EXPERIMENTAL STUDY OF TURBULENCE AND VERTICAL TEMPERATURE PROFILE IN THE URBAN BOUNDARY LAYER

Kono, H.[1], Tamura, D.[1], Iwai, Y.[1], Aoki, T.[1], Watanabe, S.[1], Nishioka, M.[2], Ito, Y.[3], Adachi, T.[4]

[1]University of Hyogo, [2] Osaka Prefecture University, [3]Kaijo Sonic Corporation, [4]University of Yamanashi

1. INTRODUCTION

Recently, the dispersion of motor vehicle exhaust gas has been predicted using the new generation models in urban areas (Valkonen et al., 1995, Werferi, 1995). The Monin-Obukhov similarity theory has often been used in the models. However, the similarity theory cannot be applied within the roughness sublayer where the flow is three-dimensional, due to the influence of individual roughness elements (Rotach, 1993). The reason why the similarity theory cannot be applied in the roughness sublayer is not known. Since the mechanical turbulence generated by buildings is large in the lower part of the urban boundary layer, the turbulence in the roughness sublayer may deviate from the empirical formula at smooth sites (i.e. Monin-Obukhov similarity theory).

We studied the turbulence and vertical temperature profile in the lower part of the urban boundary layer by conducting field observations in Himeji City, carrying out wind tunnel experiments, and numerical simulations.

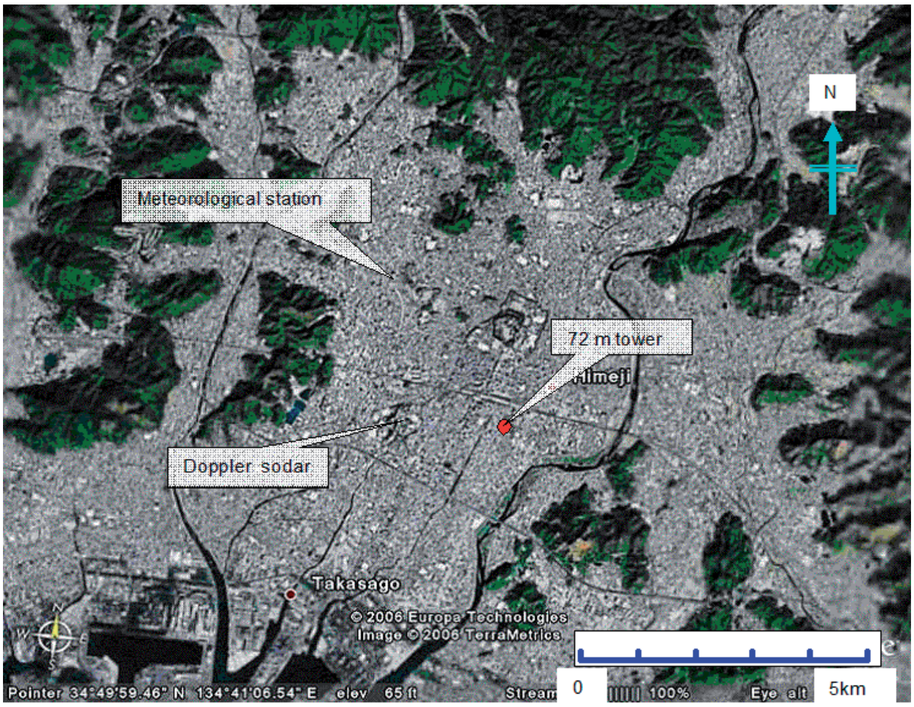

Figure 1. Urban area in Himeji city and site of a microwave-tower and the Doppler sodar.

Figure 1 shows the urban area in Himeji city and the site of a microwave tower and a Doppler sodar. The urban area is flat and surrounded by 150 to 200 m high hills in the south, west, and east. Hills that are 300 m high are in the north. The Seto inland sea is at a distance of 5 km from the observation site in the south. In the north and east of the tower, there are buildings that are 10 to 45 m in height. In the south and west of the tower, there is a commercial and residential area with houses and buildings that are 7 to 30 m in height.

2. OBSERVED VERTICAL TEMPERATURE AND TURBULENCE IN THE LOWER PART OF THE URBAN BOUNDARY LAYER

The vertical profile of turbulence and temperature was studied experimentally in the urban area in Himeji City. For one year, the vertical profiles were observed at the tower and the urban surface temperature was observed on the top of a building. A tethered balloon was used to measure vertical temperature at heights below 300 m for two days in July and November (Fig. 2). Turbulence was observed using sonic anemometers at the tower at a height of 52 m and 71 m and by using a Doppler sodar at heights below 300 m (Fig. 3).

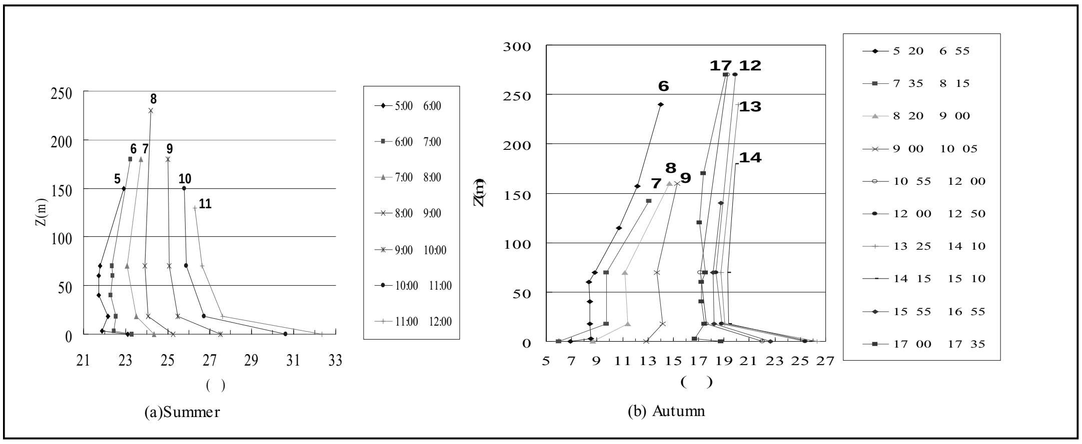

Figure 2. Vertical profile of potential temperature and surface temperature in summer (a: 19 July 2007) and autumn (b: 8 November 2007) in an urban area of Himeji City, Japan.

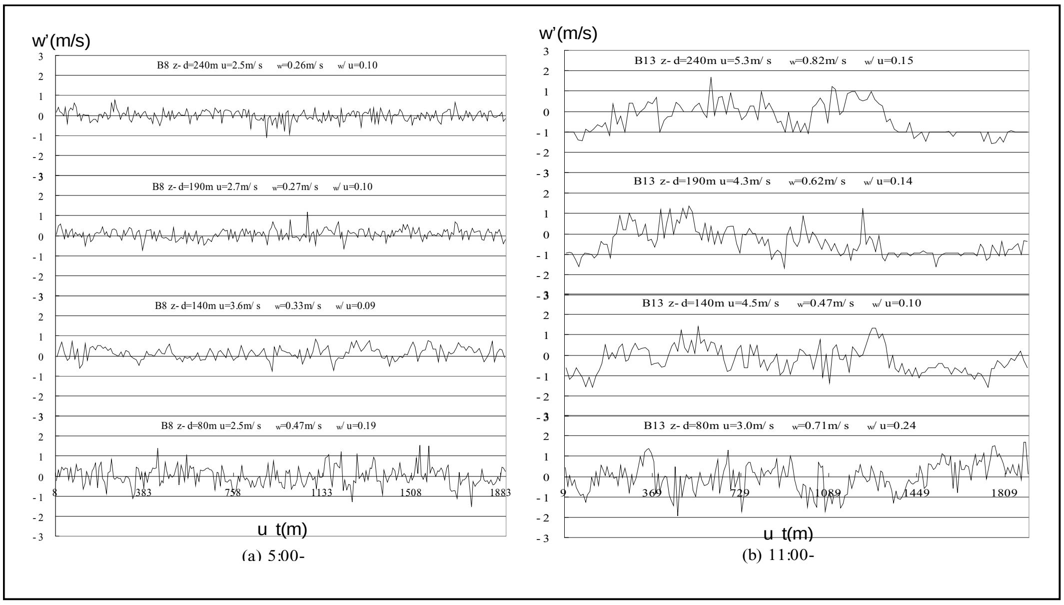

Figure 3. w' at (a) 5:00 - 5:15 and (b) 11:00 - 11:10 on 19 July (2007) measured using Doppler sodar at the centre of Himeji city.

On a clear night, upper temperature inversion was observed throughout a year, resulting in radiation cooling. The height of the inversion base was 60 m above the ground, which was 3 to 5 times the average building height. A neutral layer was observed under the inversion layer at night. The neutral layer must be the roughness sublayer (RS). The turbulence intensity in the upper inversion layer was smaller than that in the RS.

3. DEVIATION OF OBSERVED u_*/u AND σ_w/u_* IN AN URBAN AREA FROM CORRESPONDING VALUES AT SMOOTH SITES

In sunny day time, the RS was in unstable conditions, since the observed potential temperature decreased with height (-2°/100 m; averaged value in August at 14:00) and the heat flux transported upward. However, the observed values of u_*/u were close to that under the neutral condition, where u_* is the friction velocity and u is the average wind speed; these values showed a large deviation from the empirical formula presented by Businger et al. (1971), which is in agreement with the observations at smooth sites. In addition, the observed values of σ_w/u_* under unstable conditions were lower than those obtained by empirical formula presented by Panofsky et al. (1977) which is in agreement with the observations at smooth sites.

This implies that the ratio of mechanical turbulence to convective turbulence is larger in urban areas than in rural smooth areas. In addition, convective turbulence transports momentum less effectively in urban areas than in rural areas. This is also shown in the data for an unstable condition in which the correlation between u' and w' in urban areas (R=0 to -0.2) (Fig. 5) is weaker than that in rural areas (R=-0.2 to -0.35) (Kaimal and Finnigan, 1994). However, the correlation between w' and T' in urban areas (Fig. 5) is the same as that in rural smooth areas ($R_{w'T'}$=0.5) under unstable conditions. In urban areas, convective turbulence is capable of transporting heat ($R_{w'T'}$=0.5) but transports momentum less effectively. This means that eddy diffusivity in the lower part of the urban boundary layer, (z-d)/h=6, is different from that calculated from the empirical formula at smooth sites (Monin-Obukhov similarity theory) under unstable conditions, where z is the height above the ground, d (=2 m) is the displacement height, and h (=9 m) is the average building height.

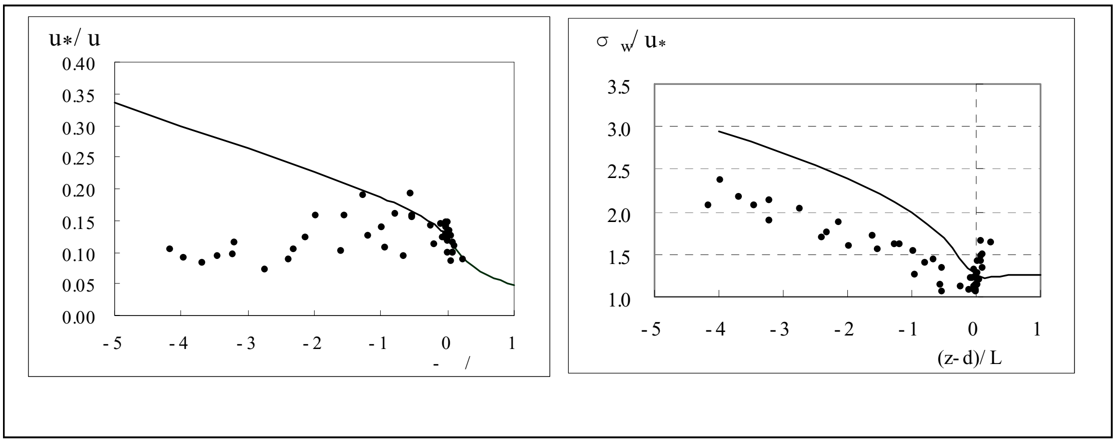

Figure 4. Observed u^*/u, σ_w/u^* at the tower (z=54 m) in Himeji city.

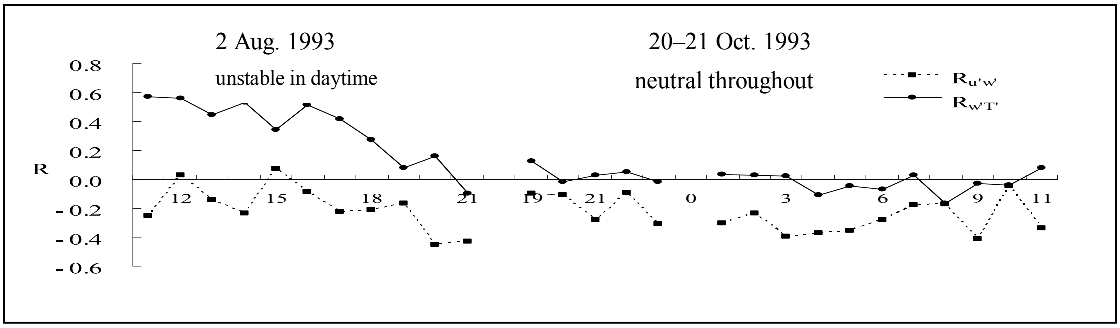

Figure 5. Observed u' and w' and correlation coefficients of $R(u'w')$, $R(w'T')$ at tower (z=54m) in Himeji city. (Kono and Koyabu, 2005).

4. WIND TUNNEL EXPERIMENTS

The wind tunnel in our laboratory has a 3 m long, 0.3 m wide, and 0.3 m high working section. In the wind tunnel, a rough wall boundary layer was simulated using cubic roughness elements (of 18 mm cubes) placed on the floor in diamond arrays. Turbulence was measured using a hot wire anemometer, and eddies were visualized with the help of smoke (Fig. 6). The spectrum of turbulence measured in the wind tunnel (Fig. 7) showed that in the RS, the size of eddies having the maximum kinetic energy is scaled with the obstacle size. However, in the inertial sublayer (IS), it is scaled with the height above the displacement height. The eddy size that has the maximum energy is proportional to the height in the IS.

5. LES

LES (Adaptive research-CFD 2000) was used to predict turbulent flow in the RS. The dimensions of the computational domain were 150 m × 22 m × 12 m in the streamwise, spanwise, and normal directions, respectively, with a grid spacing of 0.33 m. It was resolved by 450 × 66 × 26 cells. The 1.8 m cubes were placed on the floor in diamond arrays similar to those in the wind tunnel (Fig. 6). The cube was 100 times the roughness element in the wind tunnel. The inlet wind speed was 5 ms^{-1} (uniform). The logarithmic wind profile wall function for a smooth surface was used at the lower boundary and the surface of cubes. The upper boundary condition and boundary conditions for both sides in the x-z cross section were of the free-slip type. Figure 8 shows the spanwise and streamwise vorticities (ω_y, ω_x). The calculated results (Fig. 8) show that eddies are directly generated by cubes like wakes in the RS and they were transported downwind.

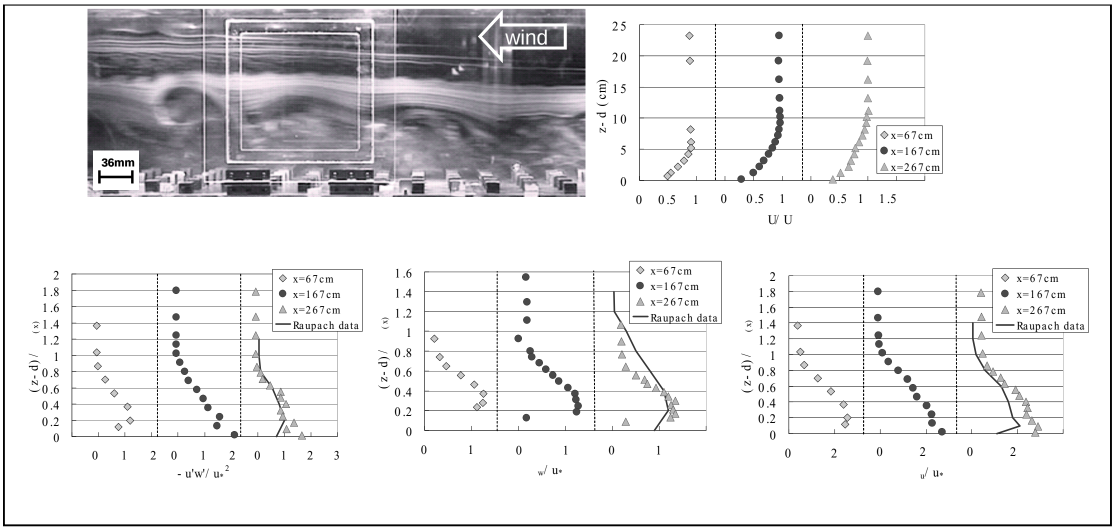

Figure 6. A visualization of the urban boundary layer and U/U_∞, $-u'w'/u_*^2$, σ_w/u_*, σ_u/u_* in the wind tunnel.

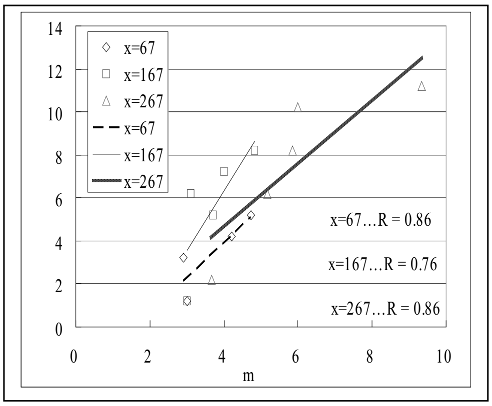

Figure 7. Eddy size λ_{zm} which has maximum energy in the wind tunnel with height, *z-d*, and *x* in cm.

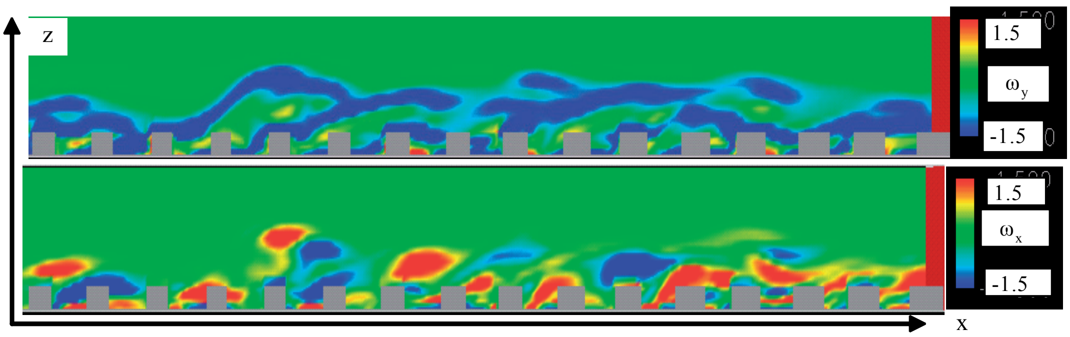

Figure 8. Vorticity (ω_x,ω_y)

6. CONCLUSION

In the upper RS, under unstable conditions, the observed values of u_*/u were close to those under neutral conditions; these values showed a large deviation from the empirical formula presented by Businger et al. (1971) which fitted observations at smooth sites. In addition, the observed values of σ_w/u_* were lower than the empirical formula presented by Panofsky et al. (1977) which fitted observations at smooth sites. The spectrum of turbulence measured in the wind tunnel showed that in the IS, the eddy size having the maximum energy is proportional to the height above the displacement height. On the other hand, in the RS, the size of eddies having the maximum kinetic energy is scaled with the obstacle size. LES showed that in the RS, eddies were directly generated by cube-like wakes and they were transported downwind. The eddy structure in the RS is expected to be different from that in the IS.

REFERENCES

Businger, J. A., J. C. Wyngaad, Y. Izumi and E. F. Bradley, 1971: Flux-profile relationships in the atmospheric surface layer. J. Atmospheric Science, 28, 181-189.

Kaimal, J.C. and J.J. Finnigan, 1994: Atmospheric Boundary Layer Flows, Capter1, 1-31.

Kono, H. and K. Koyabu, 2005: Proceedings of 10th international conference on hamonisation within atmospheric dispersion modeling for regulatory purposes, 445-449.

Panofsky, H. A., H. Tennekes, D. H. Lenschow and Wyngaard,J.C., 1977: The characteristics of turbulent velocity components in the surface layer under convective conditions. Boundary Layer Meteorology, 15, 439-446.

Raupach, M. R., 1981: Conditional statistics of Reynolds stress in rough-wall and smooth-wall turbulent boundary layers. J. Fluid Mech, 108, 363-382.

Rotach, M.W., 1993: Turbulence close to a rough surface Part 2: variances and gradients. Bound. Layer Met., 66, 75-92.

Valkonen, E., J. Härkönen, J. Kukkonen, E. Rantakrans, L. Jalkanen and S. Haarala, 1995: Application of dispersion models for evaluating the influence of urban air pollution on human heath. Int. J. Environment and Pollution, 5, Nos. 4-6, 557-566.

Werfeli, M., 1995: Modelling surface pollutant concentrations in the city of Zürich. Int. J. Environment and Pollution, 5, Nos. 4-6, 575-584.