HARMO14 - 14th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
Kos Island, Greece, October 2 to 6, 2011

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

Pieta K.K. Leung & Chun-Ho Liu*
Department of Mechanical Engineering, The University of Hong Kong
Pokfulam Road, Hong Kong, China

Parallel Session 8

Urban Scale and Street Canyon Modelling: Meteorology and Air Quality

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

H14-118: October 4, 2011

Contents

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

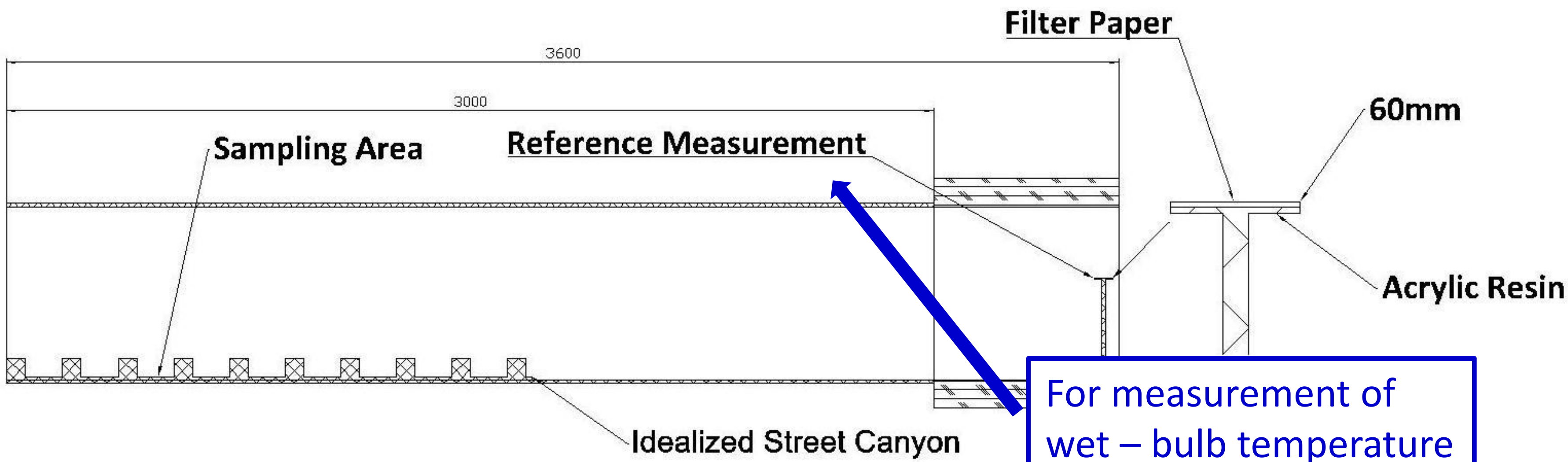
- Narita (2007) developed the water evaporation method using soaked filter papers for the measurement of mass transfer behaviors over 2D street canyons.
- Surfaces of the sample street canyon model are covered by wetted filter papers. The entire setup is then placed in the wind tunnel for a specific 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, ρ_s the saturated vapour density at evaporating surface temperature, and ρ_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).



For measurement of wet – bulb temperature required for data calculation

- 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).

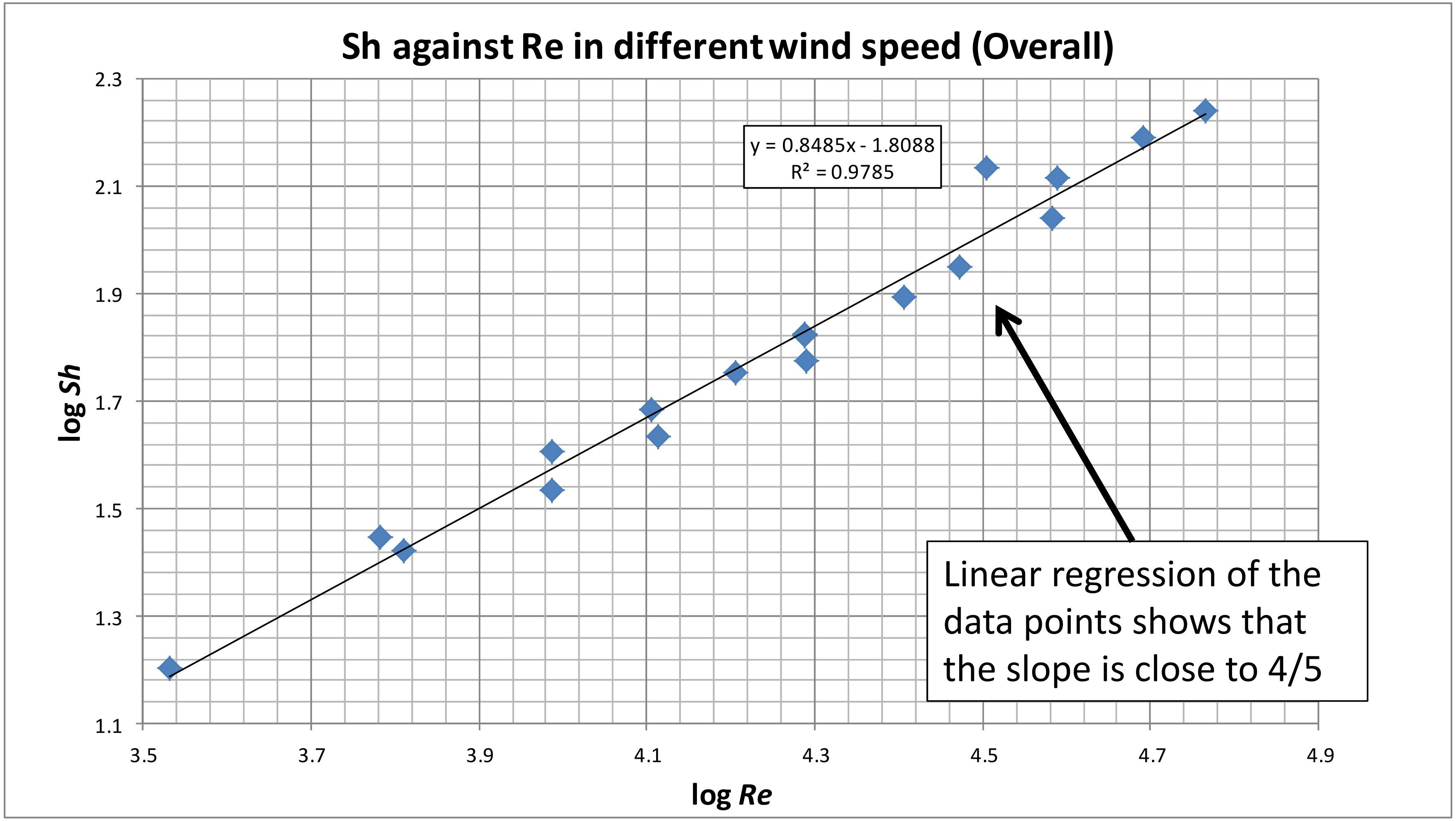
Type of blocks	Height (mm)	Width (mm)	Length (mm)
Block A	76.2	76.2	565
Block B	50	50	565
Block C	25.4	25.4	565

Blocks	Aspect Ratios
A	2, 1, 1/2
B	1/4
C	0.127, 0.147, 0.167, 0.25, 0.33, 0.67, 1

- 10 to 12 street canyons are employed for fully developed turbulent flows

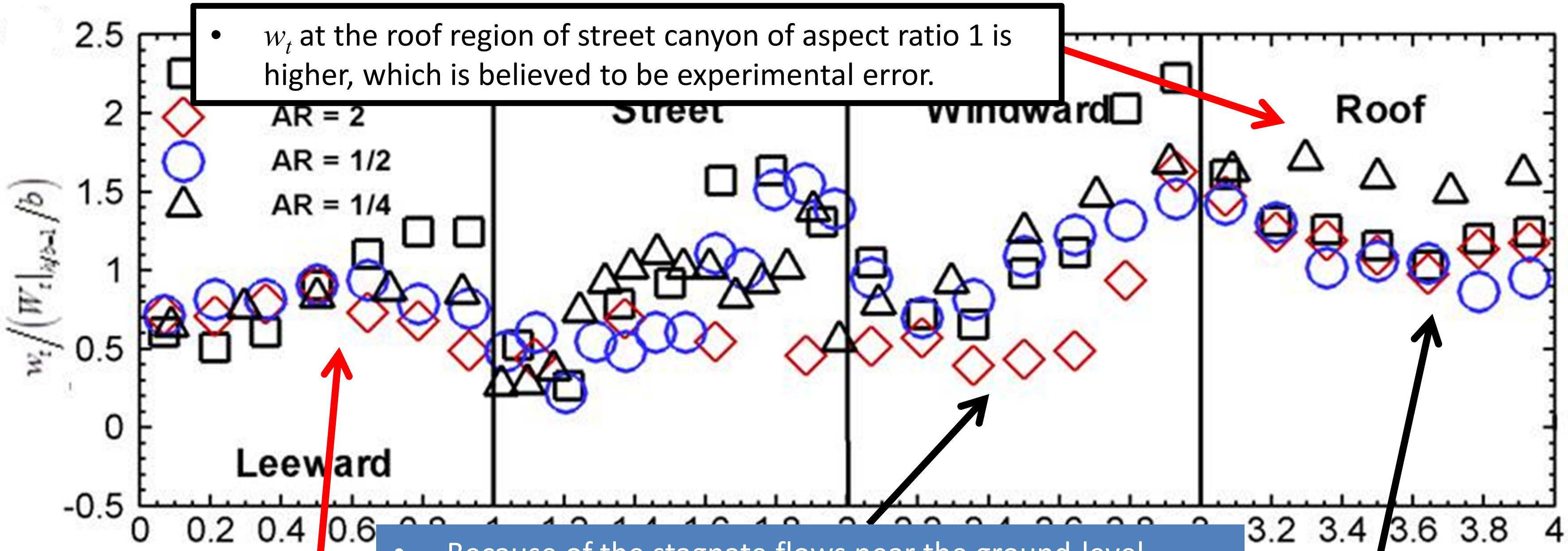
Scaling effects

- 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 (W_t) is the Sherwood number Sh:
- $Sh = ARe^m Sc^n$
- 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 .


Sh against Re in different wind speed (Overall)
y = 0.8485x - 1.8088
R² = 0.9785
log Sh
log Re
2.3
2.1
1.9
1.7
1.5
1.3
1.1
3.5
3.7
3.9
4.1
4.3
4.5
4.7
4.9
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 $w_t/(W_t|_{h/b=1}/b)$
- w_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.



- w_t 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 w_t is observed

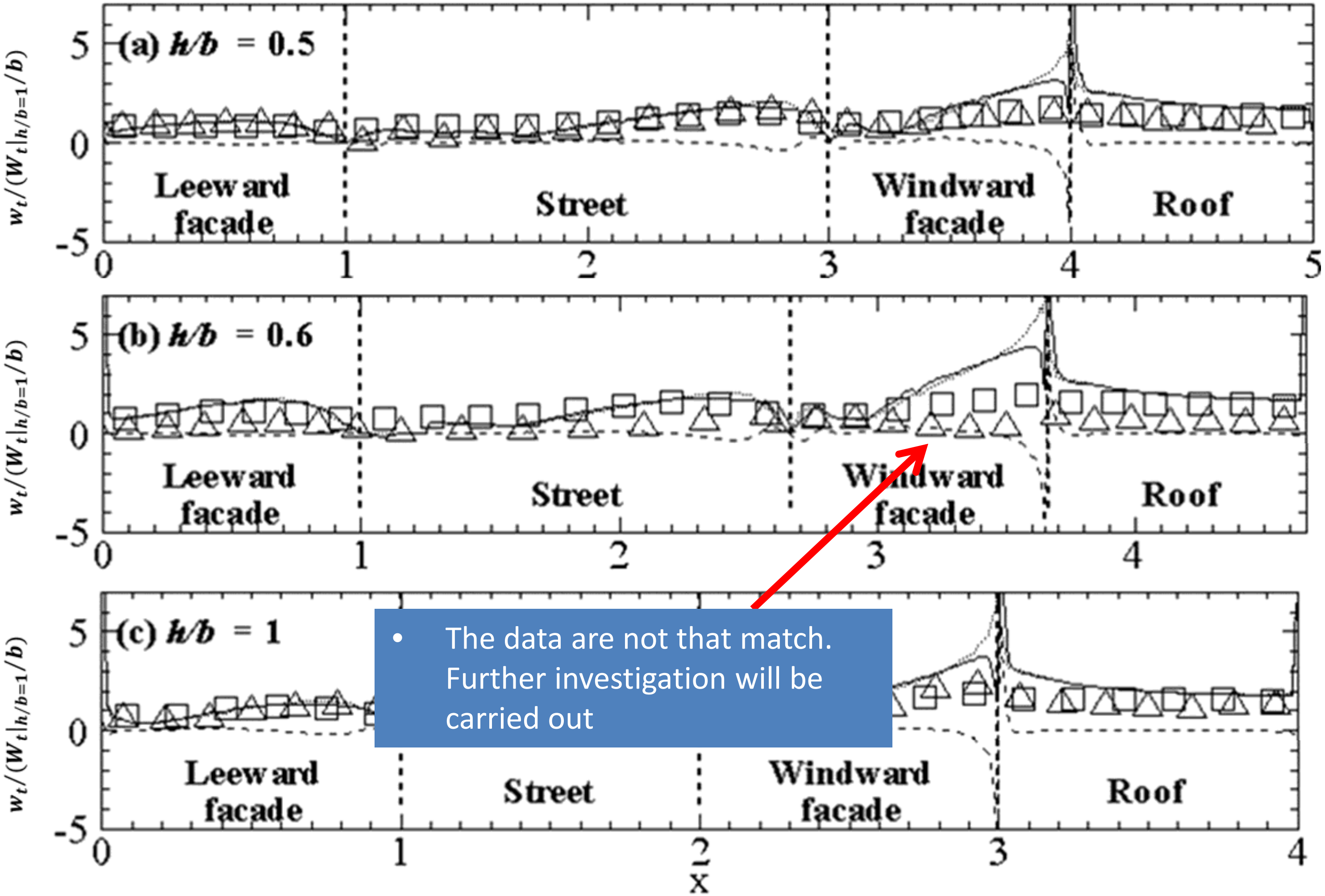
- The figure above shows the spatial distribution of the local mass transfer velocity on the surfaces of stree
- All the flows fall into the skimmi
  e UCL into the street canyons.
  street canyon that is isolated from the prevailing flow aloft.
- The mass transfer from the ground level of a street canyon to the UCL is dominated by turbulent transport (Liu et al, 2011).

- Minimum w_t at the middle of the roof due to the flow singularity at the roof-level corners.

- Maximum w_t is observed due to the vigorous upward flows at the mid-level of the street canyon.

- 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:
- $Sh = CRe^m Sc^n$
- $C = \dfrac{Sh}{Re^m Sc^n}$

  - This is the dimensionless mass transfer coefficient

- $= \dfrac{U\omega h / \kappa}{(Uh/\nu)^m (\nu/\kappa)^n}$
- $= \dfrac{U^{1-m} h^{1-m}}{\nu^{n-m} \kappa^{1-m}} \omega$

$\mathrm{Re} = \dfrac{Uh}{\nu}$ $\quad Sc = \dfrac{\nu}{D}$

Kinematic viscosity

Mass diffusivity

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

- $C = \dfrac{Sh}{Re^m Sc^n}$
- $= \dfrac{U\omega h/_{\kappa}}{(^{Uh}/_{v})(^{v}/_{k})}$
- $= \omega$

- 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
- $\nu = 1.57\times10^{-5}$, $\kappa = 2.38\times10^{-5}$
- m = 4/5, n = 1/3

- Calculated "C" with scaling effect considered:

- $3.99\ \Omega_{lab}$

CFD model from Liu et al. (2011):

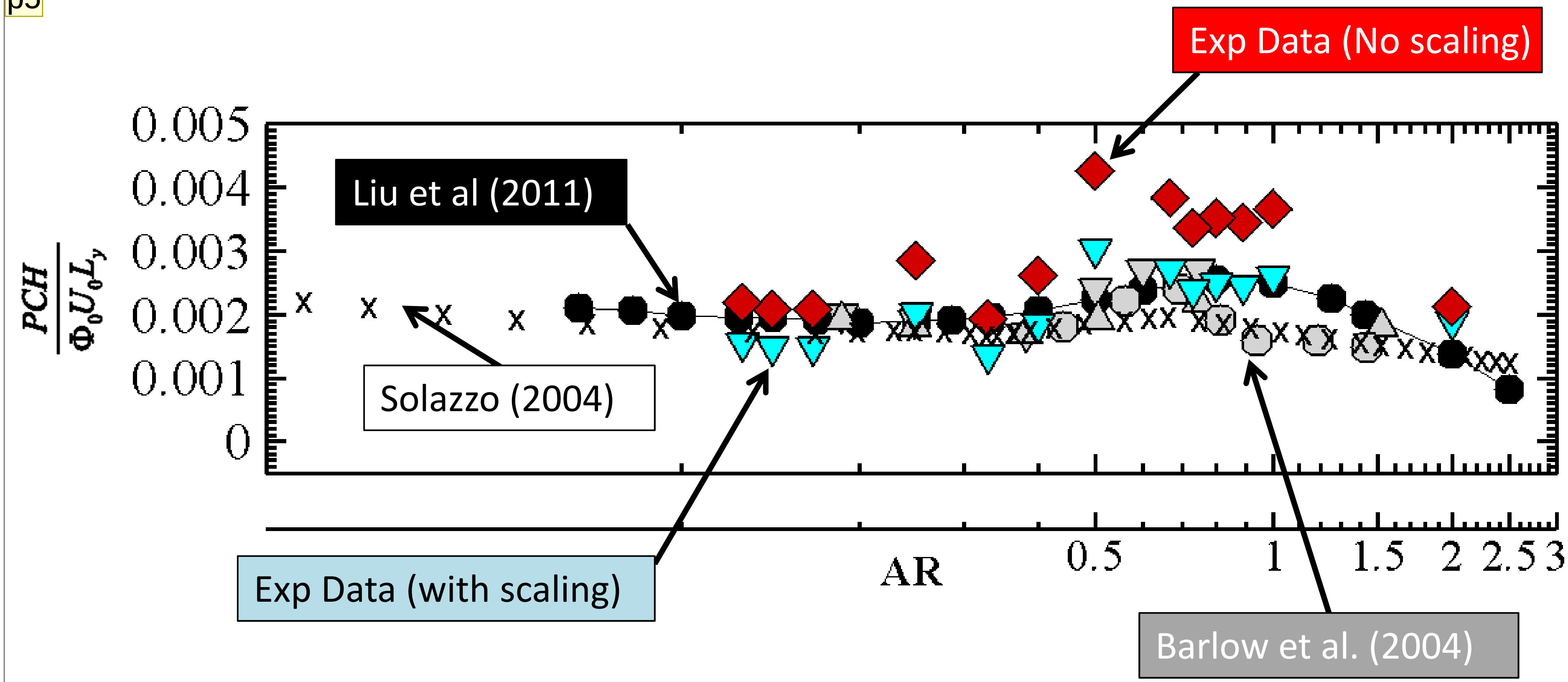
- U = 0.17, h = 1, Sc = 0.72
- $\nu = 1\times10^{-5}$, $\kappa = 1.39\times10^{-5}$
- m = 4/5, n = 1/3

- 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 ω of the entire street canyon p5



- 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).

Slide 17

p5 The lower graph is the comprision 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)

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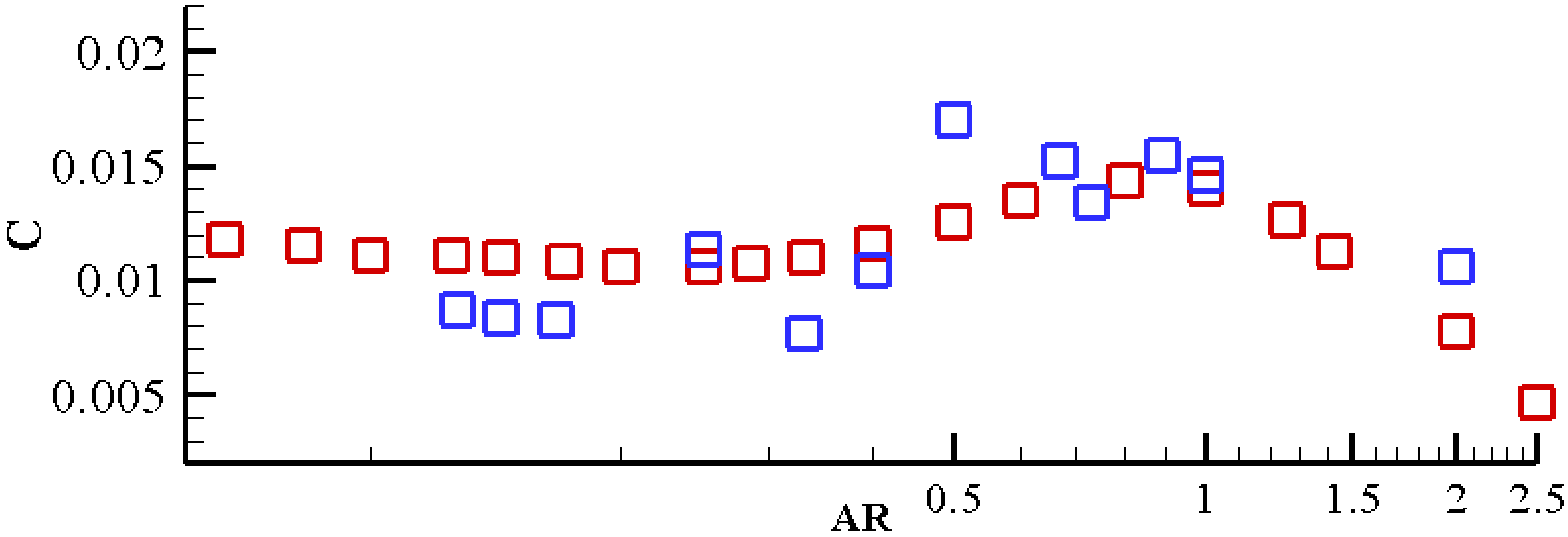


- The experimental data is compared with Liu et al. (2011) in terms of “C”
- Red square are the CFD while blue square are the experimental results
- Same as the normalized PCH with scaling effect considered in the previous figure, the experimental data exhibit a good fitting with the others
- Further 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

- Narita, K (2007), "Experimental study of the transfer velocity for urban surfaces with a water evaporation method", Boundary-Layer Meteorol. 122, 293-320.
- Liu, C.-H., Cheng, W.C., Thomas C.Y. Leung, Dennis Y.C. Leung (2010), “On the mechanism of air pollutant re-entrainment in two-dimensional idealized street canyons “
- Tracy N.H. Chung, Y.Y. Tse and C.-H. Liu (2010), “Study of pollutant transfer coeffi-cient inside street canyons in different flow regimes using large–eddy simulation and *k*-*ε* turbulence model”
- Jarrett, E.L. and Sweeney, T.L. (1967), "Mass transfer in rectangular cavities", AIChE Journal, 13, 797-800.
- Oke, T.R. (1988). “Street design and urban canopy layer climate”. Energy and Buildings, 11(1-3), 103-113.
- Incropera, F, DeWitte, D (1996) Fundamentals of heat and mass transfer, 4th edn. Wiley, New York, 981 pp

- APPENDIX

- ρ_s is the vapor density on the wetted filter paper surfaces, which can be calculated from Goff–Gratch equation:

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

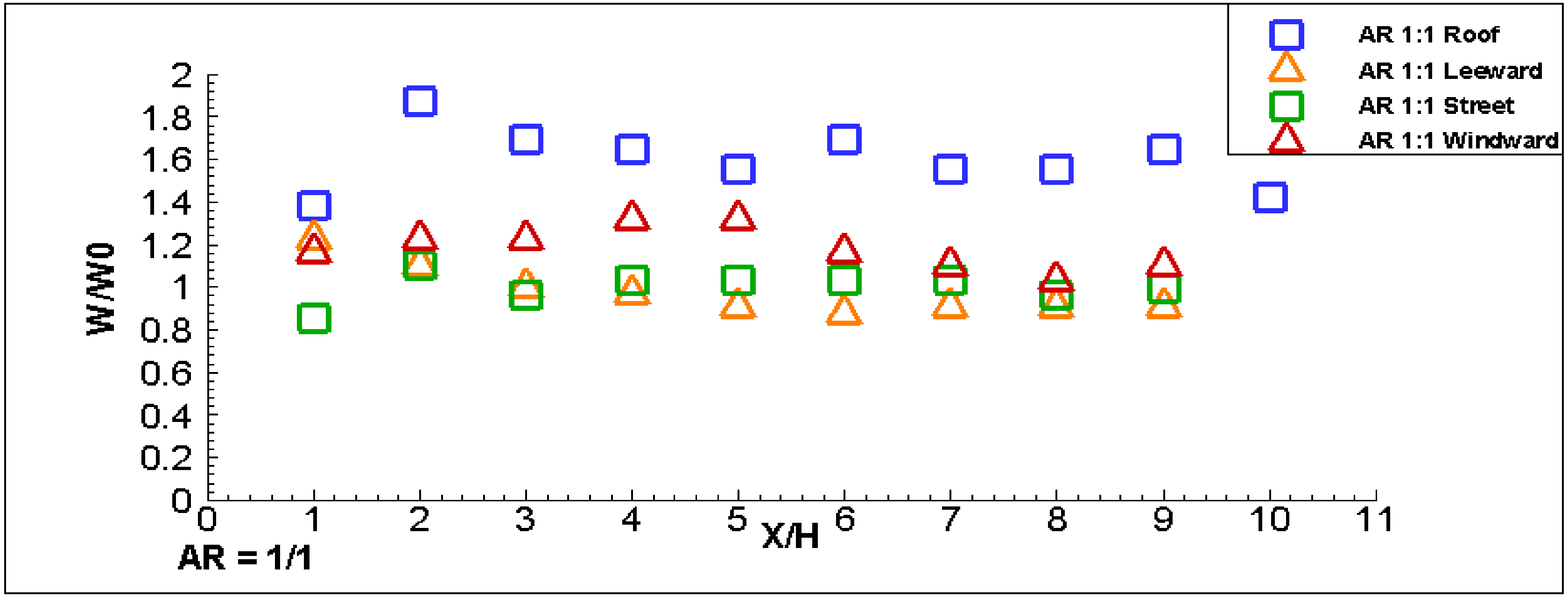
- e^* is the saturation water vapor pressure (hPa).
- T is the wet – bulb temperature in Kelvin (K)
- T_{st} is the steam-point (i.e. boiling point at 1 atm.) temperature (373.15 K)
- ${e^*}_{st}$ is e^* at the steam-point pressure (1 atm = 1013.25 hPa)
- ρ_s is calculated from e^* using the ideal gas law $e^* = \rho_s RT$

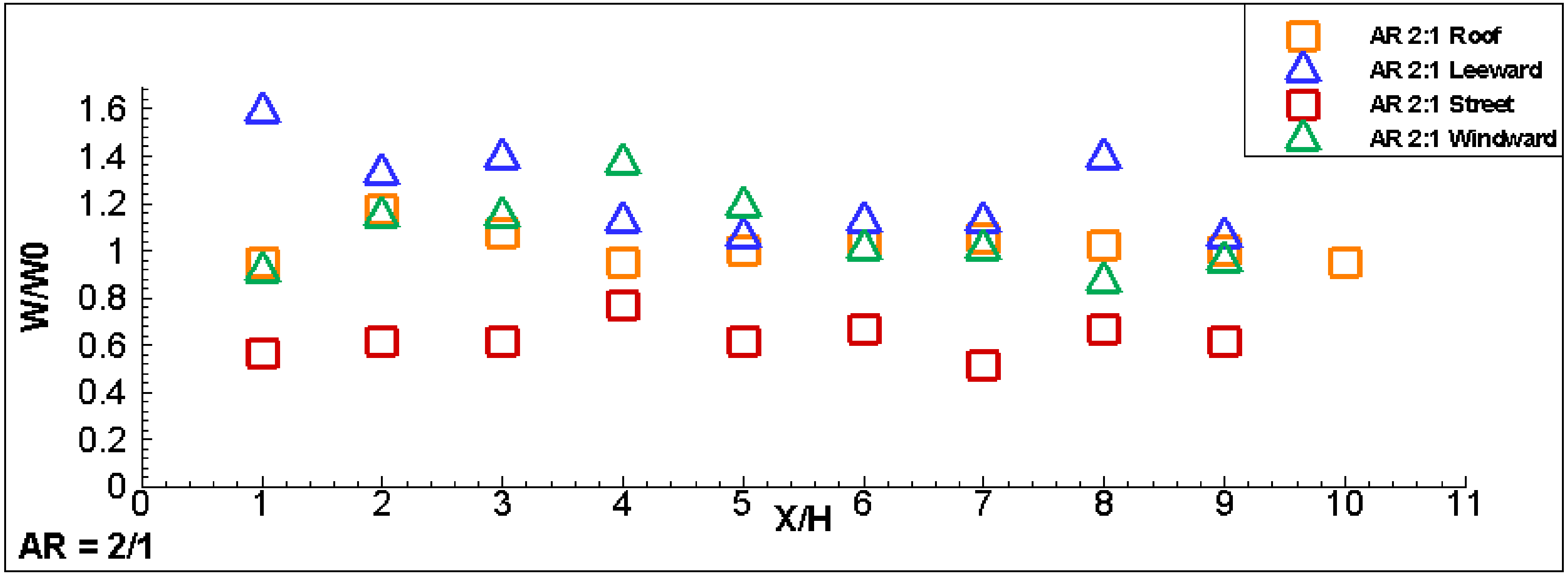
- Block C is used to measure the average transfer velocity of the whole street canyon of different aspect ratios.
- The blockage ratio of the street canyon model in the experiment is ranged from 4% to 14%
- Liu et al. (2011) used a 2D RANS k-ε turbulence model of blockage ratio 14.3%.
- The computational 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.


AR 1:1 Roof
AR 1:1 Leeward
AR 1:1 Street
AR 1:1 Windward
W/W0
X/H
AR = 1/1


AR 2:1 Roof
AR 2:1 Leeward
AR 2:1 Street
AR 2:1 Windward
W/W0
X/H
AR = 2/1