5.34 AN EXPERIMENTAL STUDY OF THE INFLUENCE OF A TWO-SCALE SURFACE ROUGHNESS ON A TURBULENT BOUNDARY LAYER

Salizzoni, P.[1]*, Cancelli, C.*[1]*, Perkins, R.J.*[2]*, Soulhac, L.*[2] *& Méjean, P.*[2]
[1]Politecnico di Torino, DIASP, Italy
[2]Laboratoire de Mécanique des Fluides et d'Acoustique, CNRS UMR 5509
Ecole Centrale de Lyon, France

INTRODUCTION

In order to model flow and dispersion in urban areas we need to be able to:

- characterise the lower part of the atmospheric boundary layer, where the flow dynamics are typically determined by the size and the density of the buildings and by the street geometry (Wieringa, 1993, Bottema, 1997, McDonald, 2000, Grimmond and Oke, 1999, Rotach, 1999)
- parameterise the mass exchange between the recirculation region in the street canyons and the external flow (Berkowitz, 2000, Souhlac, 2000, De Paul and Sheih, 1985 , Caton et al., 2003).

In this study we focus on some aspects of these processes that are still not completely understood:

- how does the presence of small scale roughness (roof shape, chimney....) at the top of the buildings affect flow and dispersion characteristics in the turbulent flow above buildings roofs?
- which are the relevant processes in determining the mass exchange between the recirculation region and the external flow – what is the influence of the small scale roughness on the structure of atmospheric turbulence, and on the shear layer instabilities at the interface?

In order to answer these questions we have performed a wind tunnel investigation of the flow dynamics and scalar dispersion in the near-ground region of a neutral atmospheric boundary layer.

EXPERIMENTAL SETUP AND MEASUREMENT TECHNIQUES

The study has been carried in a recirculation wind tunnel in the Laboratoire de Mécanique des Fluides et d'Acoustique at the Ecole Centrale de Lyon.
The boundary layer was generated using a combination of three spires located at the entrance to the test section, with a lateral spacing equal to half the spire height (Irwin, 1981) and small roughness blocks on the floor of the tunnel. The boundary layer thickness at the point where the measurements were made was about equal to 0.5 m.

An idealised street geometry was simulated by an array 2D parallel canyons, made of a set of square section bars (0.06m x 0.06m) placed normal to the wind. The influence of the roof roughness was studied by adding small scale 2D roughness elements (0.05m x 0.05m) to the tops of the bars (Fig 1).

The spacing between the bars could be varied, and measurements have been performed for three values of the height to width ratio (H/W=1, 2, ½). According to Oke (1988) the first two configurations correspond to skimming flow, whilst the third condition corresponds to wake

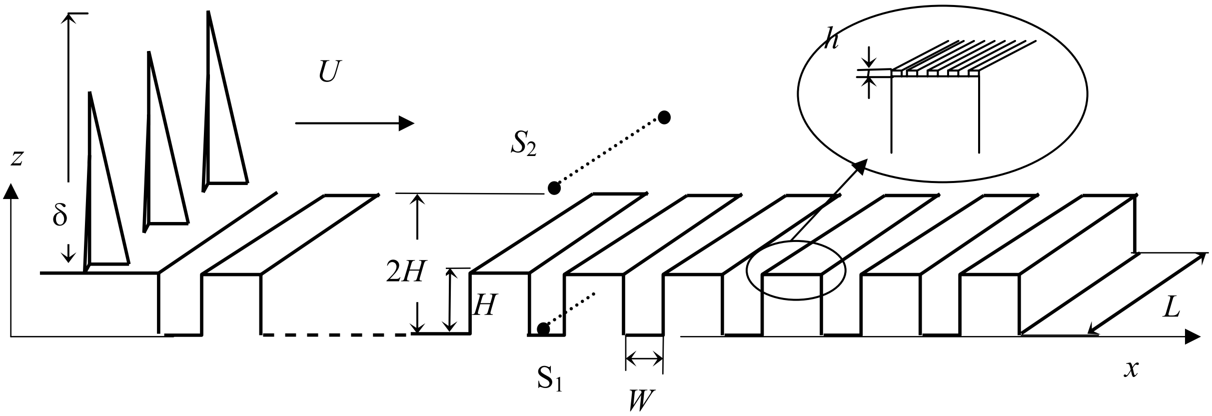

Figure 1. Experimental set up

interference flow. In all three configurations the experiments were carried out first without small scale roughness (cases 1, 2 and 3) and then with the roughness (cases 1a, 2a, and 3a).

There are therefore three typical length scales for the flow – the boundary layer thickness ($\delta \cong 0.5$ m), the 2D obstacle height (H=0.06 m) and the small scale roughness at the top of the obstacles (h=0.005 m). These dimensions were chosen to preserve a realistic ratio between an adiabatic atmospheric boundary layer thickness (~100m), a typical building height (~10m) and a smaller scale element at the top of the of buildings as chimney, roof shape (~1m); the typical scale ratio is of the order of 1/166.

Three different experiments were conducted for each geometrical configuration:

- the profiles of mean and fluctuating velocities were measured in the boundary layer above the obstacles;
- a passive scalar was released from a line source placed at a height of 2H, and concentration profiles were measured downstream of the source;
- the mass exchange between the canyon and the external flow has been estimated by measuring the time for the pollutant to be washed out of the cavity.

Fluid velocities were measured using hot wire anemometry and tracer gas concentrations were measured using a Flame Ionisation Detector. Ethane was used as the passive tracer, since its molecular weight is nearly the same as that of air.

RESULTS

Velocity profiles

Profiles of mean and fluctuating velocities are shown in Figure 2, for configuration 1 (H/W=1), without and with the small scale roughness. The results were broadly similar for configuration 2 (H/W=2) so, for clarity, these results are not shown. The small scale roughness did not have any measurable influence on the velocity profiles for the third configuration (H/W=½).

The mean velocity profiles can be modelled reasonably well using either a logarithmic profile:

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z-d}{z_0}\right) \tag{1}$$

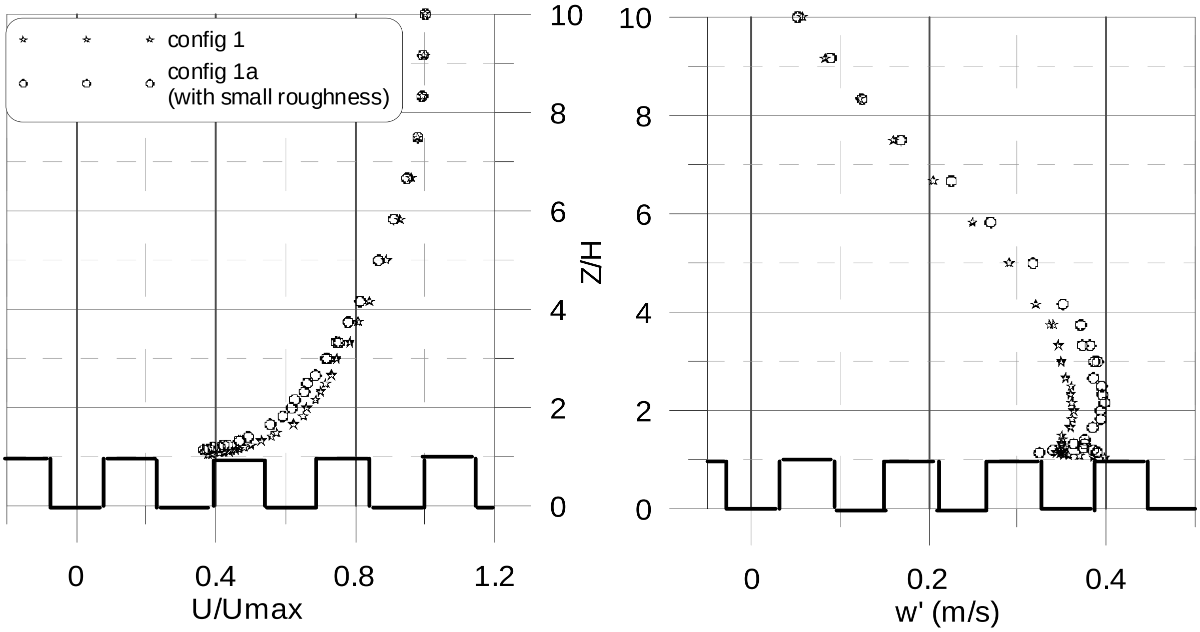

Fig 2. Mean wind speed and vertical fluctuations profiles for H/W=1 configuration

or a power law:

$$\frac{U(z)}{U_\infty}=\left(\frac{z-d}{\delta-d}\right)^n \qquad (2)$$

where κ is the Von Karman constant and δ is the boundary layer depth. The different values of roughness height z_0, friction velocity u_* and displacement height d for the different configurations are given in Table 1.

Table 1. Mean wind speed profiles parameters

	config 1	config 1a	config 2	config 2a	config 3	config 3a
H/W	1	1	2	2	1/2	1/2
Small roughness	no	yes	no	yes	no	yes
z_0 (mm)	0.263	1.147	0.191	0.500	6.345	6.346
u_* (m/s)	0.33	0.36	0.305	0.335	0.41	0.41
d (mm)	55	55	60	60	50	50
n	0.21	0.25	0.18	0.212	0.34	0.34

The profiles of fluctuating velocities (u' and w') and the Reynolds stress show that the small scale roughness causes an increase in these terms, and a corresponding decreases in the mean velocity.

The profiles for the configuration 3 (H/W=½) show that the small scale roughness does not influence the flow at all. This is probably due to the fact that the turbulence generated by shear at the interface between the recirculation region and the outer flow has enough space to grow and dominates the smaller scale structures generated by the small elements at the top of the bars.

Passive scalar dispersion

Mean concentration profiles have been measured at different distances downstream of a line source placed either on the floor of the cavity, at the mid point, or at a height of 2*H* above the

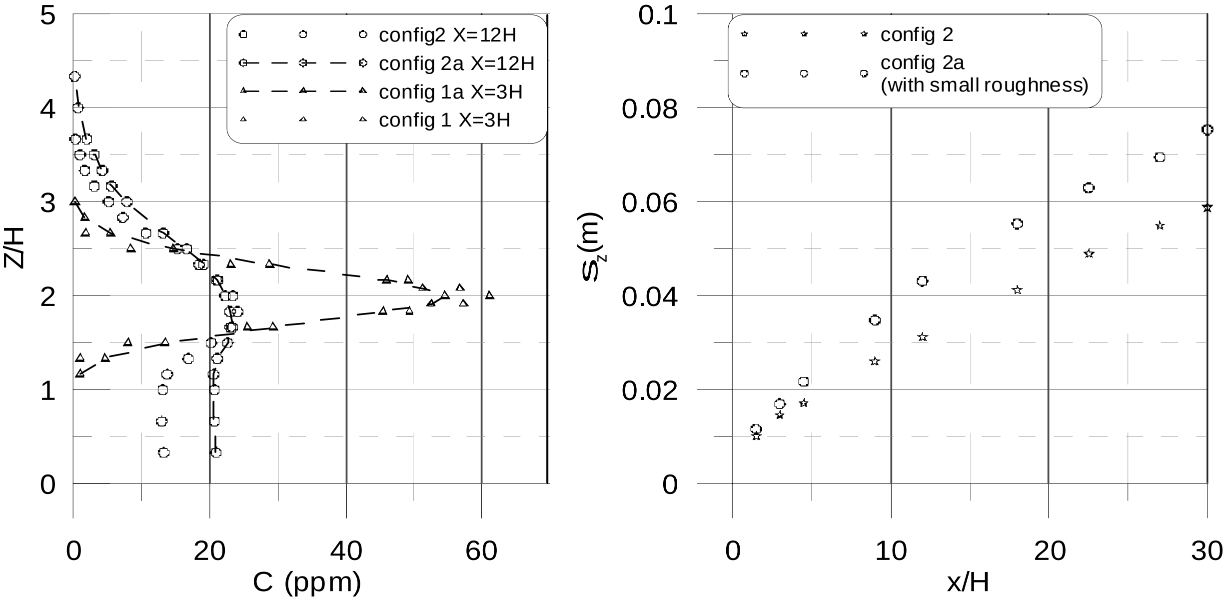

Figure 3. Mean concentration profiles at increasing distances from the elevated line source (Z=2H) and spatial evolution of the plume spreading for the H/W=2 configuration, with and without the small roughness elements

floor (Figure 1). As shown in Fig. 3a, the small scale roughness induces an increase of the vertical extent of the plume of pollutant as it travels downstream. The vertical spread of the plume (σ_Z) has been estimated by fitting a simple Gaussian plume (with image source) to the measured profiles. Figure 3b shows the evolution of σ_Z with distance from the source; this confirms that the small scale roughness increases the vertical dispersion of the tracer.

As with the fluid velocities, the small scale roughness only has a significant effect on dispersion when the cavity aspect ratio less than or equal to 1; it has no effect in the wake interference regime.

Transfer at the top of the cavity

In order to evaluate the typical time scale for mass transfer between the recirculation region and the external flow, we measured the temporal evolution of ethane concentration in the cavity as it empties (Caton et al., 2003). The concentration was measured at the centre of the cavity, and the experiment was repeated 30 times, for each configuration, to allow an "ensemble" average for the signals.

The results in Table 2 show that the wash-out time depends somewhat on the geometry of the cavity, since it falls for H/W=½. However the small-scale roughness has no detectable influence, irrespective of the canyon geometry. This is probably because the wash-out time is determined principally by the large scale eddies in the flow, which remain relatively unaffected by the small scale turbulence.

Table 2. Wash out time of the cavity (seconds)

	Without small roughness	With small roughness
H/W=1	0.77	0.77
H/W=1	0.77	0.77
H/W=2	0.77	0.77
H/W=2	0.77	0.77
H/W=1/2	0.58	0.58
H/W=1/2	0.58	0.58

CONCLUSIONS

The influence of small-scale roughness elements on flow and dispersion above a street canyon has been studied for a range of canyon aspect ratios, using wind tunnel experiments. The small scale roughness increases the turbulence and the vertical dispersion for high aspect ratio cavities ($H/W \geq 1$) but it has very little effect for low aspect ratio cavities. This is probably because the shear layer at the interface has more time to develop, and the flow is then dominated by the shear-induced turbulence. The wash-out time for the cavity decreases as we pass from skimming to wake interference flow and seems to be completely independent of the small scale roughness; this confirms the idea that the primary mechanism for transfer in and out of the canyon is the shear-induced turbulence at the interface.

REFERENCES

Berkowicz, R. 2000. Operational street pollution model – a parameterised street pollution model. Environmental Monitoring and Assessment 65 (1-2), 323.

Bottema, M. 1997. Urban roughness modelling in relation to pollutant dispersion. Atmospheric Environment 31, 3059-3075.

Caton, F., Britter, R.E. & Dalziel S. 2003. Dispersion Mechanism in a Street Canyon. Atmospheric Environment 37, 693-702.

DePaul, F.& Sheih, C., 1986. Measurement of wind velocities in a street canyon. Atmospheric Environment 20 (3), 455.

Grimmond, C.S.B. & Oke T.R., 1999. Aerodynamic properties of urban areas derived from analysis of surface form. Journal of Applied Meteorology 38, 1262-1292.

Irwin, H.P.A.H. 1981. The Design of Spires for Wind Simulation. J. Wind Eng. And Industrial Aerodynamics, Amsterdam, pp. 361-366.

Macdonald, R. W. 2000. Modelling the mean velocity profile in the urban canopy layer. Boundary-Layer Meteorology, 97, 1-21.

*Oke, T.R. 1988.*Street design and urban canopy layer climate. Energy and Buildings 11, 103-113.

Rafailidis, S. 1997. Influence of Building Areal Density and Roof Shape on the Wind Characteristics above a Town. Boundary-Layer Meteorology. 85, 255-271.

Rafailidis, S., Pavagneau, M. and Schatzmann, M. 1995. Wind Tunnel Simulation of Car Exhaust Dispersion in Street Canyons – The Effects of Slanted Roofs. In S.E. Gryning and F. Schiermeier (eds.), Air Pollution Modelling and its Application XI, Plenum Press, New York, pp. 653-654.

Rotach, M. W. 1999. On the influence of the urban roughness sublayer on turbulence and dispersion. Atmospheric Environment **33**, 4001-4008.

Soulhac, L. 2000. Modélisation de la dispersion atmosphérique à l'interieur de la canopée urbaine. Phd Thesis, Ecole Centrale de Lyon.

Wieringa, J. 1993. Representative roughness parameters for homogeneous terrain. Boundary-Layer Meteorology, **63**, 323-363.