On the Flows over Two-Dimensional Idealized street canyons with Height Variation

Colman Ching-Chi Wong & Chun-Ho Liu

Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong.

Abstract:
A series of LES models over 2D idealized street canyons with building height variation were performed. Buildings with two different heights are placed alternatively in the computational domains with building-height-to-street-width (aspect, AR) ratio = 1, 0.5, 0.25 and building height variability (BHV) = 0.2, 0.4 and 0.6. Preliminary results show that the relation between the air exchange rate (ACH) and the aerodynamic resistance (friction factor) is persisted in the current LES. It is also demonstrated that, apart from AR, BHV is another factor affecting the aerodynamic resistance and the ACHs as well. The (vertical) dispersion coefficient is also closely related to both the aerodynamic roughness and BHV. Conclusively, introducing BHV into urban areas could improve the air quality in a city.

Key words: Air pollution, CFD, LES, scalar dispersions

INTRODUCTION

Urban street canyon is the basic component of modern dense cities, the ventilation of urban street canyons could thus determine the street-level air quality. Although realistic street canyons are usually three-dimensional (3D) exhibiting diversified geometry, the simpler two-dimensional (2D) idealized street canyons are useful for investigating the fundamental mechanism. Therefore, hypothetical 2D idealized street canyons are employed in the current study to examine the basic physics of flows, turbulence and pollutant dispersion over urban roughness.

Previous studies of 2D idealized street canyons with uniform building height have shown that the air exchange rate (ACH) of street canyons increases with increasing aerodynamic roughness (Wong and Liu 2012). Besides, a strong relation between friction factor and vertical dispersion coefficient is found. Since 2D idealized street canyons with uniform building height is very different from realistic urban roughness elements so the validity of applying the theory developed in Wong and Liu (2012) to real cases of pollutant dispersion is in doubt. As such, a series of LES using 2D idealized street canyons with variable building height are conducted and compared with the results from identical street canyons in order to study the effects of random roughness on aerodynamic roughness, ACH and pollutant dispersion.

METHODOLOGY

LES of the open-source CFD code OpenFOAM 1.7 (OpenFOAM 2012) is adopted in this study. Idealized 2D street canyons of uniform height with ARs in the range of 0.083 to 2, covering all the three flow regimes of 2D street canyon defined by Oke (1988), are considered. The detailed LES configuration was reported elsewhere (Wong and Liu 2012). The model setup for LES of idealized street canyons with BHV generally follows its counterpart of uniform height. The major modification in the computational domain is rescaling the uniform building height (h) to two different building height (h_1 and h_2) placed alternatively in the streamiwse direction. The characteristic length used in the models is chosen to be the height of the higher building (h_1) or h (= $h_1 = h_2$) for building models with a uniform height. Thus, the AR is defined as the ratio of the height of the higher building to the street width (h_1/b). A new parameter, building height variability (BHV) is used to measure the inhomogeneity of the building roughness. It is defined as the difference in height between the two buildings divided by the height of the higher building ((h_1- h_2)/h_1). Four ARs (1, 0.5, 0.25 and 0.125) and three BHVs (0.2, 0.4 and 0.6) are considered. The flows in both cases are driven by a background pressure gradient ΔP_x in the urban boundary layer (UBL) over the buildings only. Hence the friction velocity is calculated by force balance in the streamwise direction $u_\tau = (\Delta P_x H/\rho)^{1/2}$. LESs are carried out for the plume dispersion from the ground-level source in neutral stratification to study the effects of roughness on pollutant transport alone. A source of passive and chemically inert pollutant with a constant concentration is prescribed on the ground of the first street canyon to mimic street-level pollution source (e.g. vehicular emission). The geometry details and boundary conditions of the computational domain are shown in **Figure 1** and **Table 1**.

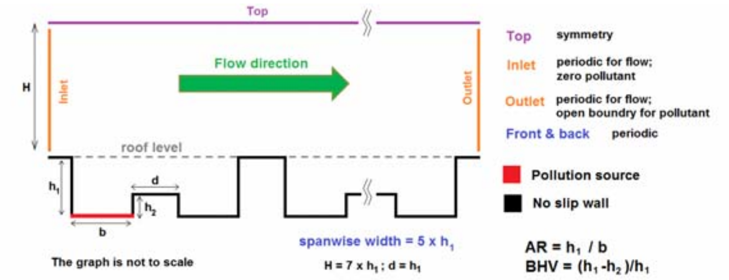

Figure 1. Computational domain and boundary conditions.

TABLE I. Computational details of the LESs for idealized street canyons.

Aspect ratio (ARs) h_1/b	**Building height variability (BHVs)** $(h_1 - h_2)/h_1$	**Domain size in streamwise direction** $[L_x/h]$	**Number of street canyons**[b]	**Number of grid points** $\times 10^6$
2	0%	24	16	~5
1[a]	0%	24	12	~36
1	20%	32	16	~7
1	40%	32	16	~7
1	60%	32	16	~7
0.59	0%	32.4	12	~6
0.5	0%	30	10	~5
0.5	20%	36	12	~8
0.5	40%	36	12	~8
0.5	60%	36	12	~8
0.25[a]	0%	30	6	~47
0.25	0%	50	10	~10
0.25	20%	50	10	~11
0.25	40%	50	10	~11
0.25	60%	50	10	~12
0.125	0%	72	5	~9
0.125	20%	72	8	~16
0.125	40%	72	8	~16
0.125	60%	72	8	~17
0.1	0%	55	5	~11
0.083	0%	52	4	~10
Flat[a]	N/A	36	N/A	~40

a. Fine-mesh LES model.
b. A unit of roughness element consists of two street canyons for models with non-zero BHV.

RESULTS and DISCUSSION

In order to use friction factor as a representative parameter of roughness length scale z_0, it is necessary to show that they exhibit a monotonic behavior. Using the equation from (Equation 18) in Wong and Liu (2013), which is derived from *log-law-of-the-wall*, it is shown that the relation between f and z_0 is.

$$\ln\left(\frac{z_0}{\delta - d}\right) = -\kappa\sqrt{\frac{2}{f}} - 1 + E\,, \tag{1}$$

where E is an error term that looks like a constant in the current study. **Figure 2** depicts the relation between f and z_0 for both street canyon models with uniform and variable building heights as well as the wind tunnel results by Hagishima *et al*. (2009) using 3D roughness elements. It is noteworthy that some assumptions were made for the data from Hagishima *et al.* (2009) in order to convert the drag coefficient to the friction factor used in this paper. A fairly linear relation is found between the left-hand side and the right-hand side of Equation (1), suggesting that E is a constant in the current configuration, and the relation between f and z_0 is monotonic. Thus f alone is sufficient to represent the roughness of the bottom surface.

For street canyons of a uniform building height, the aerodynamic resistance induced by surface roughness increases with increasing street width for narrow streets until AR = 1/10 or 1/7 and slowly drops thereafter at a lower-Reynolds-number direct numerical simulation (DNS; Leonardi *et al* 2003). **Figure 3** shows the effects of BHV on aerodynamic resistance. Similar to its counterpart of uniform street canyons, the roughness, which is either measured by friction factor or roughness length, for surfaces with BHV increases with increasing street width when AR > 1/8 even with BHV. Previous studies (e.g. Cheng and Castro 2002) mentioned that a random surface is much rougher than a uniform one that agrees well with the current LES finding. When AR > 1/4, buildings with BHV exhibit a sharp increase in friction factor that promotes the aerodynamic resistance of narrow street canyons to an extent that is comparable or even higher than that of wider street canyons with a uniform building height. When AR = 1/8, friction factor apparently no longer depends on BHV converging to a uniform level. It is interesting that building models with BHV do not show a peak of roughness higher than its uniform counterpart of AR < 1/8, implying a change of element sharp is necessary to achieve an even higher peak roughness.

Figure 4 shows the normalized ACH along the roof level of the rough surfaces. With a less uniform surface, the tendency of ACH against f still persists, i.e. ACH increases with increasing f. Combining the relation among f, BHV and AR, it is demonstrated that BHV modifies the ACH even the AR remains unchanged.

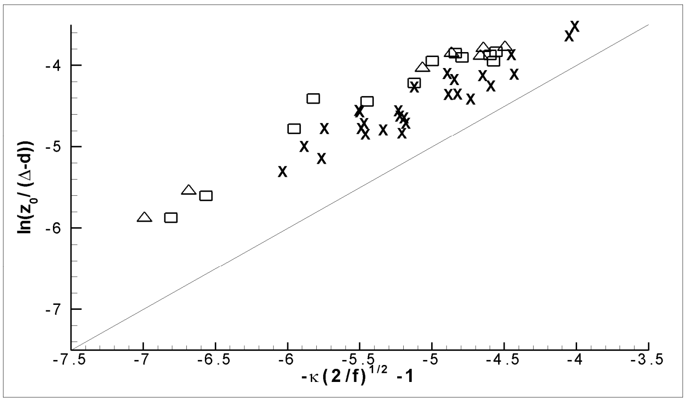

Figure 2. Roughness length scale z_0 plotted as a function of the friction factor f. LES over uniform street canyon: square; LES over 2D street canyon with BHV: triangle; and wind tunnel experiment by Hagishima *et al* (2009): cross. Solid line is the theoretical solution E = 0.

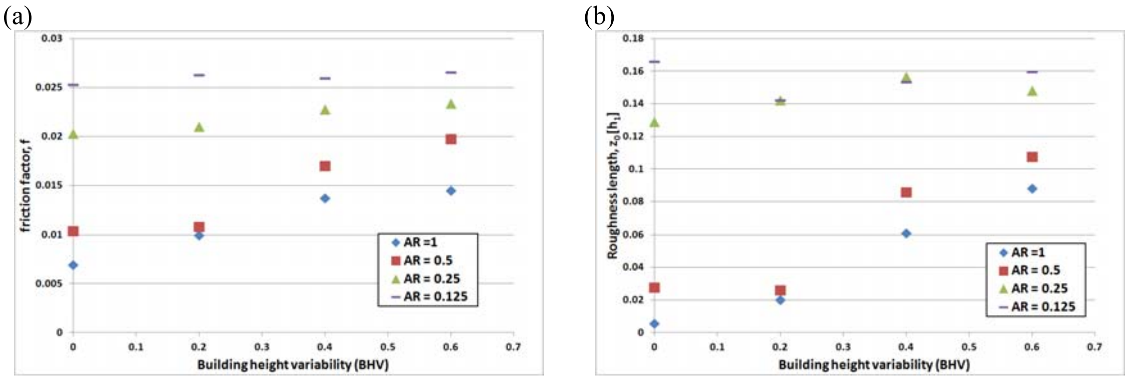

Figure 3. (a) Friction factor f and (b) roughness length z_0 plotted against building height variability BHV for street canyons of different aspect ratio AR.

The equation for vertical dispersion coefficient

$$\sigma_z = A(x - x_0)^n \tag{2}$$

is valid over 2D street canyons with uniform building height (Wong and Liu 2012). Analogously, Equation (2) is applied to 2D street canyons with BHV. **Figure 4** shows a linear relation between σ_z and x-x_0 in logarithmic scale. Hence, **Equation 2** is also applicable to idealized 2D street canyons with BHV.

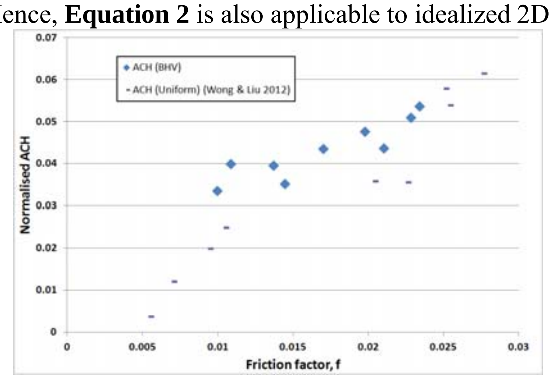

Figure 4. Normalized air exchange rate ACH plotted against friction factor f.

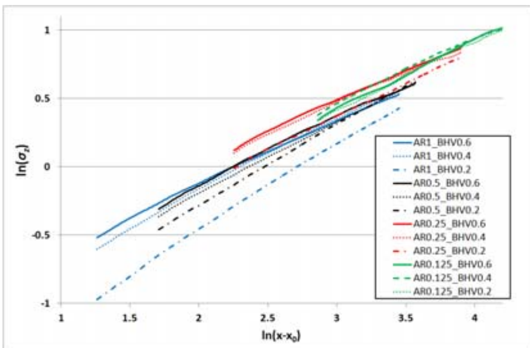

Figure 5. Vertical dispersion coefficient against streamwise distance from pollutant source in logarithmic scale.

It is previously found that A and n versus with friction factor f only when f is small and A and n become relatively constant for large f. Since there is a gap in friction factor in our previous study, which is likely caused by the substantial changes in roughness between wake interference and skimming flow regimes, the location of transition was not found. In this study, the gap in friction factor is filled by the LES data with BHV. In-line with our previous study, the current results (**Figure 6a**) show that the value of A (and n) is monotonically increasing (decreasing) when the surface is smooth until the friction factor reaches a certain value (~0.15) and A and n reach a relatively constant state. Since the relation between A and n is a monotonic function and exponential fitting gives a good approximation (**Figure 6b**), **Equation 2** could be further reduced to a function of a single independent variable.

(a) (b)

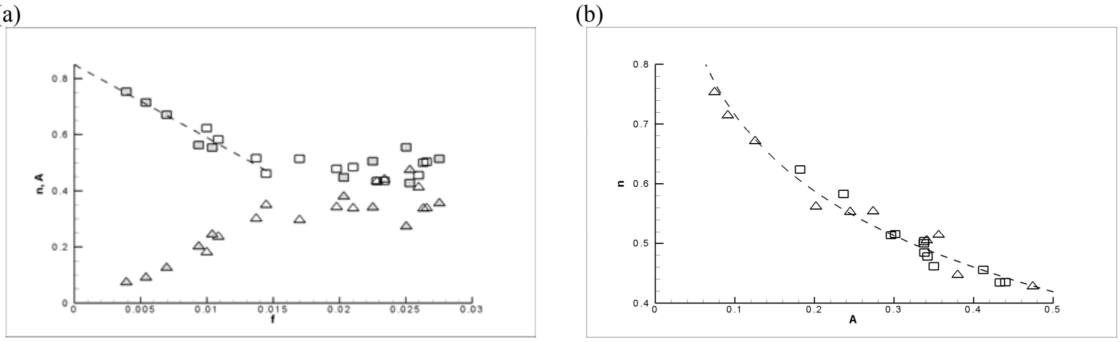

Figure. 6. (a) Empirical coefficients in Equation 2 expressed as functions of friction factor f. A: square; n: triangle; LES over uniform street canyon: filled symbols; LES over 2D street canyon with BHV: empty symbols; The linear regression n = -26.1f+0.85 with R^2 = 0.936 for f < 0:015: dashed line.
(b) Empirical coefficients in Equation 2 A versus n. LES over uniform street canyon: triangle; LES over 2D street canyon with BHV: square; The exponential regression A = 4:87exp$^{-5:433n}$ with R^2 = 0.968: dashed line.

SUMMARY AND CONCLUSION

A series of LES models over 2D idealized street canyons with building height variation were conducted and were compared with building models with a uniform height. Preliminary results show that the relation between ACH and aerodynamic resistance (f, z_0) persists in the current LES. Besides, a more detailed relation for A and n (the empirical coefficients in the vertical dispersion coefficient, **Equation 2**) and f is found. The current LES also demonstrates that, apart from AR, BHV plays an important role in the aerodynamic resistance over hypothetical urban rough surfaces.

As aerodynamic resistance increases with BHV in general and ACH increases with f in both uniform and BHV configurations. It is likely that increasing BHV is able to promote the street-level ACH, thus increases the amount of air exchange within the street canyons at the same building density. In the near-field pollutant dispersion, where **Equation 2** is dominated by A, σ_z also tends to increase with increasing f until a certain value is reached. Conclusively, introducing BHV into urban street canyons has the potential to improve the air quality for the city.

ACKNOWLEDGMENTS

This study was jointly supported by the Strategic Research Areas and Themes, Computational Sciences, and the University Research Committee Seed Funding Programme of Basic Research 200910159028 of the University of Hong Kong. The computation is supported in part by a Hong Kong UGC Special Equipment Grant (SEG HKU09). The technical support from Lilian Y.L. Chan, W.K. Kwan and N.S. Mok with Information Technology Services, the University of Hong Kong is appreciated.

REFERENCES

Cheng, H. and I. P. Castro, 2002: Near wall flow over urban-like roughness: *Boundary-Layer Meteorol.*, **104**, 229-259.

Chung, T.N.H. and C.-H. Liu, 2011: Ventilation and pollutant removal performance in street canyons of different aspect ratios: an LES solution: in Proceedings of the *13th International Conference on Wind Engineering (ICWE13)*.

Hagishima, A, Tanimoto, J, Nagayama, K, Meno, S, 2009: Aerodynamic parameters of regular arrays of rectangular blocks with various geometries: *Boundary-Layer Meteorol*, **132**, 315–337.

Leonardi, S, P. Orlandi, R. J. Smalley, L. Djenidi, and R. A. Antonia, 2003: Direct numerical simulations of turbulent channel flow with transverse square bars on one wall: *J. Fluid Mech*., 491, 229-238.

Oke, T.R., 1988: Street design and urban canopy layer climate: *Energy Build*, **11**,103–113.

OpenFOAM, 2013: OpenFOAM: The open source CFD toolbox: http://www.openfoam.com/

Wong, C.C.C. and C.-H. Liu, 2012: Pollutant Plume Dispersion in the Atmospheric Boundary Layer over Idealized Urban Roughness: *Boundary-Layer Meteorol.*, DOI 10.1007/s10546-012-9785-7.