On the Spatial Behaviors of Local Mass Transfer Coefficients Over Idealized Two-Dimensional Urban Street Canyons

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Parallel Session 8
Urban Scale and Street Canyon Modelling: Meteorology and Air Quality

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Introduction

• Nowadays, it is no doubt that anthropogenic emission contributes a major proportion to the air pollutants in urban areas.

• The removal of air pollutants by (city) natural ventilation is often governed by the coupled heat and mass transfer over urban areas.

• Urban fabric is a key source of anthropogenic air pollutants while urban morphology tightly affects pollutant dispersion.

• Their transport behaviors in street levels are rather poorly understood.
• Computational fluid dynamics (CFD) is one of the solutions.
• To offer complement solution or validation datasets for CFD findings, field measurements and laboratory experiments are required.
• A series of laboratory wind tunnel measurements are carried out to examine the mass transport behaviors over two-dimensional (2D) periodic ribs in a wide range of aspect ratios.
• Serves as a pilot trial to complement our CFD findings for the pollutant removal mechanism of urban areas in different flow regimes over idealized 2D urban street canyons.
Local Mass Transfer Velocity

• Narita (2007) developed the water evaporation method using soaked filter papers for the measurement of mass transfer behaviors over 2D street canyons.

• Surfaces of the sample street canyon model are covered by wetted filter papers. The entire setup is then placed in the wind tunnel for a specific period of time.

• The mass transfer velocity is calculated as follows:

\[ w_t = \frac{\dot{E}}{\rho_s - \rho_a} \]

• \( E \) is the evaporation rate, \( \rho_s \) the saturated vapour density at evaporating surface temperature, and \( \rho_a \) the vapour density of the incoming flow.
Methodology

• Wind Tunnel in the Department of Mechanical Engineering, The University of Hong Kong
• Wind speed is set to 2.5 m sec$^{-1}$ in the experiments
• Dimensions of the test section: 565 mm (width) × 560 mm (height) × 3,600 mm (length).
• Three different types of block are used throughout the experiments.
• Reynolds number >3,400: Flows are independent from molecular viscosity in room conditions (Hoydysh et al, 1974).

<table>
<thead>
<tr>
<th>Type of blocks</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block A</td>
<td>76.2</td>
<td>76.2</td>
<td>565</td>
</tr>
<tr>
<td>Block B</td>
<td>50</td>
<td>50</td>
<td>565</td>
</tr>
<tr>
<td>Block C</td>
<td>25.4</td>
<td>25.4</td>
<td>565</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Blocks</th>
<th>Aspect Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2, 1, 1/2</td>
</tr>
<tr>
<td>B</td>
<td>1/4</td>
</tr>
<tr>
<td>C</td>
<td>0.127, 0.147, 0.167, 0.25, 0.33, 0.67, 1</td>
</tr>
</tbody>
</table>
• 10 to 12 street canyons are employed for fully developed turbulent flows
Scaling effects

- Magnitude of the flux should depend on the sample size regardless of the flow characteristics.
- In physical modeling, different length scales must be considered.
- Parameters are usually expressed in dimensionless forms.
- For a flat plate, the dimensionless number measuring the mass transfer velocity \( \dot{W}_i \) is the Sherwood number \( Sh \):

\[
Sh = A Re^m Sc^n
\]

- \( Sc ( = v/D ) \) is the Schmidt number and \( v \) the kinematic viscosity.
- \( A, m, \) and \( n \) are empirical constants depending on the model geometry.
- Overall mass transfer velocity over street canyons of unity aspect ratio is measured in different wind speeds. The corresponding logarithmic values of \( Sh \) are plotted against \( Re \).
$y = 0.8485x - 1.8088$
$R^2 = 0.9785$

Linear regression of the data points shows that the slope is close to 4/5.
Results and Discussion

• Normalized local pollutant exchange rate is expressed as $\omega/(PCH|_{h/b=1}/b)$ in Liu et al (2011).

• A similar normalization is used for data expression in this study.

• Normalized local mass transfer velocity is expressed as $\omega_t/(W_t|_{h/b=1}/b)$.

• $\omega_t$ is the local mass transfer velocity and $W_t$ the average local mass transfer velocity in the street region of the street canyon of unity aspect ratio.
• The figure above shows the spatial distribution of the local mass transfer velocity on the surfaces of street canyons.
• All the flows fall into the skimming flow regime, which signifies that there is no entrainment from the UCL into the street canyons.
• Minimum \( \dot{w}_f \) at the middle of the roof due to the flow singularity at the roof-level corners.
• Maximum \( \dot{w}_f \) is observed due to the vigorous upward flows at the mid-level of the street canyon.

- \( \dot{w}_f \) at the roof region of street canyon of aspect ratio 1 is higher, which is believed to be experimental error.
- Because of the stagnate flows near the ground-level corner, a mild drop in \( \dot{w}_f \) is observed.
- The mass transfer from the ground level of a street canyon to the UCL is dominated by turbulent transport (Liu et al, 2011).
• Figures (a), (b), & (c) compare the normalized local mass transfer velocity of aspect ratios 0.5, 0.6, and 1. with Hagishima (2005) and Liu et al (2011)

  • All the results follow the same trend.

  • The data are not that match. Further investigation will be carried out.
Consideration of scaling effect

• Barlow et al. (2002) asserted the existence of mass transfer coefficient, which is independent from the Reynolds number.

• Narita (2007) did not agree with the linear relation, and the scaling effect is significant that cannot be neglected.

• For comparison of data with our current study, it is necessary to consider the correlation between the variation of mass transfer coefficient and the Reynolds number.
• **Empirical Correlation:**
  
  \[ Sh = C R e^m S c^n \]

  \[ C = \frac{Sh}{R e^m S c^n} \]

  This is the dimensionless mass transfer coefficient

  \[ \frac{U \omega h}{\kappa} \frac{(U h/v)^m (v/\kappa)^n} {v^n - m \kappa^{1-m}} (\omega) \]

  \[ = \frac{U h}{v} \frac{\omega h}{\kappa} \frac{(v/\kappa)^{m-n}} {(U h/v)(v/\kappa)} \]

  \[ = \omega \]

\[ \text{Re} = \frac{U h}{v} \quad \text{Sc} = \frac{v}{D} \]

Neglecting scaling effect (i.e. \( m=n=1 \))

Kinematic viscosity

Mass diffusivity
• As shown above, including scaling effect is necessary for comparison with other results available literature

• Taking Liu et al. (2011) as example. After applying the parameters, the variation of mass transfer coefficient due to scaling effect can be observed.

Laboratory Experiment:
• $U = 2.5$, $h = 0.0254$, $Sc = 0.66$
• $v = 1.57 \times 10^{-5}$, $\kappa = 2.38 \times 10^{-5}$
• $m = 4/5$, $n = 1/3$
• Calculated “C” with scaling effect considered:
  • $3.99 \, \Omega_{lab}$

CFD model from Liu et al. (2011):
• $U = 0.17$, $h = 1$, $Sc = 0.72$
• $v = 1 \times 10^{-5}$, $\kappa = 1.39 \times 10^{-5}$
• $m = 4/5$, $n = 1/3$
• Calculated “C” with scaling effect considered:
  • $5.64 \, \Omega_{cm}$

• Considering “C” is a constant
• $\Omega_{cm} = \frac{3.99}{5.64} \, \Omega_{lab} = 0.707 \, \Omega_{lab}$

Ω: average $\omega$ of the entire street canyon
• Normalized PCH for 2D idealized street canyons of different ARs is shown about.
• Large difference between the literature and experimental data if scaling effect (Red symbols) is neglected
• Magnitude of the experimental data is reduced in specific ratio as shown in the last slide (Blue symbols).
The lower graph is the comparison of the experimental data with that from WaiChi's (2010) by considering the value of "C". The upper one is the comparison of the experiment data with our usual data by multiplying the value with the factor (mentioned in the last few slides, the appendix).
The experimental data is compared with Liu et al. (2011) in terms of “C”.

- Red square are the CFD while blue square are the experimental results.
- Same as the normalized PCH with scaling effect considered in the previous figure, the experimental data exhibit a good fitting with the others.
- Further experimental parameters from other literatures are required for comparison of in terms of “C”.
Conclusion

• Water evaporation method is used to measure the distribution of local mass transfer coefficients over idealized 2D street canyons.
• Results are compared well with those available in literature.
• Pollutant removal is more favourable on the windward side and at the roof-level windward corner.
• Scaling effect should be considered for scaled physical modeling experiments.
• Reasons behind those phenomenon along the street canyon surfaces will be studied.
References

• APPENDIX
• $\rho_s$ is the vapor density on the wetted filter paper surfaces, which can be calculated from Goff–Gratch equation:

$$\log e^* = -7.90298 \left( \frac{T_{st}}{T} - 1 \right) + 5.02808 \log \frac{T_{st}}{T} - 1.3816$$
$$\times 10^{-7} \left( 10^{11.344 \left( 1 - \frac{T}{T_{st}} \right)} - 1 \right) + 8.1328$$
$$\times 10^{-3} \left( 10^{-3.49149 \left( \frac{T_{st}}{T} - 1 \right)} - 1 \right) + \log e_{st}^*$$

• $e^*$ is the saturation water vapor pressure (hPa).
• $T$ is the wet – bulb temperature in Kelvin (K)
• $T_{st}$ is the steam-point (i.e. boiling point at 1 atm.) temperature (373.15 K)
• $e_{st}^*$ is $e^*$ at the steam-point pressure (1 atm = 1013.25 hPa)
• $\rho_s$ is calculated from $e^*$ using the ideal gas law $e^* = \rho_s RT$
• Block C is used to measure the average transfer velocity of the whole street canyon of different aspect ratios.
• The blockage ratio of the street canyon model in the experiment is ranged from 4% to 14%.
• Liu et al. (2011) used a 2D RANS $k$-$\varepsilon$ turbulence model of blockage ratio 14.3%.
• The computational domain was found to be large enough for fully developed flows in the street canyons.
• Necessary to prove the correlation for Sherwood number.
• The mass transfer velocity over the roof surface of street canyon of unity aspect ratio is measured in different wind speeds.
• The data are used to calculate the Reynolds number and Sherwood number.
• If \( m = 4/5 \), the value of \( Sh \) will increase with the 4/5 power of the wind speed.
Results and Discussion

• Need to define the location of the sampling region
• The variation of wind velocity in the streamwise direction over 2D idealized stream canyons is measured.
• The values converges gradually when $X/H = 7$, where $X$ is the distance from the 1st street canyon and $H$ is the dimension of building blocks.