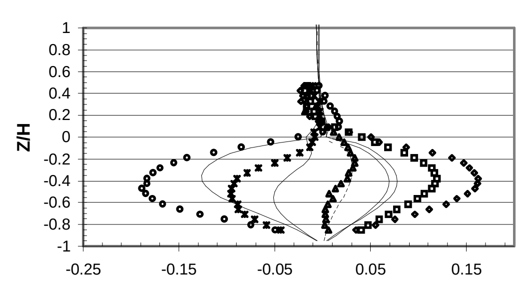
The wind tunnel measurements show, for all aspect ratios (W/H) studied, the skimming flow regime. This is in good agreement with Johnson and Hunter (1999) who observed in a field study a skimming flow regime up to a threshold of W/H=2.5, whereas Hunter et al. (1992) and Sini et al. (1996) found a threshold value of 1.54 within their numerical studies. Model predictions and measurements agree that a) for the ratios of 1.0 and 2.0 a single strong vortex is found inside the cavity, b) the 0.7 case one vortex is also observed, together with a small recirculation region near the ground next to the windward wall, c) in the 0.5 case two vortices are measured, these being a more pronounced primary vortex in the upper half of the cavity and a weaker secondary vortex covering the lower half of the cavity, d) the same feature, but less pronounced, is found for the case of 0.3, where the velocity is essentially zero in the first third above the ground of the cavity, indicating a flow that is weakly connected to that above the cavity, giving very poor ventilation properties. The comparison of the mean u wind component (Fig. 3a-e) between the wind tunnel and the numerical simulation show, for the narrower cases of 0.3 and 0.5, a good agreement inside the cavity and small discrepancies above it. This is exactly vice versa for the wider cavities of 0.7, 1 and 2:1. For the w component (Fig. 4a-e) the general behaviour of the different profiles within the different case studies is in good agreement. However, the discrepancies between the numerical simulations and the wind tunnel measurement are of the same order of magnitude as in the u component or even better. The best agreement can be found on the centreline profile for all the different cases with the exception of the narrowest case of 0.3. Obviously, here the flow is so weak that not even the flow direction agreed between calculation and measurement. The main differences occur for the u component close to the bottom of the cavity, probably due to the implementation of the wall function used by CHENSI. In general, CHENSI underestimates the u component close to solid boundaries. However, at locations where the flow is weak CHENSI generally predicts well.

Concluding Remarks

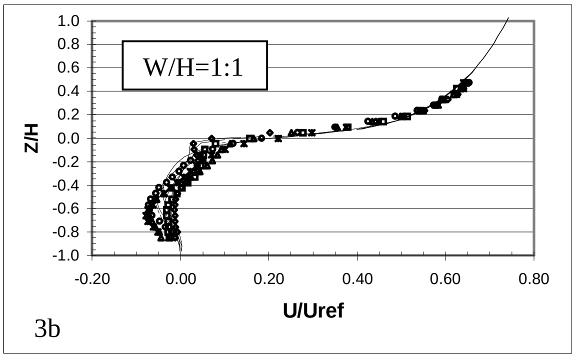
A wind tunnel investigation and a numerical study have been conducted to investigate the flow and turbulence structures within a nominally 2-D cavity with W/H varied from 0.3 to 2.0. The comparison has been performed for the mean horizontal and the vertical wind velocities. For all cases under consideration the skimming flow regime has been observed, indicating that the transition to wake interference flow takes place at a larger threshold value above 2.0. The agreement between the wind tunnel measurements and the numerical study was very good for these boundary layer conditions, as is to be expected because the same inlet conditions were used. Within the cavity the agreement was very good on the centrelines of the different cases, whereas it was less good towards the sides of the cavity. To complete the comparison the turbulent kinetic energy (TKE) will also be calculated and presented in the full paper.



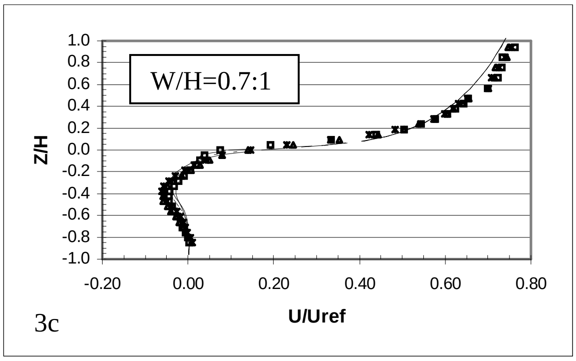
3a



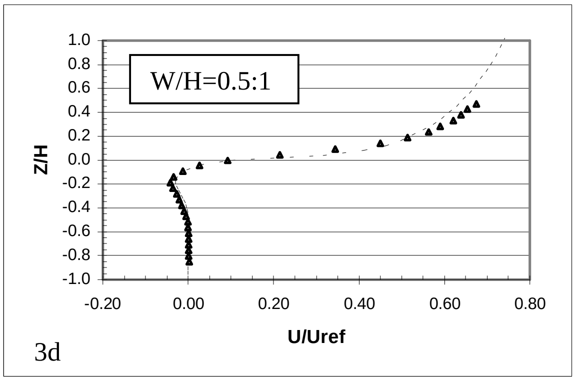
4a



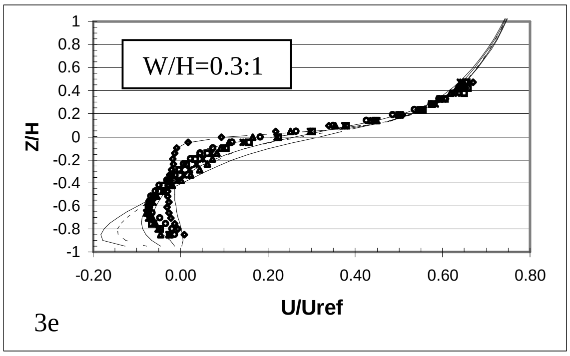
3b



3c

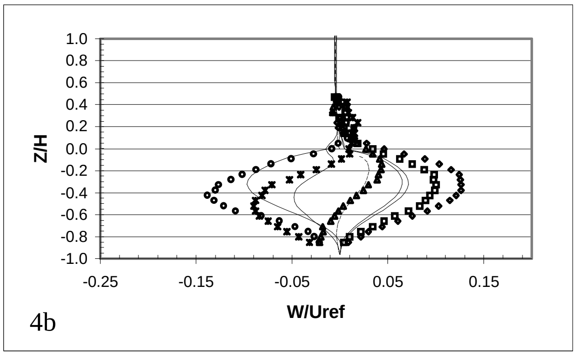


3d

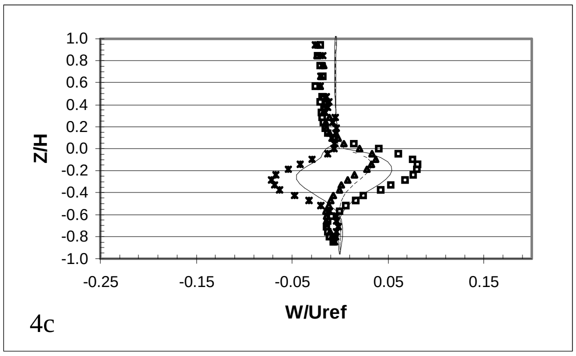


3e

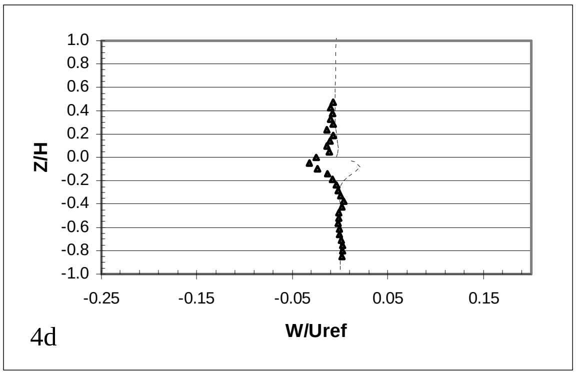
Fig. 3a-e (left) shows the profiles of the u component.



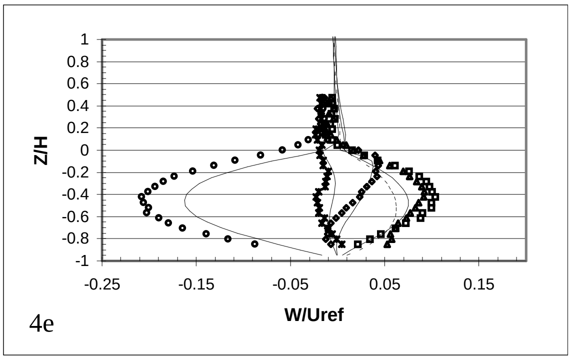
4b



4c



4d



4e

Fig. 4a-e (right) shows the w component, with from the top: 2:1, 1:1, 0.7:1, 0.5:1 and 0.3:1.

_…X/W=0.2 NC, ◊ X/W=0.2 WT, _._X/W=0.3 NC, X/W=0.3 WT, … X/W=0.5 NC, △ X/W=0.5 WT, _ _ X/W=0.7 NC, * X/W=0.7 WT, __ X/W=0.9 NC, ○ X/W=0.9 WT
(NC stands for Numerical Calculation, WT for Wind Tunnel measurement. For the cavities 0.7, 1, and 2, the first and the last profile differ slightly from the given ratio due to a necessary alignment of the pulsed wire system.)

References

Castro, IP and Cheun, BS (1982) The measurement of Reynolds stresses with a pulsed-wire anemometer, *Journal of Fluid Mechanics* **118**, 41-58

DePaul, FT and Sheih, CM (1986) Measurements of wind velocities in a street canyon, *Atmospheric Environment* **20**, 555-559

Georgii, H.W., Busch, E. Weber, E (1967) Untersuchung ueber die zeitliche und raeumliche Verteilung der Immissions-Konzentration des Kohlenmonoxids in Frankfurt am Main, *Berichte des Instituts fuer Meteorologie und Geophysik der Universitat Frankfurt am Main* **11**

Johnson, GT and Hunter, LJ (1999) Some insights into typical urban canyon airflows, *Atmospheric Environment* **33**, 3991-3999

Louka, P (2000) Internet-publication on http://www.dmu.dk/AtmosphericEnvironment/trapos/cfd-wg.htm, Code descriptions: Table_codes.doc

Hunter, LJ, Johnson, GT, Watson, I.D (1992) An investigation of three-dimensional characteristics of flow regimes within the urban canyon, *Atmospheric Environment*. **26B**, 425-432

Oke, TR (1987) Boundary layer climates, Routledge, New York, 2nd edition

Savory, E (1984) Hemispheres in turbulent boundary layers, PhD Thesis, University of Surrey

Sini, JF, Anquetin, S, Mestayer, P (1996) Pollutant dispersion and thermal effects in urban street canyons, *Atmospheric Environment*. **30**, 2659-2677

Acknowledgements

The authors gratefully acknowledge funding from the EU within the TMR project TRAPOS (Contract ERBFMRXCT97-0105). The authors should also like to thank Mr T Renouf for his contribution to this research. The ECN group also acknowledges the computer support given by Institut de Developpement et de Recherche pour l’Informatique Scientifique (IDRIS), France.