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


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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. (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 rural smooth sites.

- We studied the turbulence and vertical temperature profile in the lower part of the urban boundary layer by conducting the field observations in Himeji City, carrying out wind tunnel experiments and numerical simulations.
Urban area in Himeji city the site of a microwave-tower, tethered balloon and the Doppler sodar.
In the north of the tower is a commercial area with buildings of 10 to 45 m in height.
In the south and east of the tower is a commercial and residential area with buildings of 7 to 30 m in height.

View from the tower looking south
Instruments mounted on the 72 m tower

Vertical temperature profile
One year

Thermistor thermometer
(Espec RT-30S)

Surface temperature
Infrared thermometer MR-40

T 70 m
T 60 m
T 40 m
T 18 m
T 4 m

Sonic Anemometer
54 m
50 Hz, 60 min
46 hours
April to August, 1996
KAIJO SAT-550

Turbulences
Measurement of vertical temperature at heights below 300 m

Using tethered balloon

Summer
July 19, 2007
4:00 ~ 11:00

Autumn
November 8, 2007
5:00 ~ 17:30

At the park in the center of the city
Lifted inversion layer

Neutral layer

RS

Vertical profile of potential temperature and surface temperature in autumn (8 November, 2007)
Vertical profile of potential temperature and surface temperature in summer (19 July, 2007)

**Lifted inversion layer**

- 5:00~6:00
- 6:00~7:00
- 7:00~8:00
- 8:00~9:00
- 9:00~10:00
- 10:00~11:00
- 11:00~12:00

**RS**

Unstable
w' on 19 July (2007) measured by using Doppler sodar in Himeji city

(a) 5:00 - 5:15
(b) 11:00 - 11:10

Inversion layer

Convective turbulence

Neutral layer, RS
Summary results of turbulence measured at the tower at $z = 54$ m

Wind directions: southern (SW - ESE)

Observation period: Apr. 1, June 12 – 15, Aug. 21, 24, 2006, $n = 46$

50 Hz, 60 min,

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<th>B</th>
<th>BC</th>
<th>C</th>
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<table>
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<th></th>
<th>$u$</th>
<th>$w$</th>
<th>$\theta$</th>
<th>$(z-d)/L$</th>
<th>$u_*$</th>
<th>$\sigma_u/u_*$</th>
<th>$\sigma_w/u_*$</th>
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<td>ave.</td>
<td>4.8</td>
<td>0.11</td>
<td>294</td>
<td>-0.95</td>
<td>0.59</td>
<td>2.5</td>
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<td>330</td>
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<td>$\sigma$</td>
<td>2.2</td>
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<td>24</td>
<td>1.31</td>
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Observed $u_*/u$ at the tower ($z = 54m$) in Himeji city
wind direction: SW - ESE

Under unstable conditions, turbulence transports momentum less effectively in urban areas than in rural areas.
Observed $\sigma_w/u_*$ at the tower ($z = 54m$) in Himeji city

$u_*$ mechanical turbulence

$\sigma_w$ both mechanical and convective turbulence

$u_*/\sigma_w$ large mechanical turbulence

Panofsky et al. 1977 (rural)

Roth, 2000 (urban)
Vectors \((u', w')\) observed at the tower at \(z=54\ m\) (Kono and Koyaby, 2005)

**Oct. 21, 9:00 - 9:20 in 1993**

**Aug. 2, 12:00 - 12:20**

Strong upward convection
Momentum flux, temperature flux, correlation between $u'$ and $w'$ and correlation between $w'$ and $T'$ measured at the tower ($z=54m$)

(Kono and Koyabu, 2005)

- $0.3 < R(u'w') < 0$
- $-0.35 < R(u'w') < -0.2$ (Kaimal and Finnigan, 1994)

$R(w'T') = 0.5$ unstable (urban & rural)

Oct. 20 – 21, 1993
In urban areas, convective turbulence transports heat but transports momentum less effectively in unstable conditions. Under unstable conditions, the eddy diffusivity at the lower part of urban boundary layer, is different from that calculated from the empirical formula at smooth sites using the Monin-Obukhov similarity theory.
Test section of the wind tunnel.

Flow straightener

3m× 0.3 m× 0.3m

Wind speed 1.3 m s⁻¹

1.8 mm cube

18 mm cubes, in diamond arrays with 36 mm nearest-neighbour separation

Re = 67,000
$U$, $-u'w'$, $\sigma_w$, $\sigma_u$ in the wind tunnel

Eddy size $\lambda$ which has maximum energy in the wind tunnel

$$\lambda = \frac{U}{2\, n} , \quad d = h = 1.8\, \text{cm}$$

Scaled with obstacle size

Scaled with height
**LES** was used to predict turbulent flow in the *roughness sublayer*.

- **Adaptive research - CFD 2000**

- **Computational domain:**
  (100 times as large as those in the wind tunnel)
  streamwise 150 m, span wise 22 m, normal direction 12 m
  grid spacing 0.33 m.
  450×66×26 cells.

- **Boundary conditions:**
  The lower boundary: The **1.8 m cubes** were placed in diamond arrays.
  The lower boundary and the surface of cubes: the logarithmic wind profile wall function for a smooth surface
  The upper and the both side boundary: **free slip**
  The inlet wind speed: **5 m s⁻¹** (uniform)
Side view of calculated vorticity ($\omega_x, \omega_y$)

At $y = 11$ m (center)
View from the top

$\omega_y, \omega_x$

At $z/h = 2.5$
CONCLUSION

In the upper RS, \( u_* / u \) under unstable conditions, were close to that under neutral conditions.

These values showed large deviations from the empirical formula presented by Businger et al. (1971) which fitted observations at rural smooth sites.

Therefore, under unstable conditions, turbulence transports momentum less effectively in urban areas than in rural areas.

In the RS, the size of eddies having maximum kinetic energy is scaled with the obstacle size, in the IS, it is proportional to the height. They were shown in the wind tunnel.

LES showed that eddies in the RS were directly generated by cubes like wakes and they were transported downwind.

The eddy structure in the RS is expected to be different from that in the IS.
Thank you for your attention!
A visualization of the urban boundary layer and $U$, $-u'w'/u^*^2$, $\sigma_w/u_*$, $\sigma_u/u_*$ in the wind tunnel.
Vertical profile of potential temperature and surface temperature in summer (19 July, 2007) and autumn (8 November, 2007) in an Urban area of Himeji City.
Instruments

- Sonic anemometer: KAIJO SAT – 550, 10Hz, 60 min
- Temperature: at height 4 m, 18 m, 40 m, 60 m, 70 m
  for one year
- thermistor thermometer (Espec RT-30S)
- Surface temperature: infrared thermometer Eko Instruments Co. **MR-40**
- Doppler Sodar: KAIJO KPA200: sampling interval 3 s