833 INVESTIGATING DISPERSION OF BUOYANT EMISSIONS FROM LOW LEVEL SOURCES IN URBAN AREAS: WATER CHANNEL MODELING

Sam Pournazeri*, Qiguo Jing, Marko Princevac, and Akula Venkatram
University of California, Riverside, CA 92521

1. Introduction

After the western U.S energy crisis in 2000 and 2001, schools, businesses and hospitals moved toward the independency from centralized power generating stations (CGs) by installing on site small scale power generators, known as distributed power generators (DGs). These small power plants are highly efficient as they have heat recovery from their waste exhaust and coolant, providing both electricity and heating/cooling to the neighborhood. Although DGs were beneficial for providing power independency, they might have significant effect on air quality in urban areas especially in neighborhood (up to 1 or 2 km) and street scale (less than ~100 to 200 m) (Britter and Hanna, 2003). Unlike CG plants, exhausts from DG sources are released from relatively low stacks with heights of approximately 10 meters and can be captured in the wake produced by surrounding buildings.

Since January 2001 through May 2002, the power capacity from DGs has been increased by 400MW (Heath et al. 2005). This rapid increase in the distributed power generation raised the concerns on the air quality impacts of DGs in urban areas. Hence many recent studies examined the air quality impact of these small power generators in urban and regional scales.

Hadley and Vandyke (2003) have shown that replacing CGs with DGs can reduce the total emissions and this effect can become greater when DGs are used as both heat and electricity generators (formerly known as co-generation). In another study, Allison and Lents (2002) analyzed the tradeoff between the increase in emissions associated with urban DGs emissions and the decrease in emissions by replacing heating plants with waste heat generated from DGs. They found that emissions associated with realistic DG scenarios with the lowest emission and high waste heat recovery is nearly comparable to that in CGs. Their relatively simple analysis focused on total emissions and did not investigate the impact of these emissions on the air quality. Following the study by Greene and Hammerschlag (2000), DGs have been reported to have larger environmental impact than CGs as 1) they are less efficient in turning fuel into heat comparing to large power plants; 2) CGs have strict regulations and are constantly monitored for efficiency and emission control; and 3) DG emissions are in close proximity to its recipients, people.

Heath et al. (2006) have also examined the air quality impact of DG units relative to CG plants. They found that the air quality impact of DG units, quantified in terms of intake factors (dimensionless number representing the ratio between the amount of pollutants inhaled by population to the amount of pollutants released), could be as much as 20 times that of CG plants because a) the ground level concentrations from the elevated emissions of a CG plant are much smaller than those associated with the near surface emissions from DG units (An analysis of air quality impact of CG plants have shown that reducing the CG stack height to zero can increase their intake fraction up to an order of magnitude) and b) CG plants are likely to be located far from urban centers, while DG units are located in urban areas in close proximity to energy consumers.

Several studies have also addressed the impact of DGs on ambient ground level concentrations under realistic emission scenarios (Jing et al., 2009; Jing et al., 2010; Venkatram et al. 2004). Data from a tracer field study conducted in Palm Springs in the summer of 2008 from a gas fired 650 kilowatt (kW) DG unit (Jing et al., 2010) indicated that currently used dispersion model AMS/EPA Regulatory Model (AERMOD, Cimorelli et al. 2005), recommended by the United States Environmental Protection Agency (USEPA), does not provide an adequate description of the observed concentration field during nighttime. One of the reasons for the poor performance of these models is that they are mainly developed for the dispersion of pollutants released from large power plants in open areas. Since the process of dispersion of DG emitted pollutants is mostly affected by the complex geometry of the buildings in urban area, dispersion models needs to be modified to account for these effects.

Therefore, there is a need for comprehensive laboratory and field studies to understand the dispersion of pollutants released from these low level sources in urban areas that significantly affect the urban air quality. Since field studies are specific to the site geometry and meteorological conditions, main insight is expected to arrive from laboratory modeling in water channels and wind tunnels.

Following this need a comprehensive laboratory study has been conducted in a custom-designed water channel (Fig. 1) which is described next.

* *Corresponding author address:* Sam Pournazeri, Univ. of California, Riverside, Dept. of Mechanical Engineering, Riverside, CA92521;
e-mail: spournazeri@engr.ucr.edu

2. Laboratory Setup

2.1 Water Channel

The laboratory experiments were done in a water channel (Fig. 1) with 1.5 m long, 1 m wide and 0.5m deep test section in the Laboratory for Environmental Flow Modeling (LEFM) at the University of California, Riverside. The axial pump (Carry Manufacture, Inc.) make a flow from the settling tank and produces a maximum velocity of 0.5 m/s. Flow can be controlled through a variable frequency controller with a resolution of 1/100Hz. Two flow conditioner in the shape of honeycombs are placed at the entrance of the water channel in order to minimize the pump effect and make the desired inflow velocity profile. The channel flow can be considered as steady and fully developed in the test section. More details on the water channel facility can be found in Princevac et al. (2010).

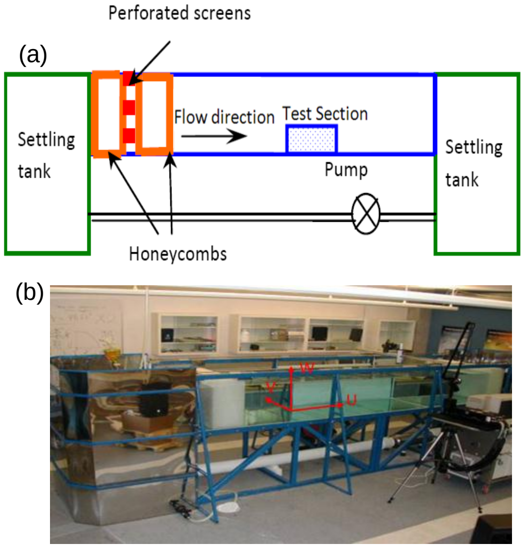

Fig. 1 (a) Water Channel Schematic (b) Water Channel facility at University of California, Riverside

2.2 Velocity Measurements

The water channel is equipped with the Particle Image Velocimetry (PIV, TSI Inc.) system for velocity measurements. A detailed velocity field can be measured in the vertical or horizontal plane. PIV measurement techniques are well established and widely used for fluid flow investigations (Adrian, 1988, 1991, 1997; Prasad et al., 1992) and will not be discussed here.

2.3 Concentration Measurements

Concentrations are measured through a newly developed system. This system, based on the concept of Laser Induced Fluorescence (LIF), utilizes optical fibers for measuring a tracer concentrations at selected points. This system consists of a 400 mJ Nd-YAG laser (Big Sky Laser Technologies Inc.) that produces a 532 nm wavelength laser beam with the frequency of up to 15 Hz, laser pulse synchronizer (TSI Inc.), high resolution (1600 x 1192) POWERVIEW 2M CCD camera (TSI Inc.), and a 575-585 nm light filter. Rhodamine 6G is used as a tracer dye. Each concentration measurement sensor (Fig. 2a) consists of two 750μm unjacketed plastic optical fibers: one for delivery of a laser beam and the second for delivering fluorescence light to the CCD camera. The laser beam is transmitted through a short optical fiber to reduce attenuation.

Since the water is recirculated in the water channel, several sensors are placed in the background for real time corrections of the background concentrations to allow for long averaging times. It was found that the sensor works best when the fibers are at an angle of 26° to each other (Kulchin et al. 2007). A photograph of the sensor appears in Figure 2a, and a schematic of the setup is shown in Figure 2b. The laser beam is focused on a bundle of optical fibers (emitting fibers). Each fiber guides laser light to the location of interest. Light from the fluorescence dye at the sensor location is then conducted to the camera through a second pair of fibers, referred here as receiving fibers. Receiving fibers are sparsely fixed in front of a CCD camera at a predetermined location so that all fibers are recorded on the same image without interference. A filter is placed in front of the camera to prevent any laser light reaching the CCD. Each sensor has to be individually calibrated.

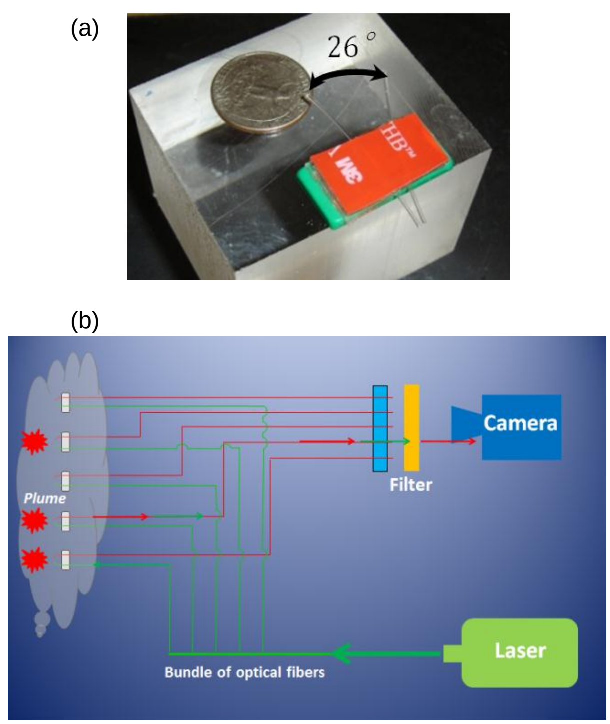

Fig. 2 (a) Optical Fiber Sensor (b) Schematics of the concentration measurement system (green fibers are emitting fibers and red fibers are receiving fibers)

2.4 *Visualization Technique*

Fluorescent dye, Uranine, is used as the tracer dye for flow visualizations as it has high light intensity in the range of visible light. Desired plume buoyancies are achieved by mixing the tracer dye with water and alcohol (specific gravity $SG = 0.8$). The dyed plume is recorded through long exposure imaging. This technique provides a picture of a time averaged plume, which is used to measure the plume rise, lateral and vertical spread under different buoyancies, flow conditions and building geometries.

3. Results from Urban Dispersion Measurements

3.1 *Ground Level Concentration Measurements*

In order to investigate the impact of DGs on air quality in urban areas at small source-receptor distances, we modeled the $15m \times 15m \times 7m$ $(L \times W \times H)$ Palm Springs DG building with stack height of 9.3m in the water channel at scale of 1:100. Ground level concentrations were measured at 15 locations downstream of the stack. In this set of experiments the effects of upstream buildings on ground level concentrations of buoyant emissions released from DG were investigated. The upstream buildings consisted of an array of 3×2 buildings of two different heights. Photographs of water channel models of the DG and buildings are shown in Figure 3.

Experiments to examine the air quality impact of DGs were conducted for three different cases: 1) DG with no upstream building 2) DG with upstream buildings with the same height as of the stack (single storey) 3) DG with upstream buildings with double the height of the stack (double storey).

(a) (b)

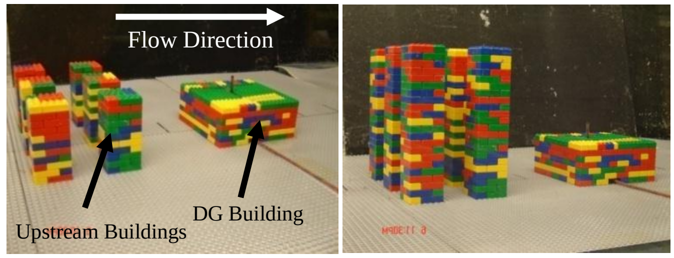

Fig.3 (a) DG and single storey upstream buildings modeled in water channel using Lego. (b) DG and double storey upstream buildings modeled in water channel using Lego

Results from concentration measurements have been compared with AERMOD predictions (Fig. 4). Comparison shows that AERMOD predicts the concentration associated with single DG well while it underestimates/overestimates concentrations associated with single/double storey upstream buildings respectively. Figure 4 also shows that the presence of upstream buildings reduce concentrations close to stack.

However, as the height of the upstream buildings is increased (double storey), the concentrations decrease much slower than the other cases. In order to understand the reasons for this performance of AERMOD, turbulence and velocity measurements as well as plume visualization experiments were performed.

3.2 *Turbulence and Velocity Measurements*

Velocity and turbulence measurements show that upstream buildings induce a low velocity as well as a highly turbulent region near the stack and this effect becomes more significant when the height of the upstream buildings is increased (Fig. 5).

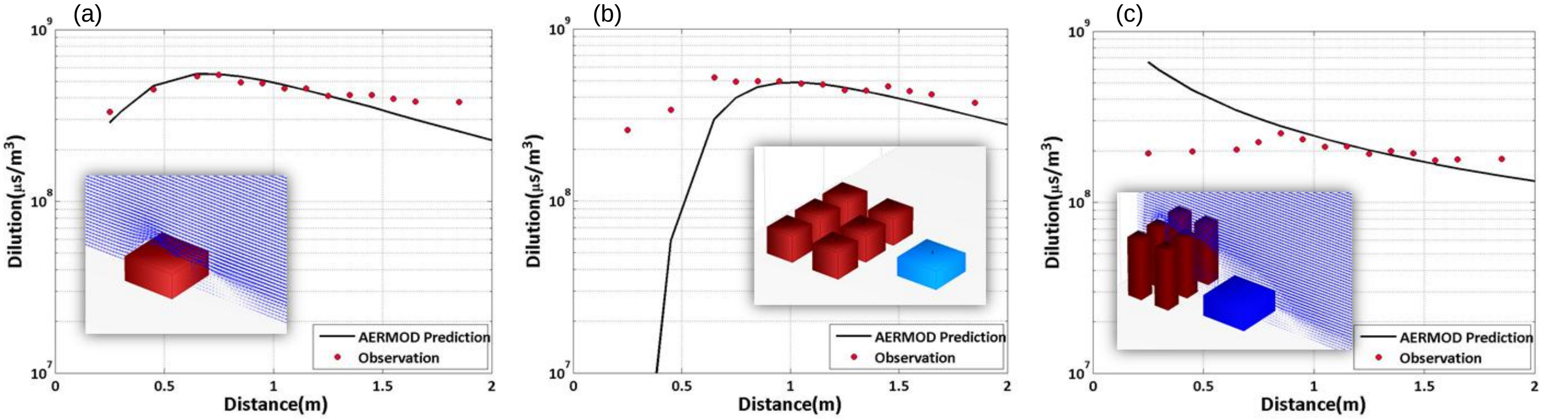

Fig. 4 Effect of the presence of the upstream building on the ground level dilution and prediction by AERMOD (a) No upstream buildings (b) Single storey upstream buildings (c) Double storey upstream buildings (Red dots(●) represents the observed ground level concentrations and solid black line(▬) represents AERMOD predictions on ground level concentrations)

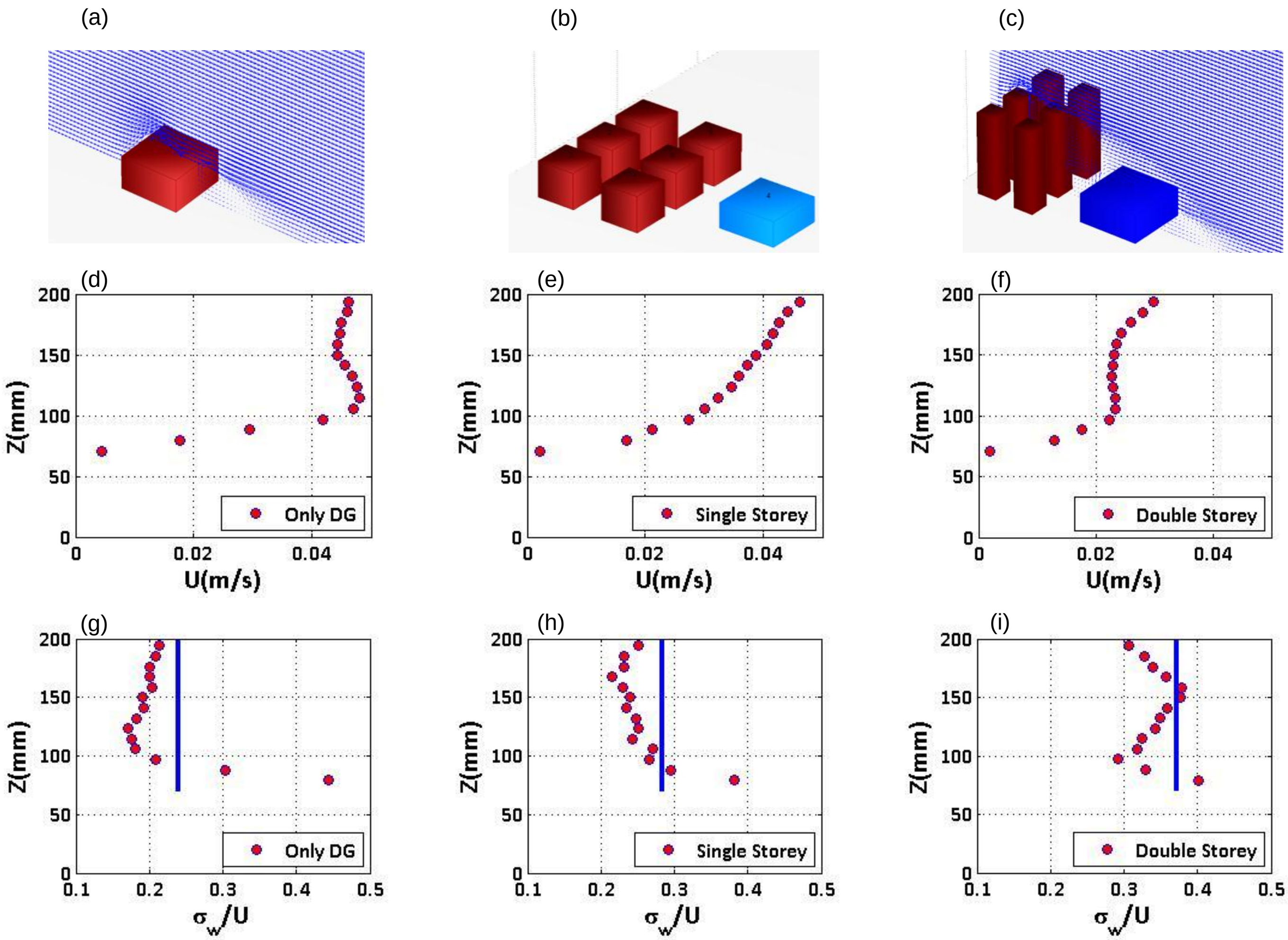

Fig. 5 Schematic of laboratory setting for (a) Only DG building case (b) DG and single storey upstream building case (c) DG and double storey upstream building case , Velocity profile close to stack for (d) Only DG building case (e) DG and single storey upstream building case (f) DG and double storey upstream building case , Vertical turbulent intensity for (g) Only DG building case (h) DG and single storey upstream building case (i) DG and double storey upstream building case

3.3 Plume Visualization

Results from plume visualization (Fig. 6) indicate that as upstream buildings decrease the wind speed near the stack, plume rise increases. However, at the same time, upstream buildings increase turbulent intensities near the stack resulting in rapid vertical mixing.

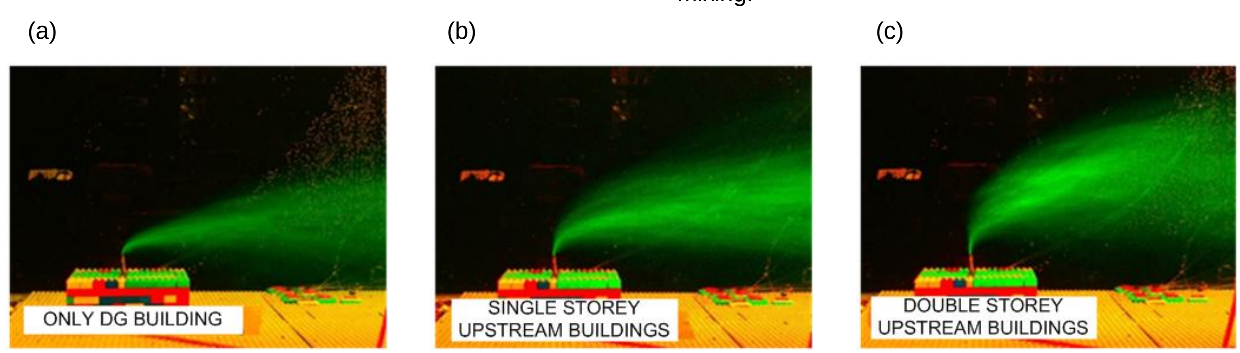

Fig. 6 Plume visualizations for (a) Only DG building (No upstream buildings) (b) Single storey upstream buildings (c) Double storey upstream buildings

Thus, the presence of buildings results in effects that counteract each other in changing the ground-level concentrations relative to the no upstream building case. A higher plume rise lowers the concentrations while increased vertical mixing increases ground level concentrations.

4. AERMOD Modifications

To overcome the problems mentioned in previous section for AERMOD predictions of the ground level concentrations, AERMOD has been modified in the sense that it treats the near field dispersion different than far field dispersion.

4.1 Model Description

The near field dispersion in AERMOD has been modified by assuming that there are no upstream buildings in the setup. Instead we used the measured meteorology of the stack region as the input meteorology and allow the AERMOD to predict concentrations up to 10 Building heights (H_b) from the DG which are called $C_{near\ field}$ (Schematic of the near field region is shown in Fig. 7). After this distance AERMOD predicts concentrations assuming that all buildings are in the setup and input meteorology is the same as that of ambient. Concentrations predicted with this approach are called $C_{far\ field}$. However, this modification can cause a discontinuity in the concentration field. To overcome this problem, the straight forward solution is to use an interpolating function between these two approaches such as:

$$C = (1-\lambda)C_{near\ field} + \lambda C_{far\ field} \quad 0 < \lambda < 1 \qquad (1)$$

where $\lambda = 0$ for $X \leq 10H_b$ and $\lambda \geq 1$ for $X = 13H_B$ (λ varies linearly between $10H_b \leq X \leq 13H_b$).

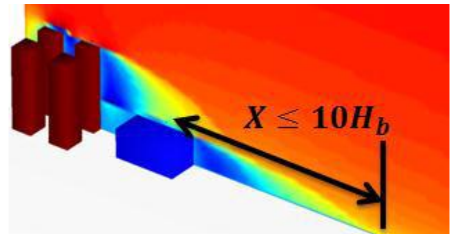

Fig.7 Schematic of the near field region in the modified version of AERMOD dispersion model

4.2 Model Evaluation

Results from this modification (Fig. 8) show an excellent agreement with the measured ground level concentrations in the laboratory.

This modification suggests that simple straight-line dispersion models, such as AERMOD, can be used to estimate concentrations close to the source in urban locations if local measurements or estimates of the mean flow and turbulence are used as inputs, since they represents the effect of upstream buildings on the dispersion of pollutants released from the stack.

As in this modification only the effect of upstream buildings is discussed, it might be inferred that this model modification is not valid for cases where both upstream and downstream buildings are present. Since the exhaust gases from DGs are released in relatively high temperatures, they undergo high plume rise close to stack and most of the plume go above the urban building canopy within several building heights downstream of the building. Thus for such cases, effect of downstream buildings can be assumed to be negligible and only upstream buildings affect the dispersion.

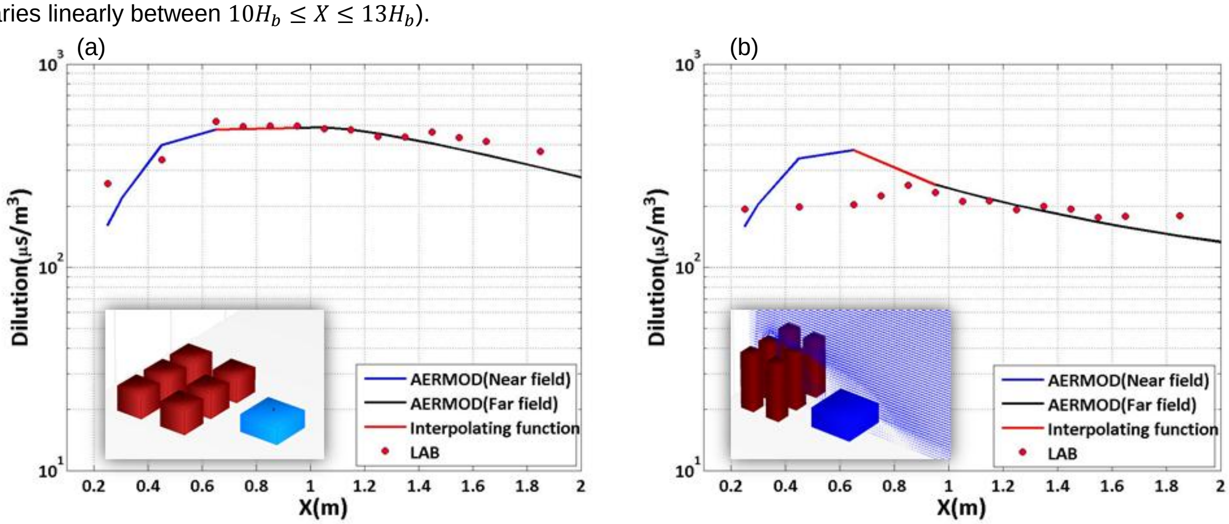

Fig.8 Modified AERMOD vs. Observations for (a) Single Storey Upstream Buildings (b) Double Storey Upstream Buildings (Red dots( ) represents the observed ground level concentrations, solid blue line( ) represents *near field* AERMOD predictions, solid black line( ) represents *far field* AERMOD predictions and solid red line( ) represents *interpolating function* predictions on ground level concentrations)

5. Summary and Conclusions

Nowadays DGs are becoming more popular due to their high efficiency (combined heat and power generation) as well as for providing power independency to local industries. However, since DGs are located in urban areas, they might have negative impact on air quality in urban areas.

Exhausts from DGs are released at relatively low heights (~10m) in urban areas. Hence, it is highly probable for the exhaust gases to be captured in the wake of surrounding buildings which can substantially increase the ground level concentrations of the exhaust plume in close proximity to DG. Therefore, there is a need to develop and apply methods to estimate the air quality impact of distributed generation at source-receptor distances of hundreds of meters.

Following the tracer field study conducted in Palm Springs in 2008 (Jing et al. 2009, 2010), it has been observed that currently used dispersion models such as AERMOD (Cimorelli et al. 2005) are unable to predict the ground level concentrations associated with low level buoyant sources in urban areas accurately.

Therefore, in order to have a better understanding of dispersion of such pollutants, a comprehensive laboratory study has been conducted in the water channel facility at UC riverside.

Palm Springs DG has been modeled in the water channel and tested under different surrounding building geometries. Ground level concentration associated with a buoyant release has been measured at different downstream distances.

Using these data, performance of AERMOD in predicting the ground level concentration associated with DGs has been evaluated. It has been shown that AERMOD performs reasonably well for predicting ground level concentrations associated with DGs when there are no surrounding buildings. However, it underestimates/overestimates ground level concentrations close to stack when single/double storey buildings are present.

In addition, data from ground level concentration measurements have been supplemented with data from velocity and turbulence measurements. Plume visualization has also been used to examine the behavior of the plume in the presence of upstream buildings. Results have shown that upstream buildings can produce low velocity regions as well as high turbulence levels near the stack. Low velocity region allows the plume from the DG stack to rise higher and decrease the ground level concentration and high turbulence levels results in larger plume spread and increase in the ground level concentration near the stack.

In order to overcome the AERMOD deficiencies in predicting the ground level concentration under complex building geometries, AERMOD has been modified for concentration predictions associated with near field $(x \leq 10H_b)$ by using the on-site measured meteorology in the vicinity of stack and the ambient meteorology for far field dispersion.

Modified AERMOD has been evaluated with concentrations measured in the water channel and it has been observed, that this simple modification substantially improves AERMOD performance in predicting ground level concentration associated with low level buoyant sources in urban areas.

Acknowledgment
The California Energy Commission (CIEE MAQ-07-03) supported this research.

References

Adrian RJ (1988) Review of particle image velocimetry research. In: The symposium on optical methods in flow and particle diagnostics, 6th International Congress on Applications of Lasers and Electro-Optics. 9, 317-319, San Diego, CA: Optics and Lasers in Engineering.

Adrian RJ (1991) Particle-imaging techniques for experimental fluid-mechanics. Ann. Rev. Fluid Mech. 23**,** 261-304.

Adrian RJ (1997) Dynamic ranges of velocity and spatial resolution of Particle Image Velocimetry, Meas. Sci. & Tech. 8(12), 1393-1398.

Allison KE and Lents J (2002) Encouraging distributed generation of power that improves air quality: can we have our cake and eat it too? J. Energy Policy, 30, 737-752.

Britter RE, Hanna SR (2003) Flow and dispersion in urban areas. Annual Review of Fluid Mechanics 35, 469–496.

Cimorelli AJ, Perry SG, Venkatram A, Weil JC, Paine RJ, Wilson RB, Lee RF, Peters WD, Brode R (2005) AERMOD: A dispersion model for industrial source applications. Part I: General model formulation and boundary layer characterization. J. App. Meteorology., 44(5), 682-693

Greene N, Hammerschlag R (2000) Small and Clean Is Beautiful: Exploring the Emissions of Distributed Generation and Pollution Prevention Policies. J. electr., 13, 5,50-60, DOI: 10.1016/S1040-6190(00)00118-4.

Hadley SW, Van Dyke JW (2003) Emissions benefits of distributed generation in the Texas market. ORNL/ TM-2003/100, Oak Ridge National Laboratory, Oak Ridge, TN.

Heath GA, Granvold PW, Hoats AS, Nazaroff WW (2006) Intake fraction assessment of the air pollutant exposure implications of a shift toward distributed electricity generation. Atmos. Environ., 40, 7164-7177.

Heath GA., Granvold PW, Hoats AS, Nazaroff WW (2005) Quantifying the air pollution exposure consequences of distributed electricity generation. Final Report to the University of California Energy Institute.

Jing Q, Venkatram A, Princevac M, Pankratz D, Qian W (2009) Modeling Dispersion of Buoyant Releases in an Urban Area,89th AMS Annual Meeting, 11th Conference on Atmospheric Chemistry Special Symposium on Aerosol–Cloud–Climate Interactions,89th Annual Meeting, Phoenix, AZ, January 2009

Jing Q, Venkatram A, Princevac M, Pankratz D,Qian W (2010) Modeling Dispersion of Buoyant Emissions from Low Level Sources in an Urban Area,90th AMS Annual Meeting, 16th Conference on Air Pollution Meteorology, 90th Annual Meeting, Atlanta, GA, January 2010

Kulchin YN, Voznesenskiy SS, Gamayunov EL, Gurin AS, Korotenko AA, Maior AY (2007) An Immersible Fiber-Optic Fluorometer , Instruments and Experimental Techniques 6. 117–122

Prasad AK, Adrian RJ, Landreth CC, Offutt PW (1992) Effect of resolution on the speed and accuracy of Particle Image Velocimetry interrogation. Exp. Fluids, 13(2-3), 105-116.

Princevac M, Baik J, Li X, Pan H, Park S (2010) Lateral channeling within rectangular arrays of cubical obstacles. J Wind Eng Ind Aerodyn. 98, 377-385, DOI: 10.1016/j.jweia.2009.11.001.

Venkatram A, Isakov V, Yuan J, Pankratz D (2004) Modeling Dispersion at Distances of Meters from Urban Sources. Atmos. Environ., 38(28), 4633-4641.