COMPARISONS OF A LAGRANGIAN PARTICLE MODEL FOR URBAN DISPERSION WITH LABORATORY EXPERIMENTS

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1. INTRODUCTION

Dispersion in urban environment can be studied using a variety of approaches. Simple analytical models are often employed to provide a quick and simple estimation of the mean concentration field, using a constant wind speed and parameterized turbulent fluctuations.

Lagrangian particle dispersion models (LPDM) are more flexible than analytical formulations, require simple input information, and can be effective and accurate for a broad range of flow configurations. For very complex flows, such as over and within an urban canopy, several configurations of the model can be used, corresponding to different levels of complexity and requiring different input. For example, the experiments of dispersion in a plant canopy conducted by Raupach et al. (1986) were modeled using a LPDM by Flesch and Wilson (1992) and Cassiani et al. (2005), which assume Gaussian inhomogeneous turbulence in the vertical direction and includes the Reynolds stresses, whereas Mortarini et al. (2009) assume non-Gaussian inhomogeneous turbulence, and use a LPDM which includes the skewness of the vertical velocity and neglects the effect of the Reynolds stresses.

In this study, we conduct preliminary simulations of dispersion in urban environment using a LPDM with uncoupled equations for vertical and horizontal dispersion, assuming non-homogeneous Gaussian turbulence in the vertical direction, and neglecting the Reynolds stresses. The acceleration term is derived according to the well-mixed condition (Thomson, 1987). The model is compared with laboratory experiments conducted for a model urban canopy.

2. EXPERIMENTS

Laboratory measurements were undertaken in a water tunnel at the Environmental Fluids Lab at the University of Delaware. The water tunnel is 400 cm long, 40 cm deep, and 25 cm wide. The Plexiglas walls enable the use of flow visualization techniques, and a free surface allows measurements to be made with micro-conductivity probes. A uniform canopy of height $H = 3.2$ cm, building width $w_b = 3.2$ cm and streamwise building length $B = 3.2$ cm was utilized for the experiments. Thus the building aspect ratios is $H/w_b = 1$. The canopy consists of 22 rows of 3 square buildings, with lateral spacing $G = 3.5$ cm and longitudinal spacing $S = 5$ cm. Figure 1 shows a schematic of the water tunnel set up. The experiment simulates a continuous ground-level release of passive contaminant.

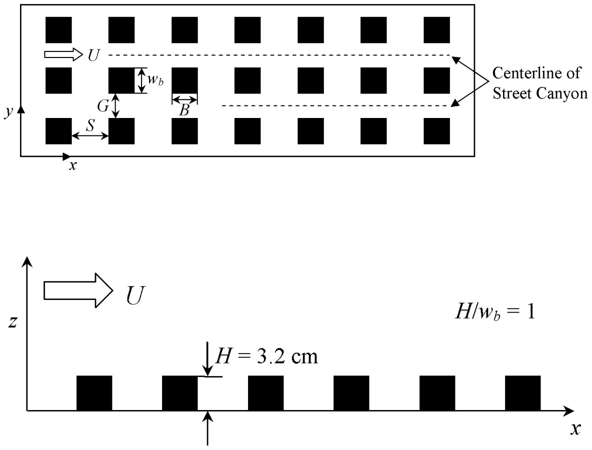

FIG. 1: Schematic of the water tunnel layout for the experiments of dispersion in idealized urban canopy conducted at the Environmental Fluids Lab at the University of Delaware.

3. DISPERSION MODEL

A one-particle stochastic Lagrangian model is written assuming inhomogeneous Gaussian turbulence in the vertical direction, and neglecting the Reynolds stresses (Thomson, 1987):

$$dx = U(z)dt \tag{1}$$

$$dz = w(z)dt \tag{2}$$

$$dw = -\frac{w}{T_L(z)}dt + \frac{1}{2}\left(1 + \frac{w^2}{\sigma_w^2}\right)\frac{\partial \sigma_w^2}{\partial z}dt + \sqrt{C_0\varepsilon}d\xi(t) \tag{3}$$

where x and z are the streamwise and vertical positions of a particle, respectively, U is the streamwise mean wind speed, w is the Lagrangian turbulent vertical velocity of a particle and σ_w is its standard deviation, T_L is the Lagrangian decorrelation time scale, $C_0 = 2$ is a constant, ε is the turbulent kinetic energy mean dissipation rate, and $d\xi$ are the random increments of a Wiener process with zero mean and variance dt. Dispersion in the crosswind direction is calculated analytically assuming horizontally homogeneous and Gaussian turbulence.

4. EXPERIMENTAL MEASUREMENTS

4.1 *Flow*

Vertical profiles of the mean velocity U were taken at five stations located at distances $x/B = 3$, 10, 22, 28 and 38 from the source. The evolution of U with distance from the source shows that the boundary layer is developing for the distances

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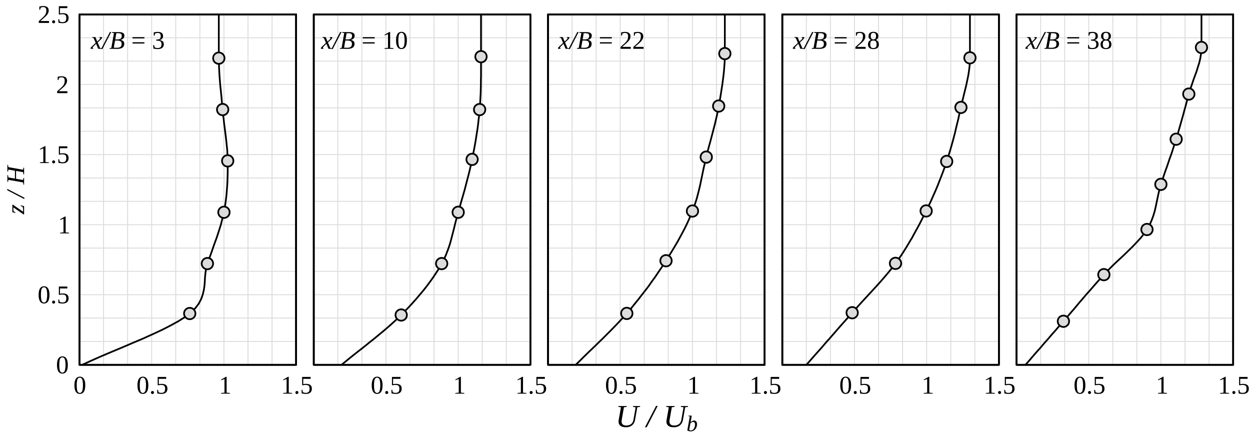

FIG. 2: Non-dimensional streamwise mean velocity U/U_b, where U_b is the mean wind velocity at building height. Circles - laboratory measurements; solid line - fit used as input to the model.

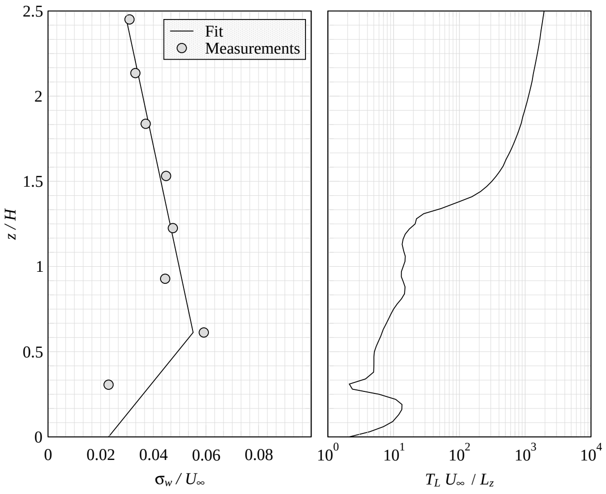

FIG. 3: Left panel - Measurements of σ_w/U_∞ (circles) along with the fit used as input to the model (solid line). Right panel - Lagrangian decorrelation time scale $T_L = 2\sigma_w^2/C_0\varepsilon$, normalized by L_z/U_∞.

considered. The non-dimensional streamwise mean velocity U/U_b, where $U_b \approx 5.2$ cm s^{-1} is the mean wind velocity at building height ($H = 3.2$ cm) is shown in figure 2. The circles are the laboratory measurements, the solid line is the fit used as input to the model. The model accounts for the streamwise non-homogeneity of the velocity field.

4.2 *Turbulence and time scale*

The left panel of figure 3 shows the vertical profile of σ_w along with the fit used as input to the model, normalized by the free-stream velocity $U_\infty = 9.4$ cm s^{-1}. The measurements were taken at the canyon centerline, at a distance $x/B = 38$ downwind of the source. Two linear functions are used to fit σ_w, with the ground-level value equal to the lowest measurement. The right panel of figure 3 shows the Lagrangian decorrelation time scale calculated as $T_L = 2\sigma_w^2/C_0\varepsilon$, where ε was estimated as $\varepsilon = -\overline{uw}\partial U/\partial z$. The time scale T_L is normalized by L_z/U_∞.

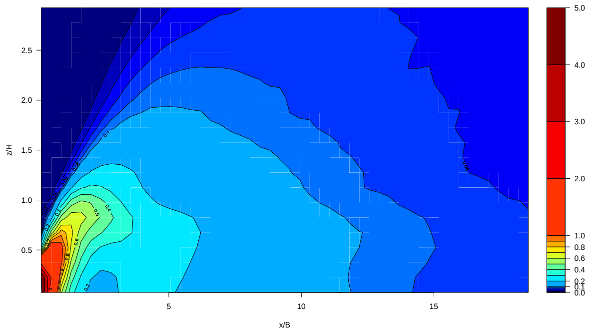

FIG. 4: Contour plot of normalized cross-wind integrated concentration (CWIC) C/C_0, where C_0 is the CWIC concentration at the source.

5. DATA ANALYSIS AND COMPARISON

5.1 *Concentration field*

Figure 4 shows the contour plot of the normalized cross-wind integrated concentration (CWIC) C/C_0 up to a distance from the source $x/B = 20$, where C_0 is the CWIC concentration at the source. The contour lines are not equally spaced, to emphasize the steep gradient of concentration near the source. The concentration field is rapidly entraining and concentrations decay with downstream distance. Vertically, concentrations are approximately uniform within the canopy, but decay above the canopy.

5.2 *Concentration vertical profiles*

Vertical profiles of the CWIC C/C_0 measured at $x/B = 2.3$, 4.8, 7.5, 13 and 17.8 from the source are reported in figure 5. The model reproduces well the profiles at all distances, although it displays an above-ground peak of concentration at

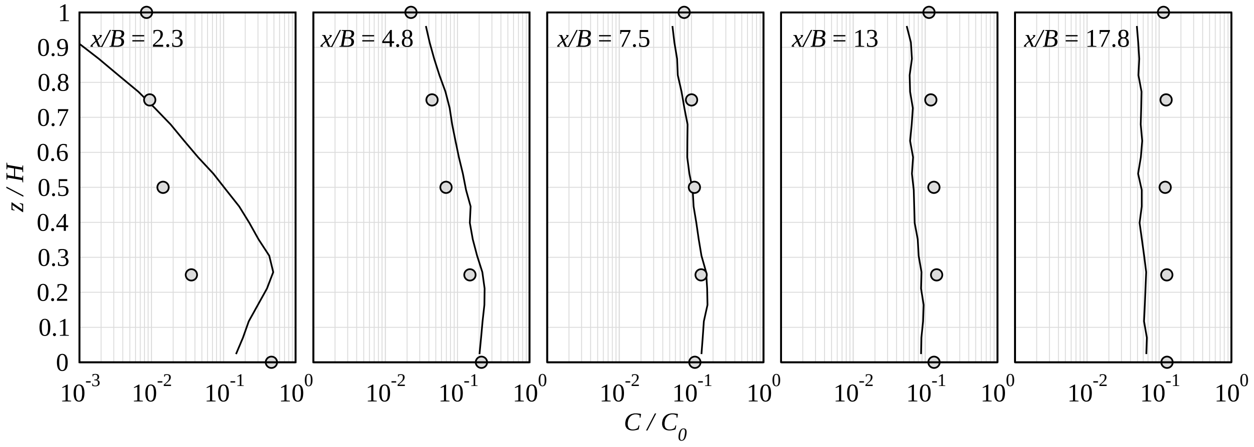

FIG. 5: Vertical profiles of normalized CWIC C/C_0 at the downwind distances reported in the figure.

$x/B = 2.3$. This is likely due to the unavailability of turbulence measurements near the ground, and the simple fitting for σ_w used in the model. Further testing with different near-ground parameterizations of σ_w will be carried on to study their impact on the near-source plume behavior.

6. DISCUSSION

The simple LPDM tested in this study for the non-homogeneous turbulent field of an urban environment is in good agreement with water tank experimental data. The current formulation only requires the measured wind speed profile, the vertical velocity turbulent component, and the mean dissipation rate of turbulent kinetic energy. The model takes into account the alongwind variation of flow and turbulence caused by the developing boundary layer.

7. ACKNOWLEDGEMENTS

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