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CHARACTERIZING POLLUTANT PLUME DISPERSION IN URBAN ATMOSPHERIC SURFACE LAYER

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Abstract: In densely urbanized cities, the dynamics in the atmosperhic surface layer (ASL) are highly complicated by the land-surface morphology. The building-induced drag modifies the wind and pollutant dispersion. Advanced understanding of the pollutant dispersion over urban areas is utmost important for public health and the formulation of pollution control strategy. Gaussian plume model is the conventional approach to pollutant dispersion estimate. Its accuracy mainly depends on the functionality of the empirical dispersion coefficients (σ_y in lateral and σ_z in vertical directions). ASL turbulence is complicated by land feature such as natural terrain or building morphology. It in turn influences the dispersion coefficients (especially σ_z), which, however, is often overlooked in the practice of pollutant dispersion modeling. Skin-friction coefficient C_f, as a measure of surface roughness in engineering flows, has been adopted to parameterize street-level ventilation using both large-eddy simulation (LES) and wind tunnel experiments. As an extension of our on-going research effort, we report in this paper our attempt to parameterize the vertical dispersion coefficient σ_z in the conventional Gaussian framework in terms of skin-friction coefficient and other flow variables. Analytical solution shows that the vertical dispersion coefficient σ_z is proportional to the friction length scale L_f (= $x^{1/2}\times\delta^{1/2}\times C_f^{1/4}$, where x is the distance after the pollutant source and δ the ASL thickness). Its functional form is verified by wind tunnel measurements for flows and plume dispersion over hypothetical urban areas assembled by aluminum square bars. A close correlation between σ_z and L_f is revealed (correlation coefficient r = 0.933), demonstrating the substantially influence of surface drag on plume dispersion over urban areas.

Key words: *Gaussian plume, dispersion coeffecient, wind tunnel,*

1. INTRODUCTION

Gaussian plume model is the well-received solution to atmospheric boundary layer (ABL) pollutant dispersion because of its cost-effectiveness in air quality management. Its accuracy, however, depends on the functionality of dispersion coefficients (σ_y in lateral and σ_z in vertical direction). Theoretically, dispersion coefficients are functions of atmospheric turbulence and surface roughness (Turner, 1994). Most σ_y and σ_z are empirically determined based on the atmospheric stability and the distance behind the pollutant source (Pasquill and Smith, 1983). Whereas, the turbulence in the atmospheric surface layer (ASL) is complicated by land feature such as natural terrain, forest vegetation or building geometry. It in turn modifies substantially the dispersion coefficients (especially σ_z), which, however, is often overlooked in the practice of pollutant plume dispersion modeling over urban areas.

This study examines the flows and transport processes over hypothetical urban areas. We attempt to parameterize the vertical dispersion coefficient σ_z in the (conventional) Gaussian framework by formulating the functional form in terms of skin-friction coefficient C_f and other flow variables. The theory is derived first in the next section. Afterward, wind tunnel results are reported to verify the mathematical hypothesis and to characterize the tracer plume dispersion as a function of surface roughness.

2 THEORETICAL BACKGROUND

The key parameter in Gaussian plume model, dispersion coefficient σ_z, can be described by the classic K-theory, anti-gradient diffusion model

$$\sigma_z^2 = 2K_z t = 2K_z \times x/U \tag{1}$$

where K_z is the eddy diffusivity in the wall-normal direction z and t (= x/U) the pollutant traveling time from the source to the receptor in the streamwise direction x (Gromke, 2011). Without loss of generality, it is assumed that the flows are uniform so the wind speed U is a constant. Isothermal conditions are considered in this paper so the eddy diffusivity can be approximated by the mixing length theory

$$K_z \propto l_* u_* . \tag{2}$$

where l_* and u_* are the characteristic scales of length and velocity of the flows, respectively. For ground-level release into an isothermal turbulent boundary layer (TBL), the TBL thickness δ and the friction velocity u_τ are the reasonable approximations to l_* and u_*, respectively. Equation (1) is then simplified to

$$\sigma_z \propto \left(x \times \delta \times u_\tau / U\right)^{1/2} \tag{3}$$

The friction-velocity-to-mean-speed ratio u_τ/U is a measure of drag over rough surfaces in the form of skin-friction coefficient C_f (= $2u_\tau^2/U^2$). We take the freestream velocity U_∞ to represent the uniform wind speed U so Equation (3) arrives the following dimensionless form

$$\sigma_z/h \propto \left(x/h\right)^{1/2} \times \left(\delta/h\right)^{1/2} \times C_f^{1/4} \tag{4}$$

that proposes the basic analytical formulation of vertical dispersion coefficient over urban areas. Equation (4) is then verified by our wind tunnel experiments and mathematical modeling results.

3 METHODOLOGY

The experiments are performed in the open-circuit wind tunnel in the Department of Mechanical Engineering, The University of Hong Kong (Figure 1). The wind-tunnel test section is 6-m long, 0.56-m wide and 0.56-m high. The design wind speed is in the range of 0.5 m sec^{-1} ≤ U ≤ 15 m sec^{-1}. To model a TBL in the test section, a 2-m long upstream section is adopted on which an array of square aluminum tubes (size h = 19 mm with separation 19 mm apart) is glued (Figure 1a). The freestream wind speed U_∞, which is measured by a Prandtl-type pitot-static tube installed upstream of the test section, is maintained at 3.3 m sec^{-1} and 6.6 m sec^{-1}, to examine the flow independence and scale similarity. Idealized models of urban morphology are fabricated in the form of identical street canyons using arrays of rib-type roughness elements. The aluminum square tubes, whose length L is 560 mm (L/h = 29), span across the entire wind tunnel. They are aligned normally to the prevailing wind at separation b apart so the aspect ratio (AR), which is adjustable to control the aerodynamic resistance, is equal to h/b (Figure 1b). Four types of rough surface are considered in this paper whose ARs are 1/2, 1/4, 1/8 and 1/12.

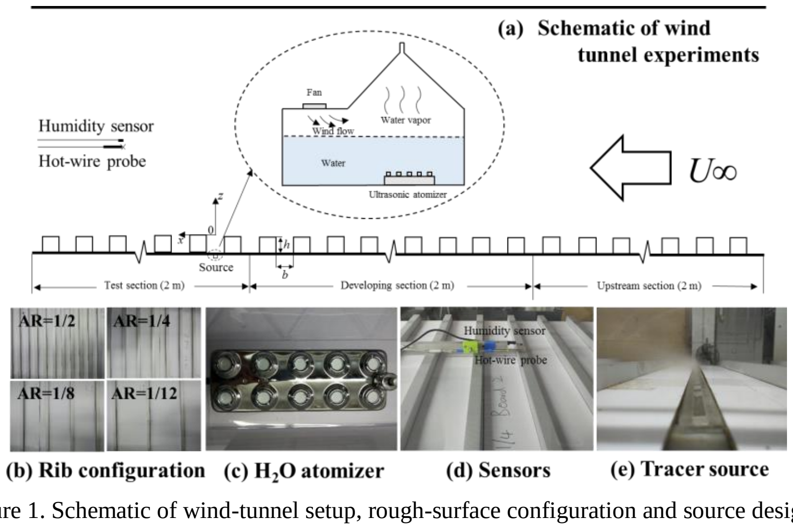

Figure 1. Schematic of wind-tunnel setup, rough-surface configuration and source design.

Water vapor, which is generated by an atomizer, is released as a tracer from the line source (Figure 1c). It is driven to the line source from a reservoir below the wind tunnel test section by an electric axial fan of constant wind speed. The flows induced by the fan (0.2 m sec^{-1}) are negligible compared with the prevailing flows in the wind tunnel. The water levels in the reservoir are the same in the experiments to ensure a constant emission rate of water vapor Q (about 2 liter an hour).

Velocity measurements are sampled by a constant-temperature hot-wire anemometer (CTA) with a *X*-wire probe (Figure 1d). The relative humidity (RH) and temperature are measured by a Humidity and Temperature Sensor SHT75 (SENSIRION AG Switzerland). Another SHT75 is placed upstream the water vapor source to monitor the background RH and temperature (Figure 1e). The whole measurement system is controlled by a desktop computer via a NI CompactDAQ chassis with LabVIEW software.

4 RESULTS AND DISCUSSION

4.1 Flows

Figure 2 shows the vertical dimensionless profiles of the spatio-temporal average of mean and fluctuating velocities. The velocity components are normalized by the freestream wind speed U_∞ and the vertical distance is normalized by the TBL thickness δ. Minor difference is found for the average velocity profiles $\langle \overline{u} \rangle$ over different arrays of street canyons (Figure 2a). This indicates that the dimensionless mean profiles are not significantly affected by different configurations of surface roughness in our wind tunnel experiments and the freestream wind speed U_∞ is an appropriate characteristic velocity scale. On the other hand, noticeable differences are observed in the fluctuating wind components over different rough surfaces at different freestream wind speeds. For instance, fluctuating streamwise velocity $\langle \overline{u"u"} \rangle^{1/2}$ (Figure 2b), fluctuating vertical velocity $\langle \overline{w"w"} \rangle^{1/2}$ (Figure 2c) and momentum flux $\langle \overline{u"w"} \rangle$ (Figure 2d). These findings suggest that the near-wall turbulence structure is strongly affected by the drag induced by the roughness elements so is the transport processes. Given the same freestream wind speed, the intensities of various fluxes generally increase with decreasing AR (widening street width). Moreover, the profiles over the array of street canyons of AR = 1/8 overlap with those of AR = 1/12, suggesting momentum flux is peaked when the building separation is wide enough.

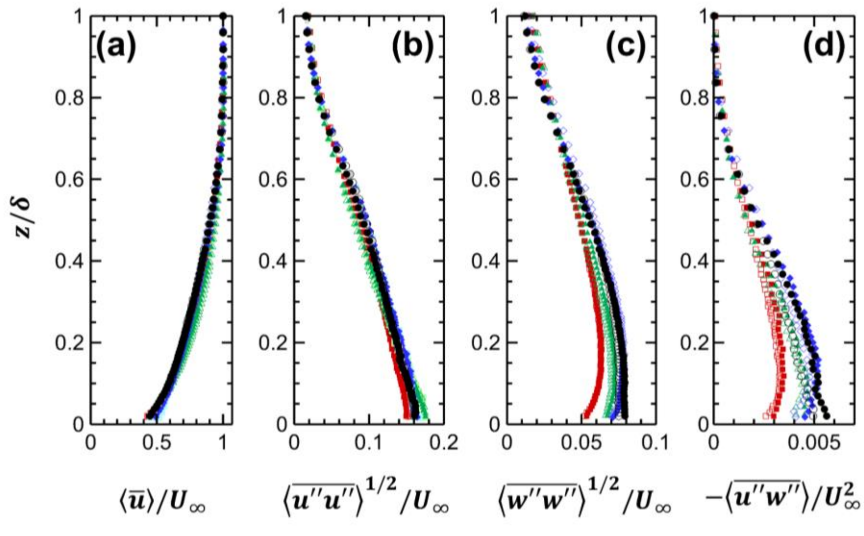

Figure 2. Vertical dimensionless profiles of flow variables plotted against wall-normal distance z/δ over arrays of street canyons of aspect ratios ARs = 1/2 (□); 1/4 (△); 1/8 (◇) and 1/12 (○) in freestream wind speed U_∞ = 3.3 m sec^{-1}. Filled symbols are the corresponding quantities in U_∞ = 6.6 m sec^{-1}.

4.2 Plume dispersion

Figure 4 illustrates the self-similar vertical dimensionless profiles of pollutant concentrations over arrays of street canyons of ARs = 1/2, 1/4, 1/8 and 1/12. The wall-normal distance z is normalized by the dispersion coefficient σ_z, while the pollutant concentration $\overline{\psi}$ is normalized by its canopy-level value $\overline{\psi}_{\text{canopy}}(x)$. This approach helps focus on the dynamics within plume coverage. The vertical dimensionless profiles of concentration $\overline{\psi}(x,z)/\overline{\psi}_{\text{canopy}}(x)$ measured at different streamwise positions x, regardless of the freestream wind speeds U_∞, collapse well with each other that fit into the theoretical Gaussian distribution Equation (2). It is hence suggested that ASL pollutant plume dispersion over rough surfaces, such as urban areas, exhibits the conventional Gaussian form similar to its ABL counterpart. A noticeable elevation of tracer concentration is observed in the near-wall region ($z \leq 0.75 \times 2^{1/2}\sigma_z$). It is mainly attributed to the flows over the windward wall of roughness elements where the sharp edges (singularities) enhance the local turbulence that in turn dilute the tracer adjacent to solid boundaries. Another possible reason is that the water vapor condenses on the (cooler) aluminum rib surfaces. It subsequently reduces canopy-level tracer concentrations that eventually raises the dimensionless tracer concentrations aloft. Huber (1991) also found an elevated peak of tracer concentration similar to that in the current study. Besides, Figure 4a depicts the vertical dimensionless profiles of tracer concentrations over an array of street canyons of AR = 1/2 (Salizzoni et al. 2009). The plume core converges to the theoretical Gaussian distribution. Although a mild deviation is observed near the canopy level, the peaked tracer concertation is obviously elevated in Salizzoni et al. (2009)

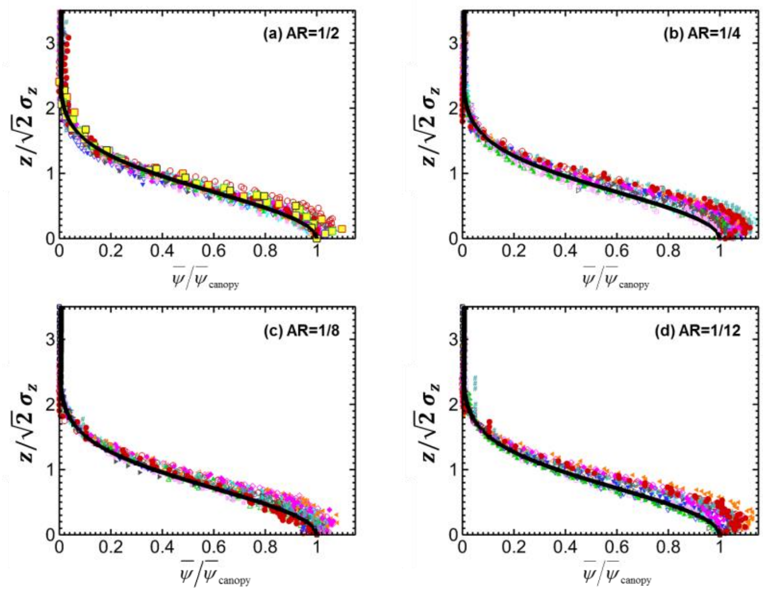

Figure 4. Vertical dimensionless profiles of tracer concentrations $\overline{\psi}/\overline{\psi}_{\text{canopy}}$ plotted against wall-normal distance $z/2^{1/2}\sigma_z$ over arrays of street canyons of aspect ratios ARs = (a) 1/2; (b) 1/4; (c) 1/8 and (d) 1/12 at $x = 10h$ (□); $15h$ (△); $22.5h$(▽); $30h$ (▷); 37.5h (◁); $45h$ (◇); $52.5h$ (+); $60h$ (-) and $67.5h$ (○) in freestream wind speed U_∞ = 3.3 m sec^{-1}. Filled symbols are the corresponding quantities in U_∞ = 6.6 m sec^{-1}. Yellow-filled symbols are the wind tunnel results of Salizzoni et al. (2009) at $x = 9h$ (□); $15h$ (□); $22.5h$ (□) and $30h$ (□) in freestream wind speed U_∞ = 6.6 m sec^{-1}. Also shown is the theoretical Gaussian-form tracer concentrations (dark solid line).

4.3 Parameterization of disperison coefficient

Theoretical background derives analytically the vertical dispersion coefficient σ_z as a function of the downwind distance measured after the pollutant source x, the TBL thickness δ and the skin-friction coefficient C_f i.e. $\sigma_z \propto x^{1/2}\times\delta^{1/2}\times C_f^{1/4}$. To verify the analytical hypothesis, the vertical dispersion coefficient σ_z is plotted against the newly proposed friction length scale L_f (= $x^{1/2}\times\delta^{1/2}\times C_f^{1/4}$; Figure 5). The variables in length dimension (σ_z, x and δ) are normalized by the size of roughness elements h. The vertical dispersion coefficient is almost directly proportional to the friction length scale $\sigma_z \propto L_f$. The tiny nonzero σ_z at $L_f = 0$ signifies the turbulent transport caused by background turbulence intensity. Scale similarity is clearly demonstrated even the data are collected in different freestream wind speeds. Linear regression shows that there is a close relation between σ_z and L_f (correlation coefficient $R^2 = 0.933$). This analytical formulation thus could be used in the parameterization of far-field pollutant plume dispersion over urban areas to handle complicated urban morphology in isothermal conditions.

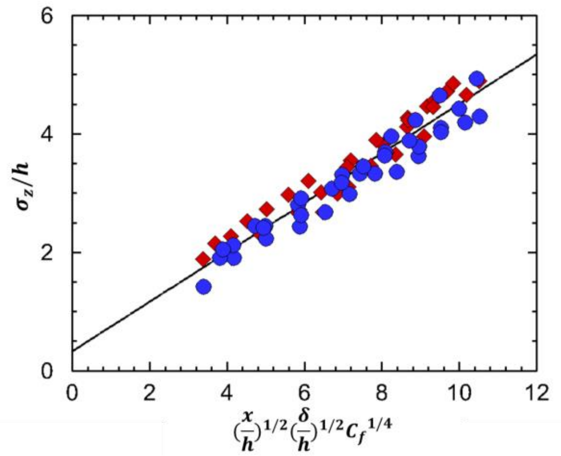

Figure 5. Vertical dispersion coefficient σ_z plotted against friction length scale L_f (= $x^{1/2}\times\delta^{1/2}\times C_f^{1/4}$) in freestream wind speed U_∞ = 3.3 m sec^{-1} (◆) and U_∞ = 6.6 m sec^{-1} (●). Also shown is the linear regression (solid line) for all the data points (correlation coefficient $r = 0.933$).

4 CONCLUSION

This paper reports the use of water vapor to study the pollutant plume dispersion over hypothetical urban areas in laboratory-scale wind tunnel experiments. The tracer concentrations over arrays of street canyons exhibit the conventional Gaussian distribution that are compared favorably with those in previous studies. It is hence suggested the feasibility of using water vapor as an affordable and harmless tracer in wind tunnel experiments. The analytical derivation and empirical solution collectively demonstrate that the skin-friction coefficient C_f, instead of the complicated urban morphology, for instance, floor plan, obstacle blockage and building orientation, could be applied to parameterize the vertical dispersion coefficient σ_z to formulate the basic functional form of transport processes over urban areas for quick, non-computational-fluid-dynamics (non-CFD) air quality impact assessment. Further studies will focus on the more complex surface roughness in attempt to validate the new solutions in a systematic manner.

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