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<td>Ho, YK; Liu, CH</td>
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Roughness-sublayer correction for the profiles of mean velocity and turbulence over urban areas

Yat-Kiu HO | Chun-Ho LIU

Background

- Monin-Obukhov similarity theory (MOST) applies in inertial sub-layer (ISL) but fails in roughness sub-layer (RSL) because the flow structure in RSL is highly inhomogeneous.
- Extrapolation of the conventional logarithmic law of wall into the RSL likely overlooks the inhomogeneity.
- Need for an analytical expression for mean velocity profile and ventilation estimate, including a new RSL correction, that is applicable over the urban boundary layer.

Analytical Expression for RSL flow correction

Assumptions:

- $\Phi_m = \phi \Phi_m$ is a generalised similarity function of ISL & RSL
- Flows above urban canopy in neutral stratification ($\phi_m = 1$)
- $\Phi_m$ is a function of the roughness elements that is independent from the MOST length scale $L$.

$\Phi_m = \phi \Phi_m = \phi \left( \frac{z}{z_o} \right)$

$z$ is the elevation & $z_o$ the RSL height.

The gradient of the wind profile in dimensionless form is,

$\frac{d\phi}{dz} = \frac{u^*}{\kappa} \frac{z}{z_o}$

$u$ is the wind speed, $u^*$ the friction velocity & $\kappa \approx 0.41$ the von Kármán constant.

Rearrange & integrate yields,

$\kappa \int u \phi dz = - \ln \left( \frac{z}{z_o} \right) + \int \frac{1 - \phi}{z_o} \frac{z}{z_o} \phi dz$,

$d$ is the displacement height & $z_o$ the roughness length scale.

We employ the (continuous) function of $\phi_m$,

$\phi_m = 1 - e^{-\mu (z/z_o)}$,

$\mu$ is an empirical constant.

Use series expansion to calculate the exponential integral, an analytical expression for the urban RSL effects is formulated

$\frac{\Phi_m}{u^* \phi_m} = \frac{1}{\kappa} \ln \left( \frac{z}{z_o} \right) - \ln \left( \frac{z}{z} - \frac{d}{z_o} \right) - \sum_{n=1}^{\infty} \frac{(-1)^n \mu (z - d)}{n \cdot n!} \cdot \frac{z}{z_o}$

$\gamma \approx 0.57721$; Euler constant.

Wind Tunnel Measurements

- The open-circuit type wind tunnel at the Department of ME, HKU was used with neutral stratification and a reference wind speed of 9 m s$^{-1}$
- Idealised 2D-roughness elements with different aspect ratio (AR = $h/b$) were used to simulate the urban areas.
- Cross-wise hot-wire measurements were performed

Flows and Ventilation Estimates over Idealised Urban Areas

- Flow inhomogeneity over idealised urban areas is revealed (Fig. 3a)
- RSL & ISL are clearly identified
- The newly proposed analytical expression performs well in both RSL & ISL for the prediction of velocity profiles over a wide range of aspect ratios, 0.5 < AR < 0.083 (Fig. 3c)
- Friction factor $f$ & vertical velocity scale $\bar{w}$ are used to parameterise ventilation performance over urban areas with RSL corrections (Fig. 3b)

Next steps

- Tests with additional roughness elements of different forms using wind tunnel experiments, i.e. cube roughness, building height variability or realistic city models.
- Quantify the effect of aerodynamic roughness on RSL flows.
- Examine the RSL turbulence using mixing length models.

*Corresponding Author: Chun-Ho LIU; Department of Mechanical Engineering, 7/F Haking Wong Building, The University of Hong Kong, Pokfulam Road, HONG KONG; liuchunho@graduate.hku.hk; Tel: +852 2859 7901; Fax: +852 2858 5415.