On Plume Dispersion over Two-Dimensional Urban-like Idealized Roughness Elements with Height Variation

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Abstract

A series of large-eddy simulation (LES) models over two-dimensional (2D) urban-like idealized roughness elements with height variation were performed. Results show that building-height variability (BHV) could enhance the aerodynamic resistance of the urban surfaces. Both the air exchange rate (ACH) and the vertical dispersion coefficient σ_z increase with increasing the friction factor, implying that the air quality in both street canyons and urban boundary layer (UBL) could be improved by increasing the surface roughness via BHV. In addition, the parameters used in the estimates of dispersion coefficient are modified substantially by the friction factor, suggesting that friction factor could be used to parameterize dispersion coefficient of urban Gaussian plume model.

1 Introduction

Vehicular emission is a major pollutant source in dense cities (Fenger 1999; Colvile *et al.* 2001). In view of refining the current practice of urban planning to cope with urban air pollution issue, we need for a simple, quick and accurate pollutant dispersion model. Nowadays, the most commonly adopted method is the Gaussian pollutant plume model. The major limitation of the Gaussian pollutant plume model is that the calculation of plume rise and dispersion coefficients only includes the effects of atmospheric stability and the distance from the pollutant source. In reality, however, the large-scale roughness elements, e.g. buildings in urban areas, could substantially modify the flows and the dispersion in the urban boundary layer (UBL) that would lead to uncertainty in the calculation of pollutant distribution using the Gaussian plume model.

Idealised two-dimensional (2D) urban street canyons have been used as the basic components of modern cities to study the flows and dispersions in hypothetical urban areas. Although realistic building roughness elements are three-dimensional (3D) in shape and size, idealized 2D street canyons are easier to handle for the systematic investigation of the fundamental transport mechanism over rough surfaces. Therefore, idealised 2D idealized street canyons are employed in the current study to examine the basic physics of flows and pollutant dispersion over hypothetical urban areas.

In the literature, the studies of 2D idealised street canyons either emphasised on flows (e.g. Kim and Baik, 2001) or pollutant dispersion (e.g. Chan *et al.* 2002; Narita 2003) below the urban canopy level. A handful of studies have looked into the problems using 3D street canyons (e.g.: Tsai and Chen 2004). The most commonly employed solution approaches are computational fluids dynamics (CFD) and/or laboratory experiments.

Instead of the roughness elements at the bottom, some studies have focused on the UCL flows and dispersion over urban areas (e.g. Coceal *et al.* 2007). Salizzoni et al. (2009) showed that a few small-scale roughness elements on top of large-scale roughness elements could modify the aerodynamic resistance of idealised 2D street canyons, especially the streets are narrow. Xie *et al.* (2005) showed that the shape of building roofs has major impact on the flows and dispersion within the street canyons. Analogously, Huang *et al.* (2000) found that the dispersion inside street canyons is affected by the difference in building height between the leeward and windward façades. Although the aforementioned studies have consistently demonstrated the (potential) factors governing the flows and dispersion in street canyons and the UBL, no unified relation among urban morphology, flows and dispersion has been formulated. This study is therefore conceived in attempt to foster an in-depth understanding of transport processes over hypothetical urban areas using idealised building block models.

Wong and Liu (2013), using 2D idealized street canyons of uniform height, showed that a tight coupling between the friction factor f and the vertical dispersion coefficient σ_z of pollutant plume dispersion over hypothetical urban areas (Wong and Liu 2013). Moreover, the roof-level ACH increases with increasing aerodynamic resistance. Since uniform building height is rare in realistic urban roughness elements, a more comprehensive study is required to demonstrate the applicability of the theory developed in Wong and Liu (2013) to practical cases. Therefore, a series of LES using 2D idealized street canyons with building height variability (BHV) are conducted. The results are compared with those based on uniform building height in order to study the effects of (more) random roughness on the aerodynamic roughness, ACH and pollutant dispersion over hypothetical urban areas.

2 Methodology

The current LES setup for BHV generally follows that employed in Wong and Liu (2013). The computational domain is rescaled, modifying the identical buildings (h) to two different heights (h_1 and h_2) placed alternatively in the streamiwse direction (Figure 1). The height of the higher building (h_1) is used as the characteristic length scale. The aspect ratio (AR) is thus defined as the ratio of the height of the higher building to the street width (h_1/b). The newly defined parameter, BHV, is used to measure the inhomogeneity of the roughness elements that is equal to the difference in building height divided by the characteristic length scale ((h_1- h_2)/h_1).

LES of the open-source CFD code OpenFOAM 1.7 (OpenFOAM 2013) is adopted in this study. Idealized 2D street canyons of uniform ($0.083 \leq \text{AR} \leq 2$) and non-uniform (AR = 0.125, 0.25, 0.5 and 1; BHV = 0.2, 0.4 and 0.6) building height covering the regimes of skimming flow, wake interference and isolated roughness of 2D street canyons (Oke 1988) are considered (Table I).

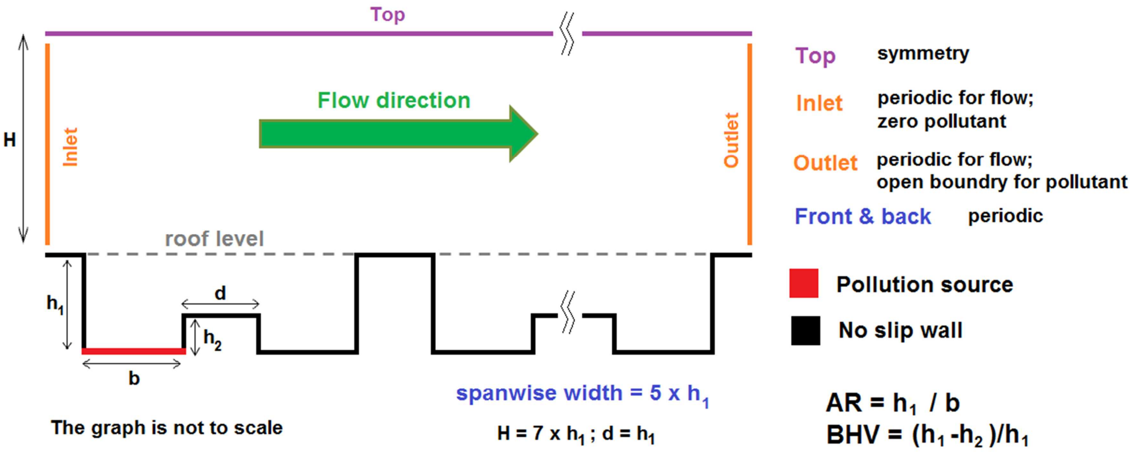

Figure 1: Computational domain and boundary conditions.

TABLE I. Computational details of the LESs for idealized street canyons of uniform and non-uniform building height.

Aspect ratio (ARs) h_1/b	**Building height variability (BHV) $(h_1 - h_2)/h_1$**	**Domain size in the streamwise direction L_x/h_1**	**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 BHV.

The driving force in the computational domain is the background pressure gradient ΔP_x which is only activated in the UBL over the buildings ($z \geq h_1$). No external force is applied inside the street canyons, hence, the friction velocity u_τ is calculated by force balance in the streamwise direction, i.e. $u_\tau = (\Delta P_x H/\rho)^{1/2}$. LESs are carried out to study the effects of urban roughness on transport processes in neutral stratification. An area source of passive and chemically inert pollutant with a constant concentration is prescribed on the ground of the first street canyon simulating a street-level pollutant source (e.g. vehicular emission or anthropogenic exhaust).

The implicit second-order accurate backward differencing is used in the temporal domain. The terms of gradient, divergence and Laplacian are calculated by the second-order accurate Gaussian finite volume integration. Structured meshes are used in the LESs. For the models with uniform buildings height, a street canyon is discretized by 16 × 16 (streamwise × vertical) grids with a stretching ratio of 2 to refine the spatial resolution near solid boundaries. A few fine-mesh models, in which the spatial resolution is doubled, are employed to ensure the LES grid dependence. For building models with BHVs, uniform grid spacing is applied in the streamwise (20 grids) and vertical (25 to 29 grids, depending on the BHV) directions of street canyons to refine the meshes near the building corners. The vertical UBL extent for the LESs with uniform building height and BHV is discretized into 140 and 120 grids, respectively, with a first-to-last-element stretching ratio equal to 3. The spanwise domain for both uniform and variable building height are discretized uniformly into 80 grids.

3 Results and discussion

Figure 2 illustrates the roughness length z_0 and friction factor f against BHV for different ARs. Our previous studies showed that the roughness of 2D street canyons increases with increasing street width when AR > 1/7. A similar behaviour is observed in the flows over urban roughness with BHV. The results also suggest that buildings with BHV enhance the aerodynamic resistance of the urban surfaces. With BHV, the roughness of the narrow street canyons (e.g. AR = 1) is increased to a level comparable to that of the wide street canyons (e.g. AR = 0.5) at the same building density (Figure 2). It is noteworthy when the street is wide enough (AR = 1/8; in isolated roughness flow regime), the contribution from BHV to the surface roughness is negligible.

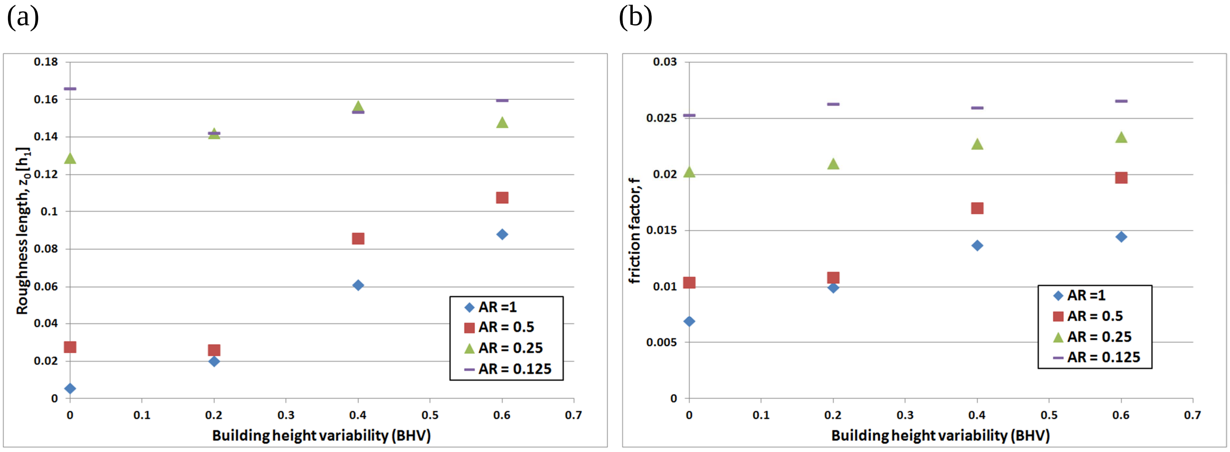

Figure 2: (a) Roughness length z_0 and (b) friction factor f plotted against BHV.

Figure 3 shows the ACH plotted against the friction factor. Data in the current LES are able to fill the gap of friction factor in-between skimming flow and wake isolated flow regimes (Wong and Liu 2013). In line with the previous study, the current LES shows that ACH increases with increasing friction factor. Hence, the air quality in narrow street canyons could be greatly improved by increasing the aerodynamic resistance by introducing BHV.

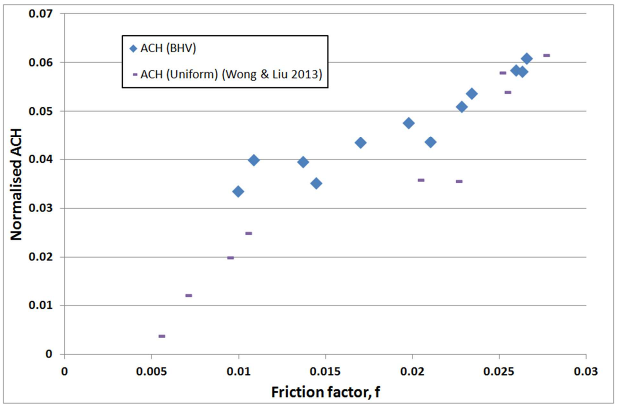

Figure 3: ACH plotted against friction factor.

The vertical dispersion coefficient σ_z is strongly correlated to the UBL pollutant concentration. Figure 4 shows the vertical dispersion coefficient in the streamwise direction for various BHV configurations. Given the same building density, urban buildings with a higher BHV have a larger vertical dispersion coefficient, implying that BHV is favourable to UBL air quality. Similar to the friction factor, BHV does not have any impact on the vertical dispersion coefficient when the streets are wide enough.

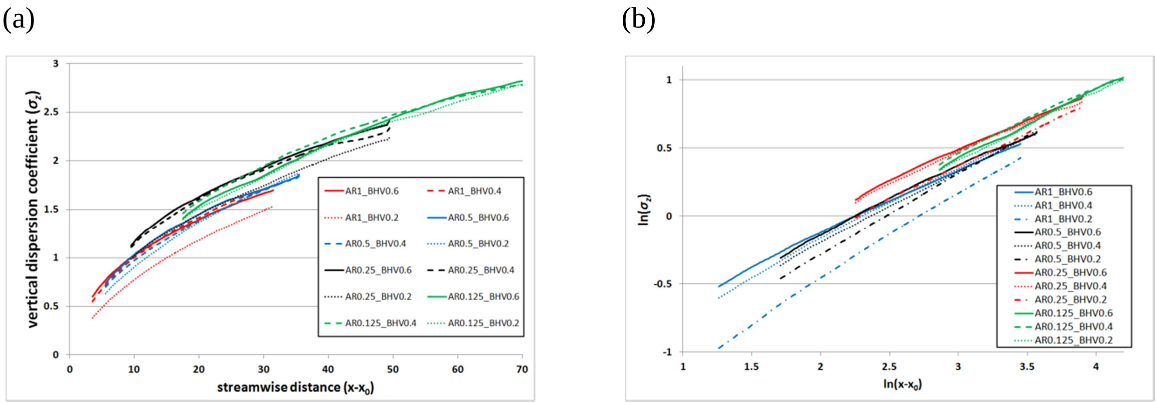

Figure 4: (a) Vertical dispersion coefficient σ_z plotted against x-x_0 and (b) ln(σ_z) plotted against ln(x-x_0)

A more systematic approach to the effect of roughness on pollutant plume dispersion is described below. The vertical dispersion coefficient σ_z is expressed mathematically in the following form

$$\sigma_z = A(x - x_0)^n \tag{1}$$

that is commonly employed in neutral stratification. Since the data in logarithmic scale (Figure 4b) collectively exhibit a linear behaviour, Equation (1) is suitable to describe the vertical dispersion coefficient calculated by the current LES. Afterwards, the values of *A* and *n* are obtained from curve fitting and data extrapolation.

Figure 5 shows the plot of *A* and *n* against friction factor *f*. As discussed in Wong and Liu (2013), both *A* and *n* increase linearly with increasing *f* initially for small *f*, Afterwards, *A* and *n* converge asymptotically to around 0.4 and 0.5, respectively, that are almost independent from *f*. Both *A* and *n* obtained in the current LESs agree well with the previous findings (Wong and Liu 2013). The current LES data not only fill up the gap in friction factor ($0.01 \le f \le 0.02$) observed using buildings of uniform height but also illustrate the range of friction factor that *A* and *n* transit from linear increasing/decreasing to constant values. The plot of *A* against *n* (Figure 6) also demonstrates their close relation. It is therefore suggested to further simplify the vertical dispersion coefficient in neutrally stratified UBL using only one single parameter.

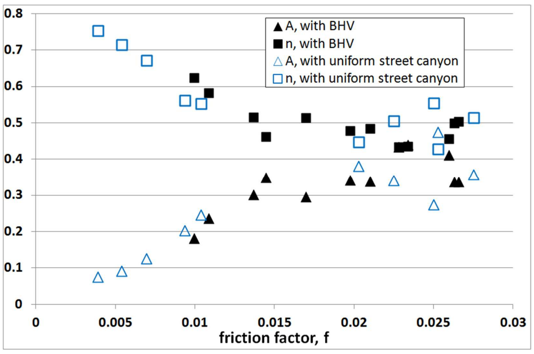

Figure 5: *A* and *n* plotted against friction factor *f*.

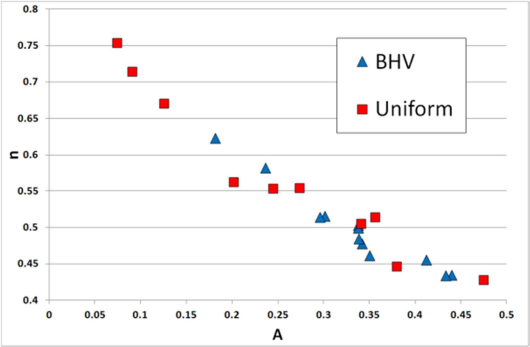

Figure 6: *A* plotted against *n*.

4 Conclusion

A series of LESs over 2D urban-like idealized roughness elements with BHV were conducted. Results show that BHV is able to enhance the roughness of the urban surfaces at the same building density for narrow street canyons. The current LES results also show that the ACH increases with increasing friction factor, hence, the air quality in narrow street canyons could be improved by increasing the aerodynamic resistance by introducing BHV. Similar to ACH, the vertical dispersion coefficient σ_z increases with BHV, suggesting that BHV is favourable to UBL air quality. In addition, the empirical parameters used in the estimates of vertical dispersion coefficient of buildings with BHV are in line with those in our previous LES using buildings with uniform height that collapse onto the same function. It is thus demonstrated that the tendency is applicable for both uniform and non-uniform idealized street canyons. In conclusion, it is suggested that the aerodynamic resistance of urban rough surfaces, e.g. friction factor, should be included in the parameterizations of pollutant dispersion coefficients.

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