J20.3 Field, laboratory and numerical study on flow and dispersion of $PM_{2.5}$ in Southern Californian cities

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1. Introduction

Vehicle emissions from arterials may present a risk to public health considering the type of surrounding built environments that can trap pollutants. Current line source models based on Gaussian diffusion equation consider factors such as particle size classes, source emission rate, atmospheric stability, vehicle wake effect as well as increased emission factors or 'idle' emission factors relevant to intersection situation and are commonly applied to evaluate the air quality impact of freeways or highways (Gokhale and Raokhande, 2008). They are limited to the applications in relatively simple terrain (Benson, 1979; Luhar and Patil, 1989). Hence, there is a need to study the flow and dispersion in built environments surrounding arterials, especially considering heavily traveled arterials in Southern Californian cities.

Previous studies concluded that the flow and dispersion characteristics at street scale include two principle aspects: a recirculating flow within the canopy and the exchange of air between the street canyon and the flow above (Britter and Hanna, 2003). Britter and Hanna (2003) discussed possible mechanism of the exchange process: turbulence may be generated by the shear layer atop of street canyon and advected into the canyon. The increased turbulence levels within the urban canopy may produce larger plume spread that reduces concentrations, resulting in enhanced canopy ventilation. Otherwise, the accompanying reduction in the advection velocity within the canopy tends to increase the residence time of pollutants within canopy, resulting in increasing concentrations (Britter and Hanna, 2003; Pascheke *et al.*, 2008).

Limited laboratory simulations or field experiments on the exchange process within urban canopy were reported. Pascheke (2008) conducted a wind-tunnel study to measure transfer velocity (w_T) and dispersion from an area source within a uniform height urban canopy and a non-uniform height urban canopy, with both plan area fraction (λ_P) and frontal area fraction (λ_F) equal to 25%. By introducing transfer velocity, which is relevant for momentum transfer into and out of the canopy, canopy ventilation may be analyzed quantitatively. It was found that the non-uniform height urban canopy had a larger transfer coefficient (w_T / U_{ref}) indicating an enhanced ventilation efficiency. However, although enhanced vertical momentum exchange due to height variability was observed, the dispersion from a limited area source within the canopy was not enhanced.

Another aspect of the dispersion within urban canopy is the residence time of pollutant. Laboratory simulations indicated that the dimensionless residence time is independent of Reynolds number (Re) in an investigated urban geometry case (Gomes et al., 2007) and also independent of atmospheric stability in an isolated obstacle case (Mavroidis et al., 1999). Their studies indicated that the residence time is more depending on the type of urban geometry.

A wider range of urban morphometry and more urban-like rough surface need to be incorporated in the study of flow and dispersion within urban canopy. In this study, we focus on different

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building arrangements and the proximity of buildings to the arterial. 5 typical building arrangements were selected from 5 Southern Californian Cities. Section 2 describes field measurements of roadside $PM_{2.5}$ concentrations, local micrometeorology and traffic flow count. One case was selected from five building arrangements to be presented here. Flow and dispersion within urban canopy were simulated both in a water channel facility (section 3) and using a numerical model (section 4).

2. Description of Field Experiment

The field measurements were conducted from June 19 2008 to August 1 2008. 5 typical building arrangements are 1) low density settlement, 2) low-rise settlement, 3) mid-rise settlement, 4) high-rise settlement, and 5) strip mall with surface parking, selected from cities of Anaheim, Pasadena, Long Beach, Los Angeles and Huntington Beach, respectively. Each study area was equipped with a sonic anemometer (CSAT3, Campbell Sci.), measuring mean wind speed, turbulence and virtual air temperature, six DustTraks (TSI Inc.), measuring $PM_{2.5}$ concentration, and three digital cameras (JVC), recording traffic flow. At each area, data were collected for three days, covering the morning and evening commute and lighter mid-day traffic.

The detailed traffic information, including traffic volumes, fleet composition (ratio of light/heavy duty vehicles) was collected. The emitted mass flow rate in the field is calculated as:

$$\dot{m}_s = ([\text{hourly traffic} \times EF_{2.5}]_{light\ \text{duty}} + [\text{hourly traffic} \times EF_{2.5}]_{heavy\ \text{duty}}) \times L_{street} \qquad 2.1$$

where $EF_{2.5}$ is emission factor of $PM_{2.5}$, [g/vehicle/mile] and L_{street} is the street length.

The sampling inlets of all 6 DustTraks were at the level of 2 m above the ground. A quality assurance procedure was performed during each measurement period. Prior to measurements, zero calibration and synchronization of DustTraks was performed. In addition, in order to minimize the error made by difference of each DustTrak readings, all six DustTraks were sampling for 10 minutes at the same time and place to get the correct factor which will be applied for accurate $PM_{2.5}$ concentration calibration. The field measurements data of mid-rise settlement case will be presented in this communication.

3. Description of laboratory simulation

3.1 Scaling method

Dimensionless length scale factor Φ_L is defined as

$$\Phi_L = \frac{[L]_{field}}{[L]_{lab}} \qquad 3.1$$

where L is length scale, [m].

Considering kinematic similarity, or equality of time scales $t^* = \frac{tU}{L}$, the dimensionless time scale factor Φ_T is defined as

$$\Phi_T = \frac{[t]_{field}}{[t]_{lab}} = \frac{\left[\frac{L}{U_e}\right]_{field}}{\left[\frac{L}{U_e}\right]_{lab}} = \frac{[L]_{field}}{[L]_{lab}} \frac{[U_e]_{lab}}{[U_e]_{field}} = \frac{\Phi_L}{\Phi_U} \qquad 3.2$$

where U_e is velocity of ambient flow, [m/s]; Φ_U is velocity scale factor.

The ambient concentration, C_e, of well mixed passive contaminant could be written as

$$C_e = \frac{\dot{m}_s \cdot t}{Volume} \qquad 3.3$$

where $\dot{m}_s$ is mass flow rate of source, [mg/s]; t is the travel time of passive contaminant, [s].

Now the dimensionless concentration scale factor is introduced as

$$\Phi_C = \frac{[C_e]_{field}}{[C_e]_{lab}} = \frac{\left[\frac{\dot{m}_s \cdot t}{Volume}\right]_{field}}{\left[\frac{\dot{m}_s \cdot t}{Volume}\right]_{lab}} = \frac{\left[\frac{\dot{m}_s \cdot t}{L^3}\right]_{field}}{\left[\frac{\dot{m}_s \cdot t}{L^3}\right]_{lab}}$$

$$= \frac{[\dot{m}_s]_{field}}{[\dot{m}_s]_{lab}} \frac{\Phi_T}{\Phi_L^3} = \frac{[\dot{m}_s]_{field}}{[\dot{V}_s \cdot C_s]_{lab}} \frac{\Phi_T}{\Phi_L^3} \qquad 3.4$$

where $\dot{V}_s$ is volumetric flow rate of source, [m^3/s]; C_s is source concentration, [mg/m^3]. Φ_C is used as a multiplying factor by which the ambient concentration of passive contaminant observed in the laboratory is scaled to that in the field.

3.2 Water channel facility

The experiments were conducted in a custom-designed circulating water channel with a test section that is 1.5 m long, 1 m wide and 0.5 m deep in the Laboratory for Environmental Flow Modeling (LEFM) at the University of California, Riverside (UCR). Flow conditioning was achieved with the profiled honeycombs and the custom-built perforated screens. The perforated screens were used to generate desired inflow velocity profiles as a part of the flow conditioning. The channel flow was steady and becomes fully developed before reaching the test section. The free stream velocity of the flow through the test section, U_e, was maintained at 0.09 m/s in this study.

3.3 Building Geometry

The highly polished acrylic models which can minimize effects of refraction and attenuation of the laser sheet utilized for the Planer Laser-Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV) measurements were used to build mid-rise settlement (Fig.1.) of the Long Beach downtown. Urban morphology was obtained from and the Los Alamos National Laboratory urban database. A 406 m × 512 m area including two major arterials perpendicular to the approaching wind direction were scaled down to a 50 cm × 64 cm (1: 800 scale). The average height of model obstacles is approximately 0.03 m. Both arterials are 0.6 m long.

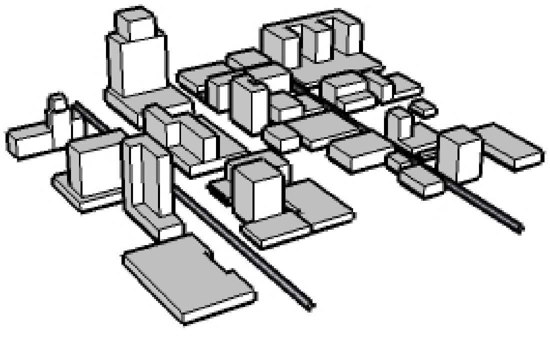

Fig.1. Mid-rise settlement in Long Beach city reproduced in the water channel

3.4 Line source

The soaker tubing was fixed on the flat board to create a line source for the dye release. No buoyancy effect was considered and constant traffic flow was simulated. Two lateral streets which were perpendicular to the free stream were investigated in separated experiments. St.1 represented East Ocean Blvd., which is a 6 lane-two way arterial and St.2 represented East Broadway, which is a 3 lane-one way arterial. Rhodamine 610 Chloride, a fluorescent dye with a wavelength of 555 nm, was used as the plume. A solution of dye and water with the concentration of Cs=3 mg/L was pumped by digital gear pump (Cole-Parmer Instrument Company) with the flow rate of 100 ml/min.

3.5 PIV/PLIF setup

Two-dimensional velocity field was measured by PIV. Fluorescent emission of the laser illuminated dye measured by PLIF system provided concentration field. A 532 nm wavelength laser beam was generated with a frequency of 1 Hz by a double-pulsed Nd: YAG laser (Big Sky Laser Technologies, Inc, model CFR400), which was expanded into a laser sheet by sheet-forming optics, which included two cylindrical lenses (-15 mm focal length). When fluorescent dye is illuminated by the laser sheet, it absorb incident light at one wavelength and re-emit light at a different wavelength. The re-emitted light intensity which is recorded by a high resolution (1600 pixel×1192 pixel) POWERVIEW 2M CCD camera (TSI Inc., model 630157) is proportional to the concentration of the fluorescent dye. This proportionality is expressed by the Beer-Lambert law and can be shown to be linear under certain conditions (Vincont *et al.*, 2000). In this study, we investigated the concentrations at two different levels of laser plane in separate experiments: 1) at one forth of the highest obstacle (1/4H), which is 3.1 cm to the ground surface and 2) at the roof level of the highest obstacle (1H), which is 12.5 cm to the ground surface.

A filter with a 10 nm bandwidth centered on the 555 nm wavelength of the dye was used together with the CCD camera in order to remove the 532 nm wavelength of the YAG lasers and the reflected light. A LASERPULSE Synchronizer (TSI Inc.) was used to trigger the laser pulse and the CCD camera with correct sequences and timing through a 2.66 GHz dual-processor workstation (Intel Xeon^{TM}). An aperture opening of 1.4 was chosen. Before each experimental sequence, 10 images of background light sheet intensity were captured. The average image was used for background subtraction from the images of the fluorescent dye in post-processing. An 8 pixel × 8 pixel grid size was chosen, which is corresponding to a grid size of 1.20 mm ×1.20 mm for 1/4H level and 1.12 mm ×1.12 mm for 1H level. 60 images were captured during each experimental sequence, and were averaged over one minute.

4. Numerical Modeling

Real scale mid-rise settlement Long Beach downtown was set in the Quick Urban and Industrial Complex (QUIC) model, which is developed by the Los Alamos National Laboratory (Pardyjak and Brown, 2002; Bagal, *et al.,* 2003). Model constructs the flow field around a cluster of buildings, and uses this information in a particle dispersion model to estimate the concentration filed associated with a release among the buildings. In this study, domain resolution is 6 m in horizontal and 2 m in vertical direction. The emission rate is determined from field data on traffic flow based on Eq.2.1.

5. Results and Discussion

5.1 Explanation of filed observation

Fig.2. shows relationship between $PM_{2.5}$ concentrations and meteorological variables at site LB4, which is one of 6 sites in the city of Long Beach on July 2, 2008. The dominant wind direction measured by sonic anemometer on that day is about 270° (westerly), almost perpendicular to the arterial. Under this wind condition, site LB4 is located at the windward side of building and arterial is just at the upwind direction of DustTrak sampling. The plot of wind direction-$PM_{2.5}$ concentration relationship shows that all concentrations more than 70 μg/m^3 appear under the condition of wind direction around 270°. The plot of w_{rms} vs. $PM_{2.5}$ concentration shows the concentration increase with increase of w_{rms} in the range from 0 to 0.4 m/s. After that, concentrations keep at low magnitudes, less than 70 μg/m^3. The plots of turbulent flux-$PM_{2.5}$ concentration relationship and sensible heat flux-$PM_{2.5}$ concentration relationship show high concentration when turbulent flux and sensible heat flux are small. When turbulent flux and sensible heat flux becomes large, concentrations stays at low level. These relationships were not found at other sites located in streets parallel to the dominant wind direction in which concentration stays constant with change in turbulence and fluxes.

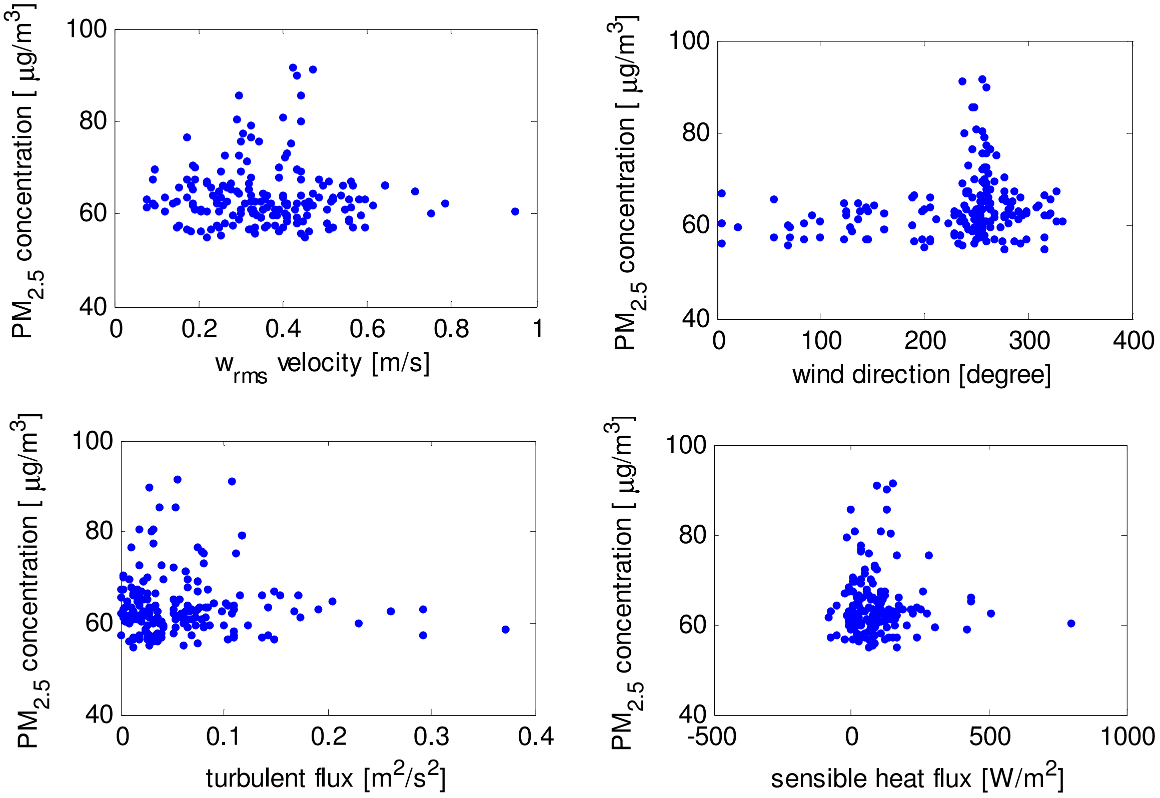

Fig.2. Relationship between PM2.5 concentrations and meteorological variables

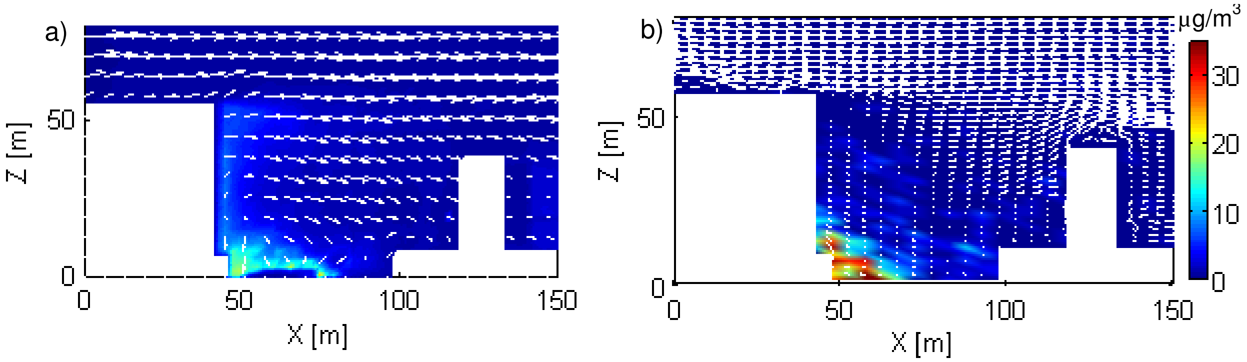

Fig.3. Velocity vectors and concentration distribution of PM2.5 in vertical plane (The colors show concentrations distribution and white arrows show 2-dimension velocity vectors) a) Water channel simulation, b) QUIC modeling

5.2 Comparison of laboratory and numerical modeling

Fig.3. shows water channel simulation and QUIC modeling of Long Beach case with PIV/PLIF measurements in vertical plane. In both, model and laboratory, the pollution is trapped in the leeward side of building, making concentrations much higher than concentrations at windward side. Since the huge difference of building geometry between leeward side building and windward side building, the recirculating flow which is usually seen within urban canopy with uniform building height and constant λ_P and λ_F is not formed here. The magnitude of mean velocity within urban canopy is higher in water channel simulation than that in QUIC modeling. The downdraft flows within urban canopy shown in Fig.3a is not present in Fig.3b. Also we can see higher mixing in laboratory (Fig.3a) and the plume is advected all the way up to the building's roof level. However, in Fig.3b, the vertical dispersion is less intense and pollutants are in higher concentration at the surface close to the leeward side.

Comparison of water channel simulation and QUIC modeling is also shown in Fig.4. by the vertical profiles of concentration. For both, lee and windward side, the concentration profile from QUIC reveals higher concentrations close to the ground level with much lower concentrations above. One explanation for these discrepancies can be the lower mean velocity produced in QUIC which results in less dispersion. From Fig.5., we can see that modeled and measured *U* velocity profiles in better agreement at windward side than tat leeward side. At leeward side, *U* velocity profile from QUIC modeling has a sudden jump at the roof level, with a negative velocity below it, while it is mostly positive from the water channel simulation. At windward side, *W* velocity shows different trends between water channel simulation and QUIC modeling. Below roof level, *W* velocity is negative from the water channel simulation, presenting the downdraft flow, while QUIC produces slight updraft.

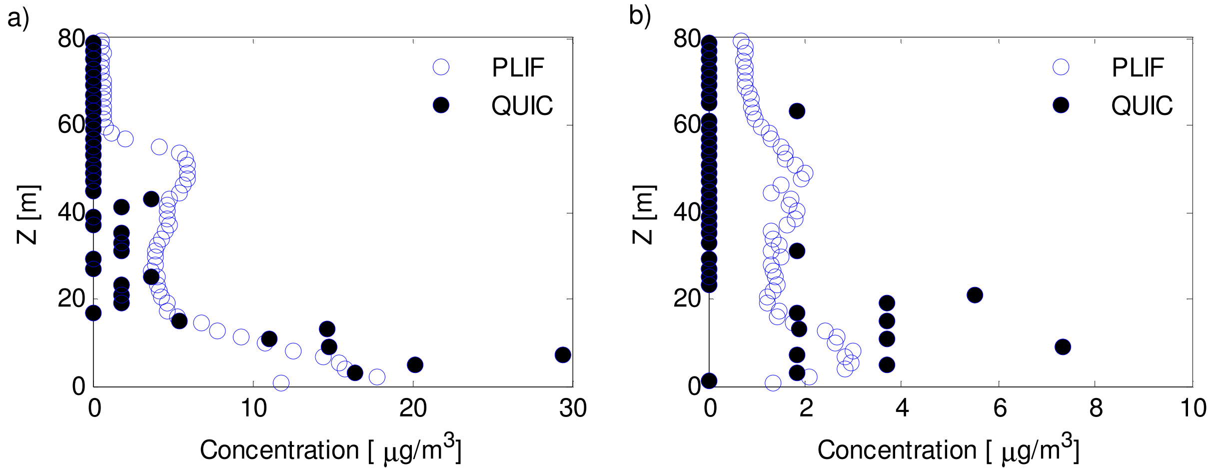

Fig.4. Vertical profile of concentration a) leeward side, x=50 m, b) windward side, x=90 m

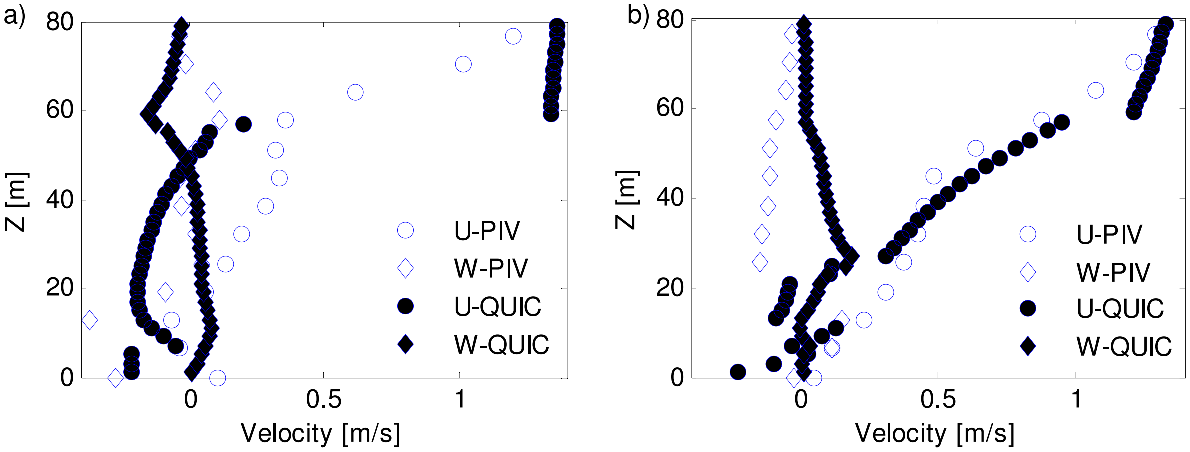

Fig.5. Vertical profile of U and W velocity a) leeward side, x=50 m, b) windward side, x=90 m

6. Summary

This study is a part of the University of California Transportation Center sponsored project ‘Near source modeling of transportation emission in built environments surrounding major arterials’. The results presented here are based on analysis of data from mid-rise settlement case.

Field experiments help us understand the influence of local meteorological variables on pollutants concentration and the role of receptor position within urban canopy. When monitor site is located at the windward side of building within urban canopy, wind direction has a significant influence on pollutions concentrations. Besides wind direction, turbulent flux, sensible heat flux and turbulent velocity, w_{rms}, can also affect concentrations, especially on producing extremely high concentrations. Detailed flow and dispersion characteristics are observed in a model urban area using a water channel facility equipped with PIV/PLIF system. Laboratory results of velocity and concentration are compared with numerical results produced by QUIC model. QUIC model performed well in complex urban setting with a slight over prediction of the near ground concentration.

Reference

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