On the Turbulence Structure over Different Surface Roughness: A Perspective from Wind Tunnel Measurements

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Outline

1. Background and motivation
2. Experimental methodology
3. Results and discussion
   • Velocity profiles in the turbulent boundary layer
   • Relation between friction factor and roughness sublayer (RSL), roof level ventilation
1. Background

- How the surface roughness influences the wind flow in the atmosphere surface layer?
- Can we parameterize the ventilation and pollutant dispersion based on the aerodynamic resistance induced by the surface roughness?

(Britter and Hanna, 2003)
2. Methodology—Wind tunnel measurements

- Measurement of two-component velocities (streamwise and vertical direction)
- Sampling frequency & duration are 2,000 Hz & 60 seconds, respectively

![Diagram showing hot-wire probe and wind tunnel sections]

- Test section (2 m)
- Developing section (2 m)
- Upstream section (2 m)

- LEGO Bricks
- Square Ribs
Square ribs

Building - height - to - street-width (aspect) ratio

AR = h/w

h = 19mm

LEGO bricks

- Frontal area \((A_F)\)
- Plan area \((A_P)\)
- Total area \((A_T)\)

\[ \lambda_F = \frac{A_F}{A_T} \]
\[ \lambda_P = \frac{A_P}{A_T} \]

Dimension of LEGO bricks: L = 16mm;
W = 16mm; H = 11.4mm
Measurement locations of vertical profiles of velocities

\[ U_\infty \]

1 2 3 4 5 6 7

\[ h = 11.4 \text{mm} \]

\[ w = 16 \text{mm} \]

\[ \text{AR} = 1/4 \]
Results and discussion

• Velocity profiles in the turbulent boundary layer
• Relation between friction factor and roughness sublayer (RSL), roof level ventilation
Velocity profiles-LEGO bricks

Note: <●> denotes spatial average
● denotes spatial average
●’’ denotes fluctuating component

\[
\frac{\langle u' \rangle}{U_{\infty}} \quad \frac{\langle u''u'' \rangle^{1/2}}{U_{\infty}}
\]

\[
\frac{\langle w''w'' \rangle^{1/2}}{U_{\infty}} \quad -\frac{\langle u''w'' \rangle}{U_{\infty}^2}
\]
Velocity profiles-Square ribs

Note: $\langle \cdot \rangle$ denotes spatial average
● denotes spatial average
'' denotes fluctuating component
Aerodynamic resistance —— **Friction factor**

\[ f = \frac{\tau_w}{\rho U_{\infty}^2/2} = \frac{2u^*}{U_{\infty}^2} \]

where \( \tau_w \) is the shear stress induced by the bottom rough surface, \( \rho \) is the fluid density, \( U \) is the free-stream velocity (Wong and Liu, 2013; Ho et al., 2015), \( u^* \) is the friction velocity, estimated using Reynolds stress (Cheng and Castro, 2002; Ploss et al., 2000).
Logarithmic law (Pope, 2009):

$$\langle u \rangle = \frac{u_*}{K} \ln \left( \frac{z - d}{z_0} \right)$$

LEGO bricks
Boundary layer thickness vs friction factor

- LEGO bricks: $y = 20395x + 50.041$, $R^2 = 0.9603$
- Square ribs: $y = 13524x + 144.29$, $R^2 = 0.949$
Roof level ventilation - Air exchange rate (ACH) vs friction factor

\[ ACH = ACH + ACH' = \int \left( \frac{\overline{w}'}{\Gamma_{\text{roof}}} \right) dx + \int \left( \frac{w'''}{\Gamma_{\text{roof}}} \right)^{1/2} dx \]

Note: The data point of roughness arrangements with too wide separation are eliminated.
Quadrant characteristics vs friction factor

AR=1
AR=2
AR=3
AR=4
AR=6
AR=8

LEGO 1:1
LEGO 1:2
LEGO 1:3
LEGO 1:4
LEGO 1:4_double
LEGO 1:4_triple

Square ribs

Increasing friction factor

LEGO bricks

Canyon top----scaled by $u_*$
Summary

• Flow structure are characterized in the turbulent boundary layer over two different types of surface elements: square ribs and LEGO bricks.

• Strong Relations are revealed between friction factor and the RSL, boundary layer thickness, roof level ventilation, etc.

• Next step research - using friction factor to parameterize dispersion coefficient over LEGO bricks.