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ON THE SPATIAL BEHAVIORS OF LOCAL MASS TRANSFER COEFFICIENTS OVER IDEALIZED TWO-DIMENSIONAL URBAN STREET CANYONS

Ka Kit Leung and Chun-Ho Liu[1]

Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China
[1]liuchunho@graduate.hku.hk

Abstract: In this paper, the correlation between the ventilation and pollutant removal behaviour over idealized two–dimensional urban street canyons is studied by means of wind tunnel experiments in the Departmental of Mechanical Engineering, The University of Hong Kong. Movable rectangular aluminium blocks are placed in the test section of wind tunnel, constructing street canyon models of different building-height-to-street-width (aspect) ratios. Throughout the experiments, water evaporation methods, which are implemented by applying soaked filter papers on the model, are used to simulate a uniform mass concentrations on the building facades and ground surface. The local mass transfer coefficients on various surfaces of street canyons of aspect ratios 0.25 to 2 are determined that are compared with those available in literature. The variations of the average mass transfer coefficients over a wider range of aspect ratios are also examined. Scaling effect, however, is needed to account for. Hence, a further in-depth data analysis is required for a more accurate comparison with our CFD findings.

Key words: *Mass transfer, skimming flow regime, street canyons, urban air quality, and wind tunnel measurements*

INTRODUCTION
Nowadays, it is no doubt that anthropogenic emission contributes a major proportion to the air pollutants in urban areas. Those pollutants, including aerosols and semi-volatile organic compounds (SVOCs), adversely affect not only the comfort but also the public health in urban areas. There is a need for the removal of air pollutants by (city) natural ventilation, which 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 transport, hence, pollutant dispersion over urban areas has been a popular research problem for decades. Because of our limited understanding of the complicated transport behaviours at street level, computational fluid dynamics (CFD) is one of the approaches to the problem. In order to provide complement solution or even validation datasets for CFD findings, field measurements and laboratory experiments are required. Narita (2007) used wind tunnel experiments to examine the flows over two-dimensional (2D) street canyons. However, the focus was the self-comparison for street canyons of building-height-to-street-width (aspect) ratios from 0.5 to 6. In this paper, a series of laboratory wind tunnel measurements are carried out to examine the mass transport behaviours over 2D street canyons for a wide range of aspect ratios. The results will serve 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.

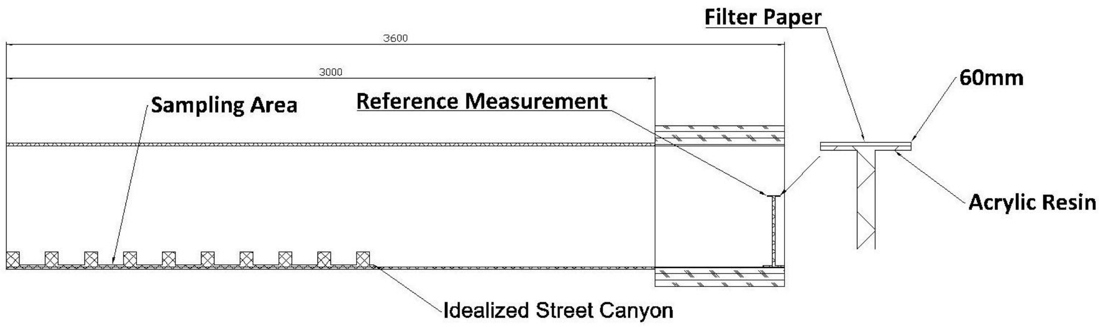

Figure 1. Experiment setup.

THEORETICAL BACKGROUND
For the measurements of the spatial behaviour of mass transfer over urban street canyons, Narita (2007) developed water evaporation method using soaked filter papers. The 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 (Figure 1). Measuring the amount of water evaporated by the weight difference of the soaked filter papers before and after the test, the mass transfer velocity is calculated as follows

$$w_t = \frac{\dot{E}}{\rho_s - \rho_a} \tag{1}$$

where $\dot{E}$ is the water evaporation rate from the filter papers and ρ the water vapour density. The subscripts *s* and *a* represent, respectively, the properties on the wetted filter paper surfaces and in the prevailing air at ambient temperature *T*. The water vapour density in the prevailing air is determined by monitoring the relative humidity in the laboratory. The filter papers are soaked, so it is assumed that they remain completely wet throughout a test. Nonetheless, the wet bulb temperature of another sample soaked filter paper on the reference plate is being monitored so as to prevent from completely dried out. The wet bulb temperature will rise quickly if the filter papers are partially dried out such that the near-surface water vapour density is no longer saturated (Narita, 2007). The Goff–Gratch equation is adopted to calculate the saturation water vapour pressure e^* *(hPa) at T*

$$\begin{aligned}\log e^* \; = \; & -7.90298\times\left(\frac{T_{st}}{T}-1\right)+5.02808\times\log\frac{T_{st}}{T}-1.3816\times10^{-7}\times\left[10^{11.344\times\left(1-\frac{T}{T_{st}}\right)}-1\right] \\ & +8.1328\times10^{-3}\times\left[10^{3.49149\times\left(1-\frac{T_{st}}{T}\right)}-1\right]+\log e^*_{st}\end{aligned} \tag{2}$$

Here, T_{st} (= 373.15 K) is the steam-point temperature at room pressure (= 1013.25 hPa) and e^*_{st} (= 1013.25 hPa) the saturated water vapour pressure at steam point. Finally, the saturation water vapour density ρ_s is calculated from the saturation water vapour pressure e^* using the ideal gas law $e^* = \rho_s RT$ where R (= 462 kJ K^{-1} kg^{-1}) is the gas constant of water vapour.

Figure 2. (a) Wind tunnel and (b) test section in the laboratory.

Table 1. Dimensions of the street canyon models.

Types	Dimensions	Aspect ratios (h/b)
Block A	76.2 mm (width) × 565 mm (length)	0.5, 1, and 2
Block B	50.0 mm (width) × 565 mm (length)	0.25
Block C	25.4 mm (width) × 565 mm (length)	0.127, 0.147, 0.167, 0.25, 0.33, 0.5, 0.67, and 1

METHODOLOGY

The experiments are carried out in the wind tunnel in the Department of Mechanical Engineering, The University of Hong Kong (Figure 2). The dimensions of the test section are 565 mm (width) × 560 mm (height) × 3,600 mm (length). For fully developed flows, the test section is extended by connecting two separated sections. Idealized street canyon models are fabricated by movable, identical square aluminium blocks to control their aspect ratios. Three types of blocks of different sizes are used in the experiments (Table 1). The building height is small compared with the test section height to ensure an urban canopy layer (UCL) of sufficient depth for fully developed turbulent flows. The prevailing flow is perpendicular to the street axis because of the repeated alignment of the building blocks in streamwise direction, representing the worst scenario of air pollutant removal. The wind speed is kept at 2.5 m sec^{-1} in the wind tunnel experiments. The Reynolds number is well over 3,400 so the flows are independent from molecular viscosity in room conditions (Hoydysh et al, 1974).

The blockage ratio of the street canyon model in the experiment is ranged from 4% to 14%, which, however, is higher than the recommended blockage ratio (approximately 5%) for more accurate measurements in the industry. On the other hand, Liu et al. (2011) used a 2D Reynolds-averaged Navier-Stokes (RANS) k-ε turbulence model of blockage ratio 14.3% in which the computational domain was found to be large enough for fully developed flows in the street canyons. Therefore, it is believed that a blockage ratio of 14% would not affect too much the accuracy of measurements.

The sample street canyon is covered by soaked filter paper ribbons (width 5 mm). The wind tunnel is an open-circuit unit so the temperature and humidity of the upstream air are monitored, respectively, by a thermistor and a capacitive hydrometer during the experiments. The reference web-bulb temperature is continuously monitored on a 60 mm × 60 mm filter paper placed on an acrylic plate upstream of the test section (Figure 1) to prevent from complete dry out of the filter paper ribbons.

In Liu et al. (2011), the local pollutant exchange rate ω is normalized in idealized 2D street canyons of different aspect ratios shown as below

$$\omega \Big/ \left(PCH\big|_{h/b=1} \Big/ b\right) \tag{3}$$

as a spatial function, where $PCH|_{h/b=1}/b$ is the pollutant exchange rate of the street canyon of unity aspect ratio. Analogously, the following normalized local mass transfer velocity is used in this paper

$$w_t \Big/ \left(W_t \big|_{h/b=1} \Big/ b \right) \tag{4}$$

where w_t is the local mass transfer velocity and W_t is the average local mass transfer velocity in the street region of the street canyon of unity aspect ratio.

RESULTS AND DISCUSSION

Mass transfer inside the street canyon

Figure 3(a) compares the spatial distribution of the local mass transfer velocity on the surfaces of street canyons of different aspect ratios. All the flows fall into the skimming flow regime (Chung et al, 2010) so the prevailing wind does not entrain from the UCL into the street canyons. Only one recirculation is developed in a street canyon that is isolated from the prevailing flow aloft. Under this circumstance, the mass transfer from the ground level of a street canyon to the UCL is dominated by turbulent transport (Liu et al, 2011).

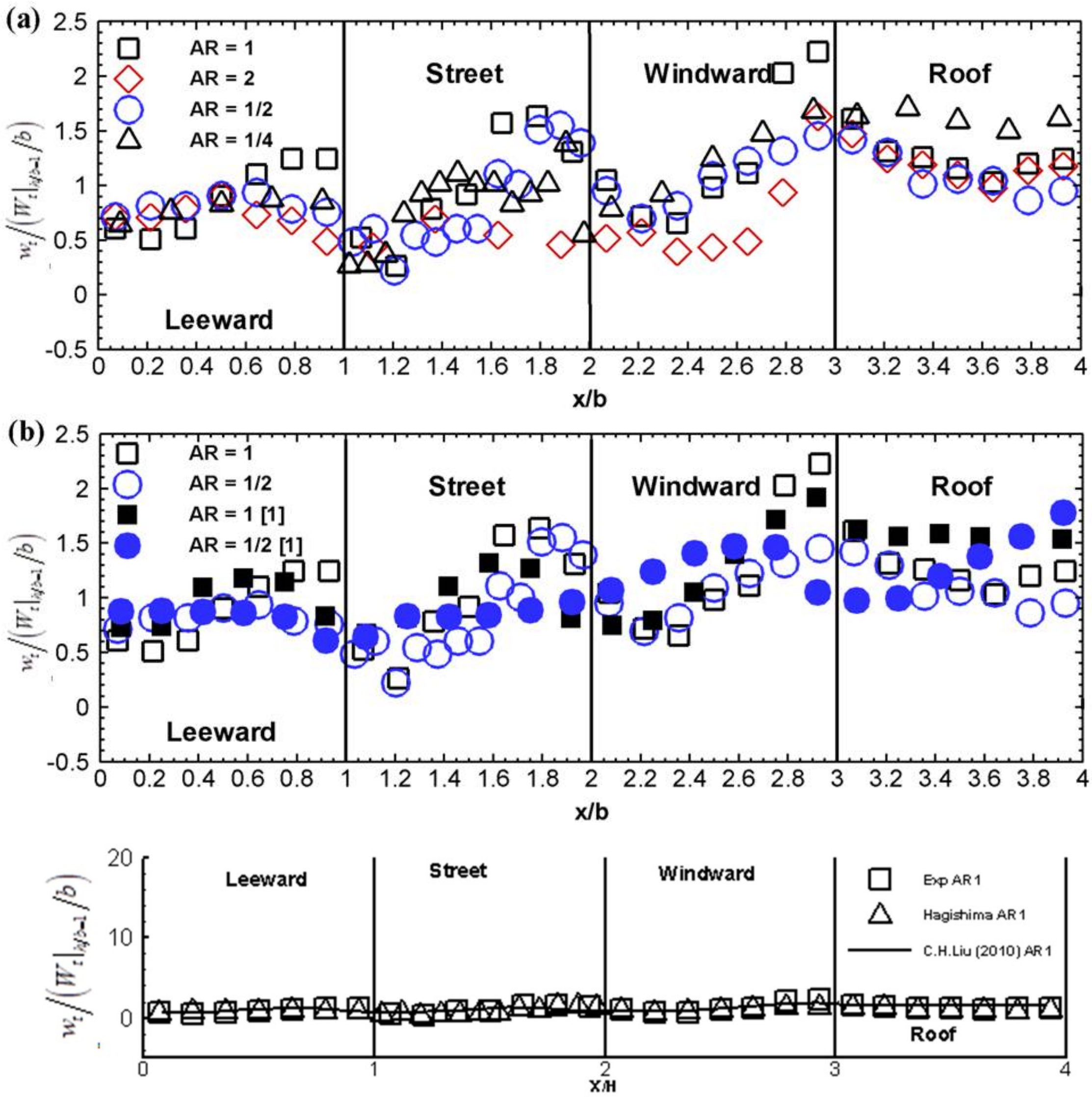

Figure 3. Spatial distribution of normalized local mass transfer velocity for street canyons of different aspect ratios. (a) The current study; (b) Comparison with the results of Narita (2007); and (c) Comparison with Narita (2007) and Liu et al. (2011).

On the leeward facade, a local maximum w_t is observed because of the vigorous upward flows at the mid-level of the street canyon. Chung et al. (2010) realized that w_t increases in the streamwise direction on the street surface, arriving a local maximum on the windward side. Because of the stagnate flows near the ground-level corner, a mild drop in w_t is observed on the windward façade. It then increases in the vertical direction, developing another local maximum of w_t at the roof-level windward corner. The local mass transfer velocity shows a local minimum at the middle of the roof due to the flow singularity at the roof-level corners. Compared with the others, it is noteworthy that the average w_t is smaller in the street regions of aspecr ratio 2. Besides, in the roof-level windward corner and the ground-level leeward corner, w_t for the street canyon of aspect ratio 1 is larger than that of the others. The average value of w_t at the roof region of street canyon of aspect ratio 1 is higher than that of the others, which is believed to be experimental error.

The current experimental results are comparable with those of Narita (2007) using water evaporation method (Figure 3b). Parametric CFD tests were also performed in Liu et al. (2011) to elucidate the relation between air pollutant concentration distribution and street canyon aspect ratios. These findings have been revealed by different approaches, nonetheless, agree well with each other (Figure 3c).

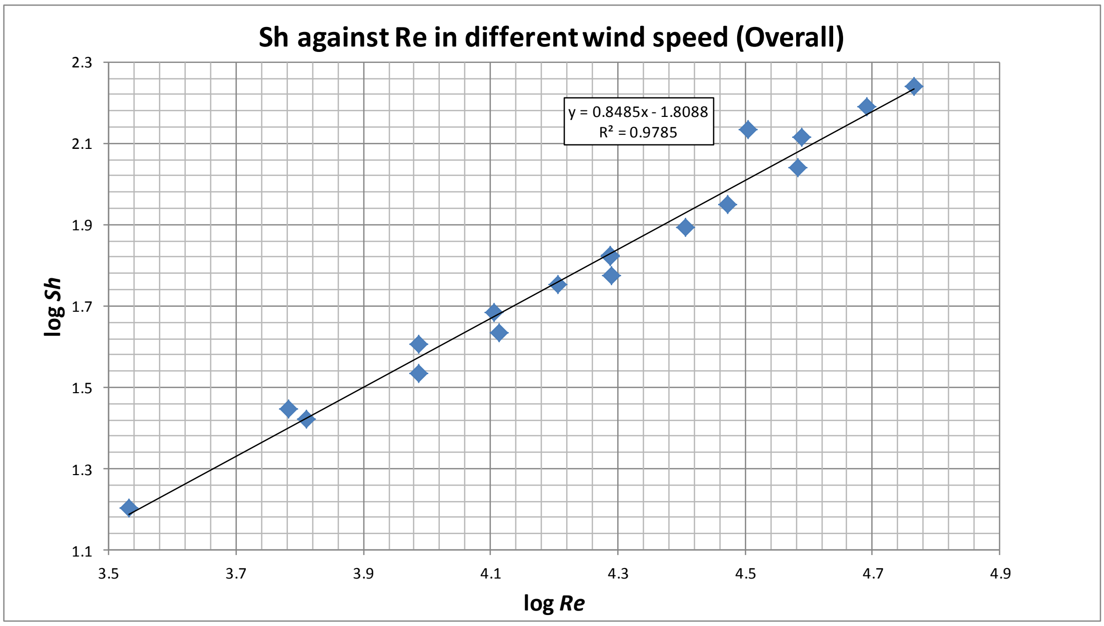

Figure 4. Sherwood number plotted against Reynolds number.

Scaling Effect

Probably attributed to the scaling effects often occur in laboratory experiments, the flow characteristics are independent from the Reynolds number but the mass fluxes are unavoidably functions of the sizes of model and prototype (Narita 2007). In order to examine the uncertainties of scaling effect in the experiments, the analogy of mass transfer over a flat plate and street canyons is adopted. Given the definition of Sherwood number,

$$Sh = \frac{W_t X}{D} \tag{5}$$

that is the ratio of convective-to-diffusive mass transport where D is the molecular mass diffusivity and X is the length of the plate, it is a function of the Reynolds number and the Schmidt number Sc ($= \nu / D$) for turbulent convective mass transport empirically by

$$Sh = A\mathrm{Re}^m\, Sc^n \tag{6}$$

where A are 0.0296 and 0.037 for the local surface and the whole surface, respectively, for the fully developed turbulent flows over a flat plate (Incropera and DeWitte, 1996). To examine the scaling effect, the overall mass transfer velocity W_t over street canyons of unity aspect ratio is measured in different wind speeds. The corresponding logarithmic values of Sh are plotted against Re (Figure 4). Linear regression of the data points shows that the slope is close to 4/5. Hence, the dimensionless turbulent mass transfer is a function of the characteristic velocity and length scales even the flows are already independent from the Reynolds number. Under this circumstance, comparison between data of different scales, such as CFDs and field experiments, should be performed with caution.

From Equation (6), we modify and propose to compare *A* instead of ω , the ratio between the mass transfer velocity to the prevailing wind speed is called mass transfer coefficient (.Barlow et al. 2002)

$$A = \frac{U^{1-m}h^{1-m}}{v^{n-m}\kappa^{1-m}}\omega \quad (7)$$

in order to account for the scaling effects. Here, *U* is the wind speed, *h* the model height, *v* the kinematic diffusivity and κ the mass diffusivity. Equation (7) demonstrates that turbulent mass transfer of idealized 2D street canyons depends on the flows and scales of the model. Additional data analyses should be conducted for a more meaningful result implementation.

CONCLUSION

Water evaporation method is used to measure the distribution of local mass transfer coefficient over 2D idealized street canyons. The results are compared well with those available in literature. It is found that pollutant removal is more favourable on the windward side and at the roof-level windward corner. Additional tests are currently undertaken to examine the flows and turbulence structures behind those phenomena.

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