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POLLUTANT DISPERSION OVER TWO-DIMENSIONAL IDEALIZED STREET CANYONS: A LARGE-EDDY SIMULATION APPROACH

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Abstract: A series of two-dimensional (2D) street canyon models with a wide range of building-height-to-street-width (aspect) ratios are employed in this study to elucidate the pollutant transport over idealized urban areas. The large-eddy simulation (LES) is used to resolve the turbulent flows and pollutant transport in the urban boundary layer (UBL) over the street canyons. An area source of uniform pollutant concentration is applied on the ground of the first street canyon to examine the pollutant plume dispersion behaviors over the downstream building roughness elements. The LES results show that, for the street canyon with the pollutant source, the pollutant removal is governed by atmospheric turbulence in both skimming flow and wake-interference regimes. Statistical analysis reveals that the turbulent kinetic energy (TKE) is peaked near the top of the building roughness elements that contributes most to turbulent pollutant removal. The roof-level TKE distribution also demonstrates that the turbulence production is not governed by local wind shear. Instead, the descending TKE from the UBL plays a more important role. In the UBL, the vertical pollutant profiles illustrate self-similarity behaviours in the downstream region. The pollutant disperses rapidly over the buildings, exhibiting a Gaussian-plume shape. Maximum vertical pollutant dispersion coefficient is observed at aspect ratio equal to 1/10. A strong correlation between friction factor and dispersion coefficient is found, implying that the downstream air quality could be improved by increasing the roughness of urban area.

Key words: *LES, urban roughness, and urban street canyon.*

INTRODUCTION

A simple and reasonably accurate pollutant dispersion model is helpful to urban planning. The classic method is using the Gaussian pollutant plume model that determines the plume rise and plume dispersion coefficients by the atmospheric stability and distance only. This method worked very well for rural area with aerodynamically flat terrain. However, its validity for applying over urban areas, where large-scale roughness elements presented, is in doubt. Macdonald et al. (1998) pointed out that, using wind tunnel experiments and field measurements, a Gaussian plume model around urban buildings must take into account of the details of the geometry obstacles and their layout as well.

Oke (1988) classified the flow patterns in 2D street canyons into three characteristic regimes as function of the building-height-to-street-width aspect (AR) ratio. The skimming flow regime, which is also known as *d*-type roughness, is in the range of AR > 0.7. In this flow regime, the mean flow from the urban boundary layer (UBL) does not enter into the lower street canyon. Instead, stable and isolated recirculation(s) develops inside the street canyon, resulting in poor air ventilation and pollutant removal. Street canyons of 0.4 < AR < 0.7 fall into wake-interference flow regime. In this flow regime, the mean flow from the UBL could enter the upper portion street canyon but cannot touch the ground. Although the air exchange rate in the wake-interference flow regime is better than that in the skimming flow regime, a stronger pollutant re-entrainment is found which may lead to a higher pollutant concentration within the street canyons. Street canyon of AR < 0.4 is in the isolated roughness regime. In this flow regime, the mean flow from the UBL could reach the ground of the street canyons so the air ventilation and pollutant removal is much better compared with the other two flow regimes. Although the pollutant transport within the street canyon is strongly related to flow regime, the plume in the UBL may not directly related them.

To elucidate the relationship between urban roughness parameters and pollutant plume dispersion behaviour, large-eddy simulation (LES) of plume dispersion over idealized 2D street canyons was conducted.

METHODOLOGY

The open-source CFD code OpenFOAM 1.7.0 (2011) was used in this study. The computational domain, boundary conditions (BCs) and other modeling details are described in this section.

The computational domains in this study are based on the LES in Cheng and Liu (2011) with extended domain size and various aspect ratios. The domain bottom consists of repeated, identical street canyons to construct an idealized 2D urban roughness with building height *h*, building width *d* (= *h*), and building separation *b* in streamwise direction. The domain above the building roof represents the UBL of height H (= 7*h*). The spanwise domain size is 5*h*. For the flow field, no-slip BCs are applied on the roughness at the bottom and a free-slip BC is applied on the domain top develop an UBL of thickness δ (= $H+h$) . Periodic BCs are applied in the horizontal directions in order to simulate the flow over an infinitely large urban area. The flow is driven by a background pressure gradient, which is only applied in the UBL, in the streamwise direction. The flow in the current LES is assumed to be incompressible and isothermal. For the pollutant transport, a constant concentration source Φ is prescribed on the ground of the first street canyon after the inlet. Zero-gradient BCs are applied on other ground surfaces, the building facades, and the top boundary. Zero-pollutant and open BCs are applied at the domain inlet and outlet, respectively, to prevent from the interference of background pollutant concentration and pollutant reflection.

The schematic of computational domain and BCs of the model of unity AR is shown in Figure 1. The geometry and BCs of the current computations are similar to each other. The major differences among those models are the ARs, domain size in the streamwise direction, and the number of street canyons. In this study, the ARs of the models are in the range of 0.1 to 2.0 which is sufficient to cover all of the three flow regimes in 2D street canyons proposed by Oke (1988). A flat model consisting of a single street canyon of unity AR, a roof-level long flat surface, is used to simulate the plume dispersion over a flat terrain with the same source characteristics. The detailed information of the computational domain is listed in Table 1.

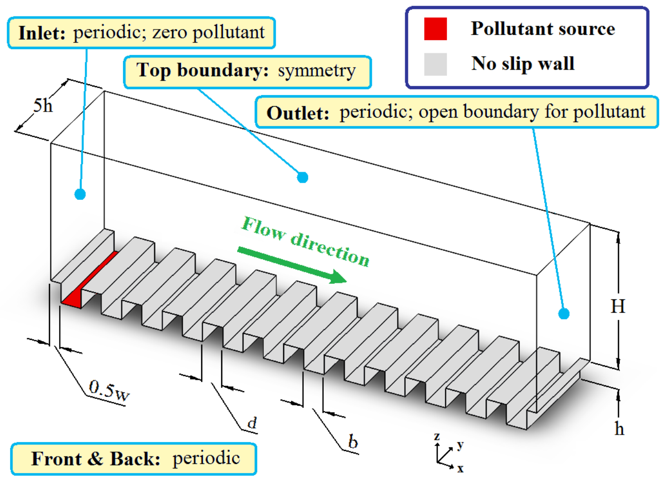

Figure 1. Computational domain and boundary conditions (AR = 1)

In the current LES, the continuity, Navier-Stokes equations, and the Smagorinsky subgrid-scale (SGS) model (Smagorinsky, 1963) are adopted to calculate the flow field. The one-equation SGS model suggested by Schumann (1975) is used to calculate the SGS TKE conservation. The transport of a passive and inert pollutant is solved by the advection-diffusion equation at Schmidt number *Sc* (= 0.72). The implicit second-order accurate backward differencing is used to integrate the temporal domain. The gradient, divergence, and Laplacian terms are handled by second-order accurate Gaussian finite volume integration scheme, which is based on the summation on cell faces. The center value on a cell face in the integration scheme is determined from the linear interpolation of cell-center values.

Structural grids are used in the LESs. The building is discretized into 16×16 (streamwise×vertical) grids with a simple cell stretching ratio of 2 in order to refine the grids near the building corner. The spanwise domain is discretized uniformly by 16 elements per *h*. The vertical domain in the UBL is discretized by 140 grids with a last-to-first-element-length ratio of 3. A few fine-mesh models have been conducted to examine the grid sensitive to the LESs. They have double grid density with the same stretching ratio as the normal LESs. The number of grids in each model is tabulated in Table 1.

The centers of first layer of elements next to the solid boundaries are placed at $z^+ \approx 5$ to 10 in wall unit so the spatial resolution is fine enough handling the near-wall flows accurately. The Reynolds numbers based on the free-stream flow speed, which is taken at the domain top boundary, and the building height Re (= Uh/ν) are in the range of 6,500 to 16,000 for all the models. The respective Reynolds numbers based on the friction velocity Re_τ(= $u_\tau h/\nu$) are in the range of 550 to 850.

Table1. Detailed information of the computational domain

Model (ARs)	L_x *(h)*	*# SCs*	*# grids SC*	*# grids UBL*	*Total # of grids*	**Re**
Flat(a)	36	1	32×160×32	880×160×280	~40 M	14859
0.083	52	4	192×80×16	832×80×140	~10 M	6844
0.1	55	5	160×80×16	880×80×140	~11 M	6527
0.125	45	5	128×80×16	720×80×140	~9 M	6942
0.25	50	10	64×80×16	800×80×140	~10 M	7513
0.25(a)	30	6	128×160×32	960×160×280	~47 M	11045
0.5	30	10	28×80×16	440×80×140	~5 M	10088
0.59	32.4	12	28×80×16	528×80×140	~6 M	10296
0.8	36	16	20×80×16	576×80×140	~7 M	11407
1(a)	24	12	32×160×32	768×160×280	~36 M	16067
2	24	16	12×80×16	448×80×140	~5 M	12858

Remark: (a) Denotes fine-mesh model; L_x: Domain size in the streamwise direction; # SCs: Number of street canyons; # grids SC: Number of grids in a street canyon (streamwise×spanwise×vertical); # grids UBL: Number of grids in the urban boundary layer; Total # grids: Total number of grids; Re: Reynolds number based on the free-stream flow velocity and building height.

RESULTS AND DISCUSSION

Figure 2 shows the net vertical pollutant flux at the roof level of the first street canyon defined by Equations (1) and (2).

$$Net\ Mean\ flux = \int_{roof} \langle \overline{w} \rangle \langle \overline{\phi} \rangle dx / Q \tag{1}$$

$$Net\ Turbulent\ flux = \int_{roof} \langle w''\phi'' \rangle dx / Q \tag{2}$$

where Q is the pollutant source strength.

It is found that the mean flow helps pollutant removal only in the isolated roughness regime. Besides, a substantial net pollutant entrainment, which is carried by the mean flow, is found in the skimming flow regime. The importance of turbulent flux drops with increasing ARs. If the trend persist, the mean flux dominates the pollutant removal when AR < 0.01. However, characteristic flows in the isolated roughness regime are very unlikely to occur in urban street canyons so the pollutant removal from urban areas is dominated by atmospheric turbulence.

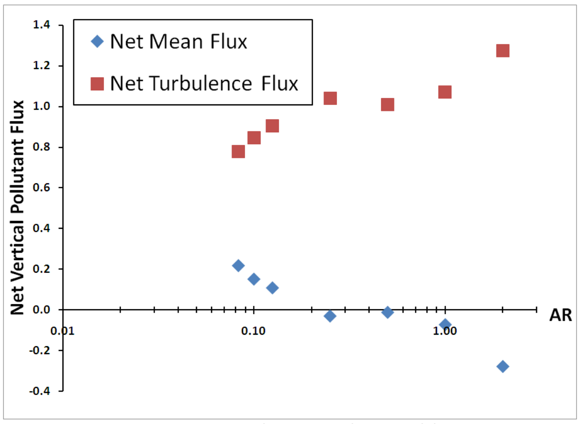

Figure 2. Net vertical pollutant flux at roof level of first street canyon.

The streamwise velocity and TKE along five vertical segments (Figure 3) are depicted in Figures 4(a) and (b), respectively, within the street canyon of unity AR. Although the maximum velocity gradient consistently occurs near the leeward roof-level corners of the building, the maximum TKE is shifted toward the roof-level windward corner. This finding apparently suggests that the roof-level turbulence is not cascaded from local wind shear. Instead, the TKE likely descends from the UBL to the ground level. As the turbulent transport is the main mode for pollutant removal and the ground-level turbulence is not directly come from local wind shear, the mean wind speed contributes rather limitedly to the pollutant removal.

The validity of using the LES in OpenFOAM for the flows within 2D street canyon was demonstrated by Cheng and Liu (2011) by comparing the flow structure with wind tunnel experiment as well as other CFD results available in literature. Whereas, its validity for the flows and plume dispersion in the UBL over 2D street canyons is in doubt. Table 2 shows the roughness length and friction factors of the LES computations. The roughness length of the current LES fits reasonably well with that in Salizzoni et al. (2009), demonstrating the accuracy of the current LES handling the flows in UBL.

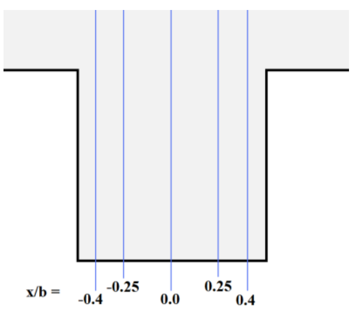

Figure 3. Five segments, x/b =: −0.4, −0.25, 0, 0.25, and 0.4, in a street canyon.

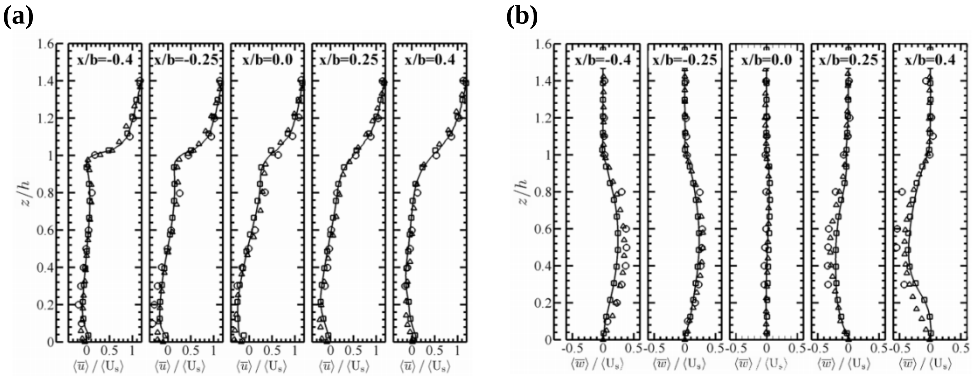

Figure 4. Vertical profiles of the ensemble average of: (a) streamwise velocity ; (b) TKE . ○: Brown *et al.* (2000); Δ: Cui *et al.* (2004); □: the LES of Cheng and Liu (2011); and —: current LES.

Table 2: Roughness parameters

Model (ARs)	*d* (*h*)	z_0 (*h*)	*f*	z_0/δ	z_0/δ, Salizzonli et al. (2009)
Flat(a)	1	0.00059	0.0039	0.00007	
0.083	0.65	0.15084	0.0250	0.01886	
0.1	0.62	0.16868	0.0275	0.02109	
0.125	0.63	0.16597	0.0253	0.02075	
0.25	0.69	0.12928	0.0203	0.01616	
0.25(a)	0.61	0.15673	0.0225	0.01960	
0.5	0.89	0.02785	0.0104	0.00348	0.0034
0.59	0.93	0.01981	0.0094	0.00248	
0.8	0.97	0.00863	0.0074	0.00108	
1(a)	0.98	0.00572	0.0069	0.00072	0.00062
2	1.01	0.00210	0.0054	0.00026	0.00026

Remark: (a) Denoted fine-mesh model; *d*: displacement offset; z_0: roughness length; *f*: friction factor; δ: boundary layer thickness (= H + *h*).

Figure 5 (a) shows the normalized vertical plume profiles along different vertical transverses at various streamwise locations for model of unity AR. The vertical location is normalized by the vertical dispersion coefficient σ_z which is defined in Equation (3).

$$\sigma_z^{\ 2} = \frac{\int (z - z_c)^2 \langle \overline{\varphi} \rangle \partial z}{\int \langle \overline{\varphi} \rangle \partial z} \tag{3}$$

where z_c is the plume center height; $\langle \overline{\phi} \rangle$ is the ensemble average of resolved-scale pollutant concentration $\overline{\phi}$ in the spanwise and temporal domain. z_c is defined as the elevation of maximum concentration which is found to be located at the roof level ($z = h$) in the current LESs. The pollutant concentration is normalized by the roof-level concentration along the same vertical transverse. Over a range of ARs, the normalized plume profiles are generally converged after the 4th street canyon, implying that four street canyons are the minimum requirement for achieving a self-similar plume shape. Inhomogeneous plume profiles in the horizontal direction are found in the near-roof region only. Figure 5(b) compares the self-similar profiles of different ARs. The results show that the pollutant plume over idealized 2D street canyon are Gaussian in general, especially in the wake interference regime, leaving the dispersion coefficient the major parameter determining the plume characteristic.

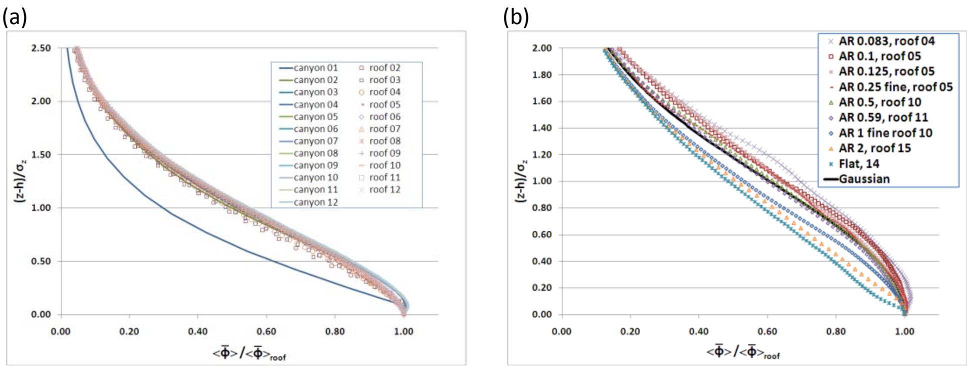

Figure 5. (a) Normalized vertical plume profiles (AR =1); (b) Self-similar profiles

Figure 6 compares the plume dispersion coefficients of different ARs. In the skimming flow and wake interference regimes, the dispersion coefficient increases with increasing street width. In the isolated roughness regime, the dispersion coefficient first increases with increasing street width, arrives the peak at AR = 1/10, then drops thereafter. Comparing the trend of plume dispersion coefficient with the roughness parameters (Table 2), the plume dispersion coefficient is strongly correlated to the friction factor. Hence, the downstream air quality is a function of urban roughness parameters.

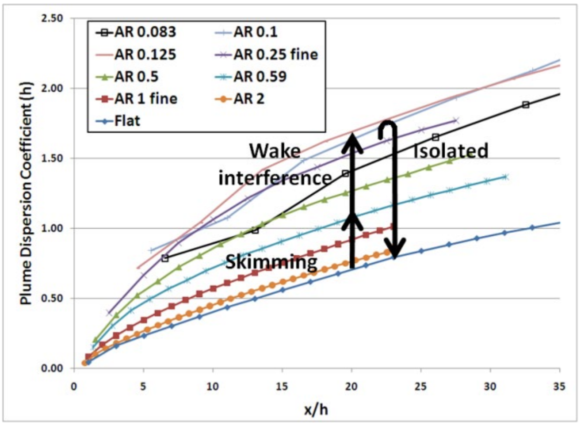

Figure 6. Dispersion coefficients along the streamwise direction

CONCLUSION

LES of idealized two-dimensional (2D) street canyon models with a large range of ARs are employed in this study. The LES results show that the pollutant removal is largely governed by atmospheric turbulence in urban street canyons in general. Statistical results show that the roof-level TKE, which contributes to the turbulent pollutant removal, is not mainly produced by local wind shear. Instead, the TKE descending from the UBL plays a more important role. Increasing free-stream wind speed does not help much in both direct and indirect pollutant removal via local turbulence generation. The pollutant plume shapes in the UBL exhibit a self-similar behavior (Gaussian shape), demonstrating that the downstream pollutant concentration level can likely be parameterized as a function of dispersion coefficient in the streamwise direction. The trend of pollutant dispersion coefficient is in line with the friction factor, suggesting that the downstream air quality can be improved by increasing the roughness of urban areas.

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