FIELD, LABORATORY AND NUMERICAL STUDY OF TRANSPORTATION EMISSIONS IN BUILT ENVIRONMENTS SURROUNDING MAJOR ARTERIALS IN SOUTHERN CALIFORNIAN CITIES

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ABSTRACT

Under the sponsorship of the University of California Transport Center, field measurements accompanied with laboratory experiments and numerical modeling were conducted for five southern Californian cities: Los Angeles, Long Beach, Huntington Beach, Anaheim and Pasadena. The goal of the study was to address transport of vehicle induced particulates in major urban arterials. Sites were selected to cover four typical urban settings: 1. Low density settlement; 2. Low-rise settlement; 3. Mid-rise settlement; 4. High-rise settlement. In addition, a relatively open area was also selected to serve as a base site. Mean wind, turbulence and virtual temperature were measured by a sonic anemometer at a sampling rate of 10Hz, particulate concentration ($PM_{2.5}$) was measured with six DustTraks with a sampling rate of 1 Hz, and traffic counts are made by digital cameras. Three days measurements were performed in each area and three rush-hour periods for each day were covered.

The rapid decrease of the $PM_{2.5}$ concentrations in the afternoon was observed in the field measurements. The lower concentrations in the afternoon are the consequence of stronger versical mixing, convective motions caused by high sensible heat flux, which resulted in efficient mixing and growth of the urban boundary layer. Concentrations were compared at leeward side of building and windward side of the building. The influence of building arrangement and meteorological conditions on concentrations were revealed.

To conduct experiments under controlled conditions model cities were built for testing in the water channel. Transparent acrylic blocks were used as model buildings. The Particle Image Velocimetry (PIV) was used for flow measurements and the Planar Laser Induced Fluorescence (PLIF) was used for concentration measurements. The Quick Urban and Industrial Complex (QUIC) model was used to simulate flow and dispersion in all cites. The QUIC model performed well in complex urban setting with a slight over prediction of the near ground concentration

INTRODUCTION

In modern cities, vehicular related $PM_{2.5}$ emission is one of main concernes for the health impact assessment, since these emissions occur in close proximity to pedestrians and residences. Current line source models based on Gaussian diffusion equation are limited to the applications to relatively simple environments. The prediction of dispersion of vehicular pollutants in built environments surrounding major arterials requires detailed information of the urban flow and turbulence.

In the past, there were extensive studies focused on flow and turbulent characteristics within street canyon or regular obstacle arrays. The relationship between roof wind direction and canyon wind direction in the street canyons was observed (Nakamura and Oke, 1988). Vortex development and circulation in the street canyon was reported (Eliasson et al., 2006; Simoëns et al., 2007). Numerical models, such as k-ε model (Baik and Kim, 1999) and large-eddy simulation (Liu and Barth, 2002), also achieved the reasonable mean flow and turbulence characteristics within street canyon. Britter and Hanna (2003) reviewed the well-understood flow characteristics of archetypal street canyons: the typical recirculating flow consisting of a downdraft flow on the windward side and updraft flow on the leeward side that causes a larger concentration at the leeward side than at the windward side except for a step-down configuration.

For the flow through a group of obstacle arrays, Kim and Baik (2004) explained the ideal flow patterns through 4 by 4 regular arrays of cubic obstacles with L/W= H/W=1 by running k-ε model. Most studies focus on the measurements and modeling of velocity profile within urban canopy and extension to upper layer of roughness sublayer (Rotach, 1995; Macdonald, 2000; Hanna et al., 2002; Kastner-Klein et al., 2004) and the modification of plume structure as the plume entered regular arrays (Macdonald et al., 1998), for example, in the case of ground level point source releasing from upstream of the arrays with wide obstacles, significant initial increases in the vertical and lateral plume spreads was observed in water channel and wind tunnel experiments (Yee et al., 2006).

In order to understand more complex flow and dispersion characteristics in real situation, several field campaigns were conducted in different cities: URBAN 2000 in Salt Lake City (Allwine et al., 2002), tracer experiment in Los Angeles (Rappolt et al., 2001.), JU2003 in Oklahoma (Klein and Clark, 2007; Nelson et al., 2007), MSG05 in New York City (Hanna et al., 2006), BUBBLE in Basel, Switzerland (Rotach et al., 2004), and DAPPLE in London, UK (Arnold et al., 2004; Patra et al., 2008).

Although the studies on flow and dispersion in urban area have been conducted for decades, near source studies on dispersion of vehicle exhaust pollutants in built environments are still limited. 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. Thus, in this study, we focus on different building arrangements and the proximity of buildings to the arterial. 5 typical building arrangements were selected from 5 Southern Californian Cities. Field experiments section 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 (Laboratory simulation section) and using a numerical model (Numerical modeling section).

FIELD EXPERIMENTS

The field measurements were conducted from June 19 2008 to August 1 2008. Sites were selected to cover five typical urban settings: 1. Low density settlement: One or two story buildings; density range 4-12 dwelling units/acre (du/acre); 2. Low-rise settlement: Three to four story buildings; found in parts of the more densely settled portions of greater Los Angeles; 3. Mid-rise settlement: Building heights of typically ten to twenty stories. The most dense settlement and the most urbanized settings in Southern California often associated with office parks or recent high-rise residential or mixed use developments. Density levels can exceed 60 du/acre; 4. High-rise settlement: Building heights of more than twenty stories found in most downtowns; 5. Relatively open strip mall with surface parking separating arterial and buildings. Five building arrangements were selected from cities of Anaheim, Pasadena, Long Beach, Los Angeles and Huntington Beach, respectively. Mean wind, turbulence and virtual temperature were measured by a sonic anemometer (CSAT3, Campbell Sci.) at a sampling rate of 10Hz, particulate concentration ($PM_{2.5}$) was measured with six DustTracks (TSI Inc.) with a sampling rate of 1 Hz, and traffic counts are made by digital cameras. Three days measurements were performed in each area and three rush-hour periods for each day were covered. Rush hour periods were: morning 7am-9am, lunch/midday 11am-1pm, and afternoon 4pm-6pm. Measuring locations in all cities are enumerated as S1 through S6.

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:

$$\dot{m}_s = ([hourly\ traffic \times EF_{2.5}]_{light\ duty} + [hourly\ traffic \times EF_{2.5}]_{heavy\ duty}) \times L_{street} \quad (1)$$

where $EF_{2.5}$ is emission factor of PM2.5, [g/vehicle/mile] and L_{street} is the street length.

The sampling inlets of all 6 DustTraks were at 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.

LABORATORY SIMULATION

Scaling methods

The scaling methods applied in laboratory simulation are based on three dimensionless scale factor. Length scale factor Φ_L is defined as

$$\Phi_L = \frac{[L]_{field}}{[L]_{lab}} \quad (2)$$

where *L* is length scale, [m].

Time scale factor Φ_T is defined as

$$\Phi_T = \frac{[t]_{field}}{[t]_{lab}} = \frac{\left[\frac{L}{U_e}\right]_{field}}{\left[\frac{L}{U_e}\right]_{lab}} = \frac{[L]_{field}}{[L]_{lab}}\frac{[U_e]_{lab}}{[U_e]_{field}} = \frac{\Phi_L}{\Phi_U} \quad (3)$$

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

The concentration scale factor is introduced as

$$\Phi_C = \frac{[C_e]_{field}}{[C_e]_{lab}} = \frac{\left[\frac{\dot{m}_s t}{L^3}\right]_{field}}{\left[\frac{\dot{m}_s t}{L^3}\right]_{lab}} = \frac{[\dot{m}_s]_{field}}{[\dot{m}_s]_{lab}}\frac{\Phi_T}{\Phi_L^3} \quad (4)$$

where C_e is ambient concentration, $\dot{m}_s$ is mass flow rate of source, [mg/s]; t is the travel time of passive contaminant, [s]. 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. This scaling method is consistent with the dimensionless similarity used by other researchers (Meroney et al., 1996; Vincont et al., 2000; Hanna et al., 2007).

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 axial pump (Carry Manufacturing, Inc., 20HP, 8" in diameter) drives the flow from the settling tanks. The pump can produce a maximum mean velocity of 0.5 m/s in the test section. A variable frequency controller (AC Tech 20HP) allows pump control with a resolution of 1/100 Hz, which corresponds to the mean velocity change of 0.1 mm/s. 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 0.089 m/s and neutral background stability condition was simulated in this study.

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 of the Long Beach downtown. Urban morphology was obtained from 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 length of both line sources are 0.6 m. The average height ($\overline{H}$) of model obstacles is approximately 0.04 m. As it is argued by Yee (2006), a more relevant characteristic length scale (H^*) instead of $\overline{H}$ for the flow interaction with the obstacles could be used for Reynolds number estimation. Here $H^* \equiv A_f^{1/2}$, that is the square root of the projected frontal area of the obstacle. Yee suggested that the lower limit of 4000 for Reynolds number independence of shear flow around surface mounted cubes is good criteria for water channel study. That is, for physical modeling of flows around sharp-edged obstacles, Reynolds number $\mathrm{Re}_{H^*} = U_e H^* / \nu > 4000$ is acceptable. In our study, H^* for the obstacles of mid-rise settlement is calculated as 0.046 m and $\mathrm{Re}_{H^*} = 4100$.

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 separate experiments. One street represented East Ocean Blvd., which is a 6 lane two-way arterial and the other street represented East Broadway, which is a 3 lane one-way arterial. Rhodamine 610 Chloride was used as the plume. It is a fluorescent dye with a peak absorption wavelength of 555 nm and broad absorption spectrum permitting excitation at 532 nm. A water solution of dye with the concentration of C_s=3 mg/L was pumped by digital gear pump (Cole-Parmer Instrument Company) with the flow rate of 100 ml/min.

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) and a spherical lens (200 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 centered on the 580 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$^{\mathrm{TM}}$). 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.

NUMERICAL MODELING

Real scale mid-rise settlement Long Beach downtown was set in a semi-empirical fast response model-Quick Urban and Industrial Complex (QUIC) model, which is developed by the Los Alamos National Laboratory (Pardyjak and Brown, 2002). Model constructs the flow field (QUIC-URB) around a cluster of buildings, and uses this information in a particle dispersion model to estimate the concentration filed (QUIC-PLUME) associated with a release among the buildings. The calculation of wind field in QUIC model is based on Röckle diagnostic wind modelling strategy and continuous improvements which were made to achieve more realistic flow field were evaluated (Singh et al., 2008). In this study, domain resolution is 6 m in horizontal and 2 m in vertical direction. The emission rate is determined from field data

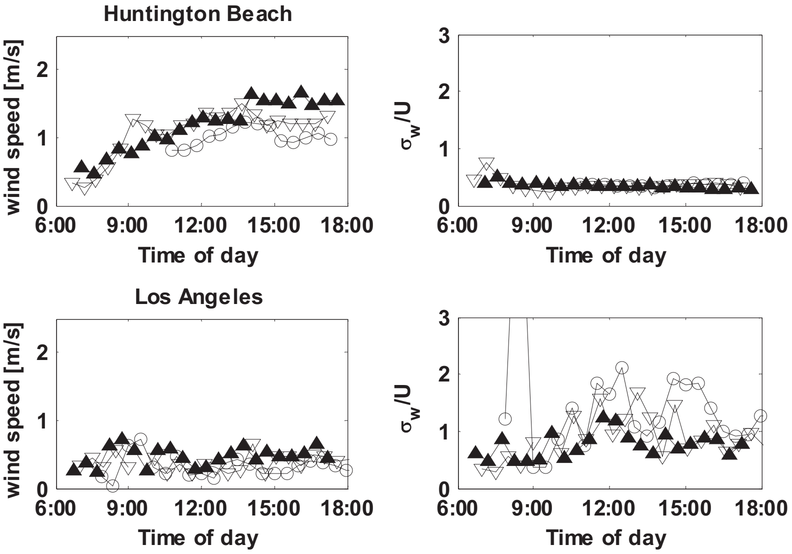

Fig.1 Mean wind speed and vertical velocity fluctuations (circle, triangle and solid triangle indicates three different days)

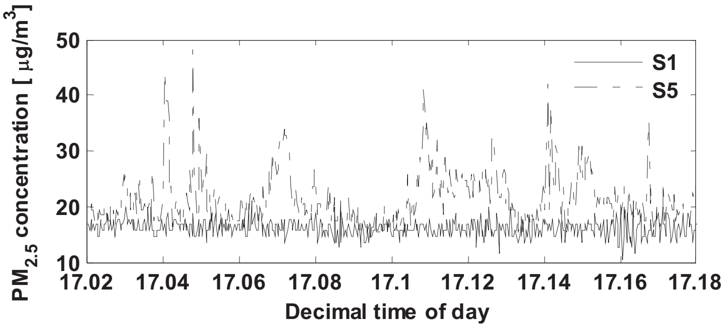

Fig.2 Time series of PM2.5 concentration at site1 (windward side) and site 5 (leeward side) in Los Angeles

on traffic flow based on equation (1).

RESULTS AND DISCUSSION

Field experiments explanation

The meteorological data collected by sonic anemometers were averaged each 30 minutes. The locations of sonic anemometers for all 5 cities are chosen to be far away from arterials to avoid being affected by traffic induced turbulence. Three of them (Huntington Beach, Anaheim and Los Angeles) are on the street level and the other two (Long Beach and Pasadena) are on the roof level.

Figure 1 shows averaged mean wind speed, U , and turbulent intensities, σ_w/U . Comparing sonic anemometers data from surface measurements, Los Angeles data is significantly different from Huntington Beach data. The maximum mean wind speed in Los Angeles is less than 1 m/s, while in Huntington Beach, the maximum mean wind speeds are close to or exceed 2 m/s. However, vertical velocity fluctuation in Los Angeles is comparable with Huntington Beach. Therefore, turbulent intensity, σ_w/U, in Los Angeles is much higher than Huntington Beach, which has turbulent intensities varying around 0.5. This is reasonable since the building arrangement at Los Angeles is classified as high-rise settlement, thus, although mean wind speed is low, high turbulence is still attained.

Figure 2 shows time series of $PM_{2.5}$ concentration with 1 Hz sampling frequency in Los Angeles. Site S1 is located at the windward side and site S5 is located at leeward side. $PM_{2.5}$ concentration peaks always appeared at leeward side while concentration at windward side stayed at low level. At this location, buildings height at windward side and leeward side are almost the same.

Figure 3 shows wind direction and meteorological variables at site 4 in the city of Long Beach on July 2, 2008. The dominant wind direction measured by sonic anemometer on the roof of the building on that day is around 270° (westerly), almost perpendicular to the arterial. Under this wind condition, site4 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 (Figure 4) shows that all concentrations more than 70 μg/m3 appear under the condition of wind direction around 270°. At this

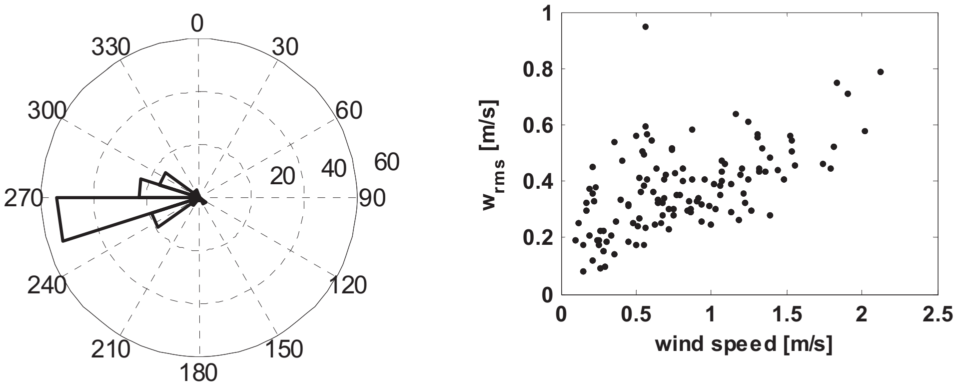

Fig.3 Wind rose and relation between wind speed and w_{rms} on 07/02/2008 at Long Beach

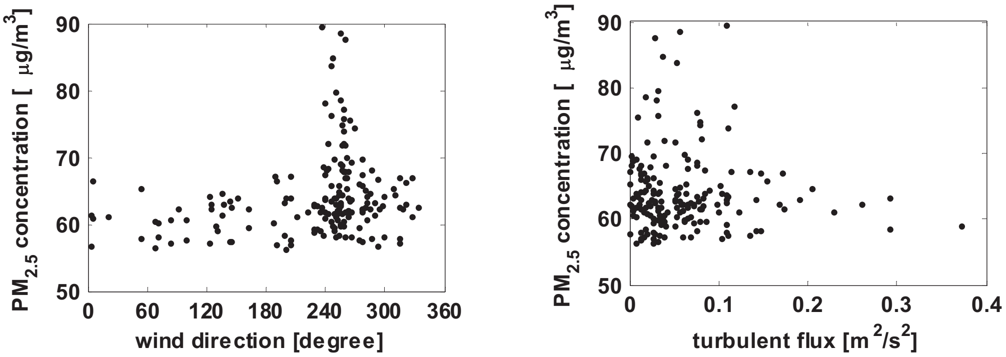

Fig.4 Relation between PM2.5 concentrations and meteorological variables

location, buildings height at windward side is much lower than buildings height at leeward side. The plot of turbulent flux-PM2.5 concentration relationship shows that high concentration appears when turbulent fluxes are small. When turbulent 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.

Comparison of laboratory and numerical modeling

Water channel simulation and QUIC modeling of Long Beach case with PIV/PLIF measurements in vertical plane were compared. In both, model and laboratory, the pollution is trapped in the leeward side of building, making concentrations much higher than concentrations at windward side. Because of the big 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 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 observed in laboratory simulations is not present in QUIC modeling. Also we can see higher mixing in laboratory and the plume is advected all the way up to the building's roof level. However, in QUIC modeling, the vertical dispersion is less intense and pollutants are in higher concentration at the surface close to the leeward side.

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. In addition to 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.

Contents Main

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.

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