The 2012 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM' 12)
Seoul, Korea, August 26-30, 2012

Wind Tunnel Measurement of Turbulent Boundary Layer over Hypothetical Urban Roughness

*Yat-Kiu Ho[1)] and Chun-Ho Liu[2)]

[1), 2)] *Department of Mechanical Engineering, The University of Hong Kong, Hong Kong*
[2)] *liuchunho@graduate.hku.hk*

ABSTRACT

Effects of urban morphology on flows in and over urban street canyons are experimentally investigated by wind tunnel measurement. In our previous studies, most of the efforts had only been sought on developing different numerical models (large-eddy simulation, LES, and Reynolds-averaged Navier-Stokes, RANS, k-ε turbulence models) to enrich our knowledge of the transport processes in idealized urban areas. This wind tunnel study was thus initiated to complement our modeling results. Hot-wire anemometry (HWA) was employed to measure the flows over two-dimensional (2D) street canyons in the wind tunnel in our University. Particular emphasis at the beginning of this study was put on fabricating of hot-wire probes, setting up data acquisition system, and signal processing technique, etc. Preliminary experiments were performed with single hot-wire probe. Vertical profiles of the ensemble-averaged streamwise velocity and turbulent intensity at three different segments over the street canyons of unity aspect ratio were collected. It was found that our previous LES results agree well with the current wind tunnel measurements. Further experiments are undertaken using X-probe hot wire to measure the vertical profiles of two velocity components simultaneously in order to elucidate the mechanism of transport processes and pollutant dispersion in urban street canyons. Preliminary results of X-probe measurement are also reported in this paper.

1. INTRODUCTION

With the rapid development in modern cities, the associated drawbacks on environment and urban climate have been affecting human activities since the last decade and are continuously intensified. In particular, the urban-area air pollution problems, because of the dense traffic in narrow streets surrounded by high-rise buildings (a form of random roughness), reduced significantly the efficiency of natural ventilation in between the street canyon and the atmospheric boundary layer (ABL). Elevated pollutant levels are built up inside urban street canyons especially at the near-ground level. Besides, complex urban morphology affects the near-ground ABL structure which in turns complicates the wind flows and pollutant dispersion over urban areas. Therefore, a detailed investigation is crucial to improve our understanding of

---

[1)] Graduate Student
[2)] Assistant Professor

these essential physical processes.

Street canyons are the fundamental units constructing the urban ABL. Various research works have been conducted using idealized two-dimensional (2D) street canyons to elucidate the ventilation and pollutants transport mechanism in and over urban areas. Both physical modeling (e.g. wind tunnel. Ahmad 2005, and water channel, Li 2008) and numerical simulation are the techniques commonly employed to address the air pollution problems in street canyons.

Meroney (1996) carried out a wind tunnel study to investigate the effects of street geometry on pollutant dispersion. It was reported that the dynamics and dispersion characteristics of flows in open-country canyons and canyons of different aspect (building-height-to-street-width) ratio, *h/b* were rather different. Improved street-level ventilation was observed in the former case compared with the latter one. Next, Pavageau (1999) performed another wind tunnel experiment to examine the turbulent characteristics and statistical properties of developing pollutant concentration field in urban street canyons. They highlighted that, from the results obtained, both the internal and external flows played important roles on pollutant dispersion inside street canyons. Afterward, Chang (2003) investigated experimentally and numerically the dispersion mechanisms of pollutant in street canyons. They focused on the effect of buildings arrangement on the corresponding flow patterns, wind forces, pressure distributions and pollutants dispersion on a three-dimensional urban array. They also reported the ventilation behavior in different street canyon configurations.

In our previous research works, different numerical models (large-eddy simulation, LES and k-ε turbulence models) are developed to improve our knowledge of the transport processes in idealized urban areas. Liu (2004) employed the LES technique to introduce two new concepts, air exchange rate (ACH) and pollutant exchange rate (PCH), for comparing ventilation and pollutant removal performance of street canyons. Afterward, Cheng (2009) used a k-ε turbulence model to examine the mechanisms of ventilation and pollutant removal for a 2D street canyon of unity aspect ratio in unstable thermal stratification. Recently, Cheng (2011) developed a LES model to study the flows and pollutant transport in and above urban street canyons. The flows inside the street canyons are successfully resolved with a higher spatial resolution and the results obtained showed a good agreement with other numerical studies, as well as wind tunnel and water channel measurements. While most of our previous studies have focused on numerical simulations that have unavoidably overlooked laboratory measurements, we initiate this wind tunnel study to address the problems in another approach in attempt to arrive a complementary solution. One of the advantages of using wind tunnel measurement is the full control of the testing parameters and sampling locations.

On the other hand, most of the previous works have emphasized only the physical processes inside the street canyons but apparently overlooked the transfer process in-between the street canyons and the external flow, and the shear layers or even at higher elevations above the urban ABL. Canton (2003) concerned the pollutant transfer between the street and exterior flow by means of water channel experiments. They visualized an evolution of concentration field, showing the role of the roof-level shear layer. While limited research effort has been sought in this area. In this study, we attempt to use hot-wire anemometry (HWA) measure the flows over 2D street canyons to examine the behaviors of wind flows over the shear layer of urban areas. The specific objective is to examine how idealized urban roughness could affect the ABL structure and flow characteristics over urban roughness. Preliminary results with a single-wire senor and the data with a X-probe sensor are collected and compared with our LES results. The data obtained would be useful not only for validating our numerical studies but also as a complementary solution to improve our current understanding of urban climate and pollutant dispersion.

2. EXPERIMENTAL DESIGN

2.1. Open-looped wind tunnel

The experiments are performed in an open-looped type wind tunnel which is located at the Department of Mechanical Engineering, The University of Hong Kong (Fig. 1). The wind speeds range from 0 to ~15 m/s.

Fig.1. Open-looped wind tunnel at The University of Hong Kong

The test section is 200 cm long, 56.5 cm width and 55 cm height (Fig. 2).

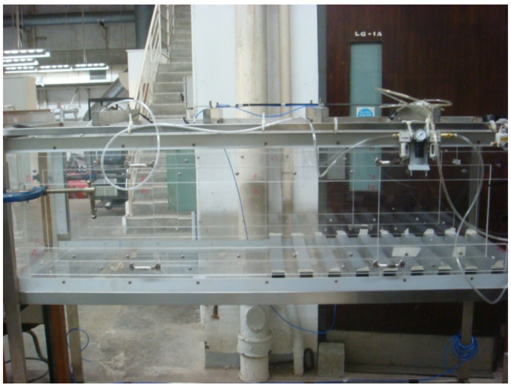

Fig.2. Side view of the test section

2.2. Urban roughness modeling

Rectangular aluminum bars of size 56.5 cm (width) and 5 cm (height) are used for modeling flat-roof buildings. Ten identical bars are placed in the test section in cross flow that are fully spanning the width of the wind tunnel to ensure 2D flows. The aluminum bars are equally spaced at 5 cm apart to form street canyons of aspect (building-height-to-street-width) ratio, *h/b*, equal to one (Fig. 3). The seventh street canyon, counting from the upstream, is selected as the sampling street canyon where measurements are taken. At this beginning stage of study, it is estimated that, from our LES studies, the inflow turbulent boundary layer is fully developed at the sampling street canyon. Nevertheless, further experiments are conducted to verify the estimate.

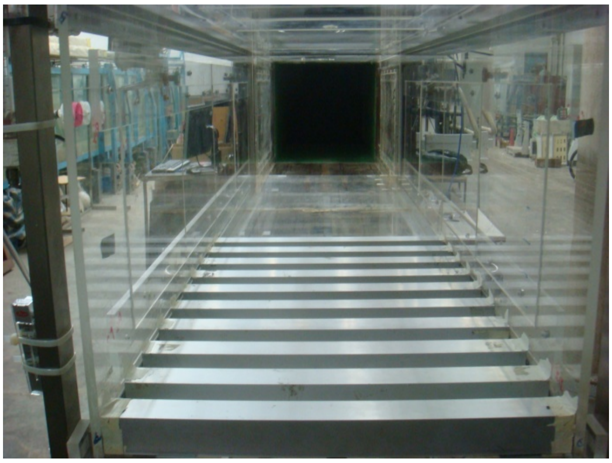

Fig.3. Arrangement of roughness elements in test section

The prevailing wind speed U_f is set at 3 m/s and the value of the Reynolds number

$$\mathrm{Re} = \frac{U_f h}{\nu} \qquad (1)$$

calculated based on the building height *h*, prevailing wind speed U_f and kinematic viscosity ν, is around 10,000, which was larger than the threshold value (3,400) suggested by Hoydysh (1974) to ensure that the flow is independent from molecular viscosity

2.3. Velocity Measurement

The wind flow velocities and velocity fluctuations are measured by the hot-wire anemometry (HWA). Pitot tube is also employed to monitor the prevailing wind speed such that it is kept at constant throughout the experiment. In order to gain a better understanding of the HWA behavior, we decided not to use the readily available instruments in the market. Instead, we fabricated and set up our own set of sensor probes and data acquisition system. Therefore, particular emphasis is put on managing the signal processing technique, e,g, the voltage-velocity conversion. At the beginning stage, single-wire sensors are used because of its simplicity. Afterward, X-wire sensors are used instead. LabVIEW hardware and software package are employed to build the data acquisition platform. Through an A/D convertor, the analog voltage signal collected could be transferred to a digital computer for post-processing.

Figure 4 illustrates the actual setup of the experiment. The hot-wire sensor is secured on a clamp and a stand, that is aligned parallel to the flow in order to measure the streamwise velocities and the fluctuations.

Fig. 4. Actual experimental set-up

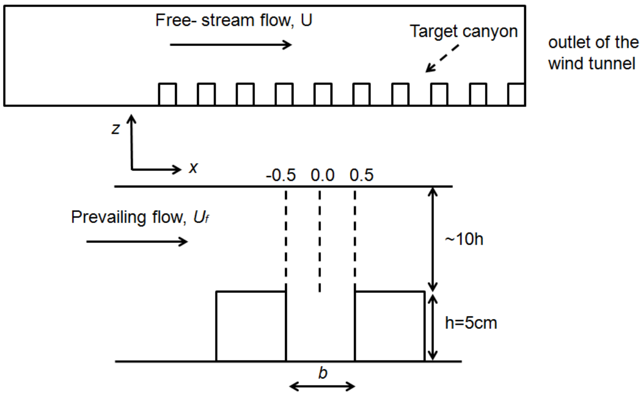

Fig.5. Schematic diagram of a detailed view of the sampling street canyon

A detailed view of the sampling street canyon is illustrated in Figure 5. The height of the buildings, *h* and the width of the streets, *b* is kept constant in such way that an urban street canyon of unity aspect ratio is modeled. It is then divided into three segments (*x/b*= -0.5, 0.0 and 0.5) to examine the flow characteristics over it. The vertical wind profile in streamwise and vertical direction on the mid-plane of spanwise direction of the selected segments is measured by HWA. At each sampling point, mean wind velocities and velocity fluctuations are recorded for a time period of 60 s and thus, for each point, 6,000 HWA voltage data were collected. Voltage-velocity mapping were then applied to resolve the actual wind velocity in the flow field. For the first set of data, a full calibration curve for the unique sensor probe was produced and the mapping was based on it. On the other hand, we attempt to generalize our hot wire signal outputs by mapping with the commonly adopted hot wire universal function reported by Brunn (1975) in order to achieve a more accurate velocity-voltage mapping results.

3. RESULTS AND DISCUSSIONS

In this paper, we focus on the region over the street canyons. Two sets of preliminary experiments are carried out to examine the flow characteristics over the idealized urban roughness elements of aspect ratio equal to one. In particular, in the latter set, the two-component flow velocities and velocity fluctuations (in streamwise and vertical directions) are measured. Besides, the data presented in this section are compared with our LES model findings to formulate a complementary solution. Our current 2D LES study used a computational domain of height 8h, where h is the building height. Free-slip boundary condition is applied to the upper boundary and periodic boundary condition is applied to horizontal domain extent so an infinitely repeating street canyon is modeled. The prevailing flow is driven by a background pressure. It is our objective that these preliminary results could serve as fundamental guidelines for our future physical modeling works as well as ideas and validation database for numerical models.

3.1. Preliminary results with single-wire sensor

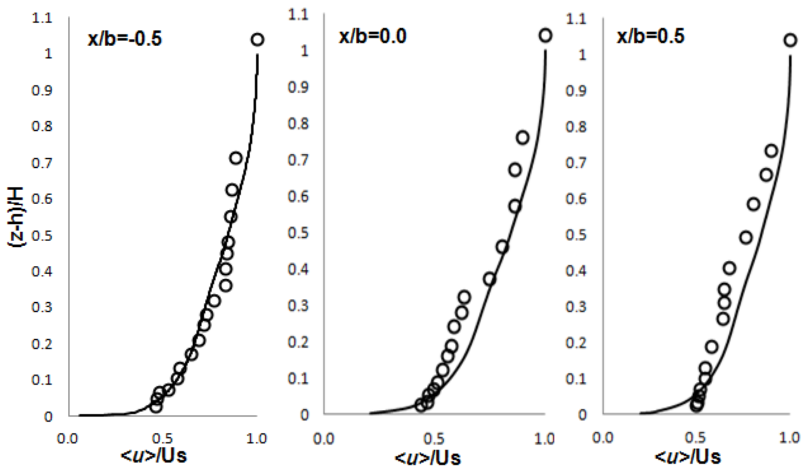

Fig.6. Vertical profiles of the ensemble average streamwise velocity $\langle u \rangle / U_s$.
— : LES results and o : current experimental results

A single hot-wire probe is applied in the first set of experiments. One-component flow velocity and turbulent intensity are collected. Figure 6 shows the vertical profiles of the ensemble average steamwise velocity, $\langle u \rangle$. The measured value is normalized by the characteristic velocity scale, U_s which is the maximum wind velocity along the segment and the characteristic length scale is the boundary layer thickness. A typical boundary layer flow is revealed in which a noticeable velocity gradient is developed along the roof level. Figure 7 compares the profiles of current experimental results of streamwise velocities fluctuation with those of our LES calculation. The trend of velocities fluctuation at three locations along the street canyon is fairly constant. Peaks are observed at the position right over the roof level.

The first set of experiment serves as a validation of the methodology and the current experimental setup. Our previous LES results are generally agree well with the current experimental results. However, owing to the limitation of single-wire sensor that can only measure one single component of flow velocity. Hence, an X-wire sensor is used instead in the next set of experiment.

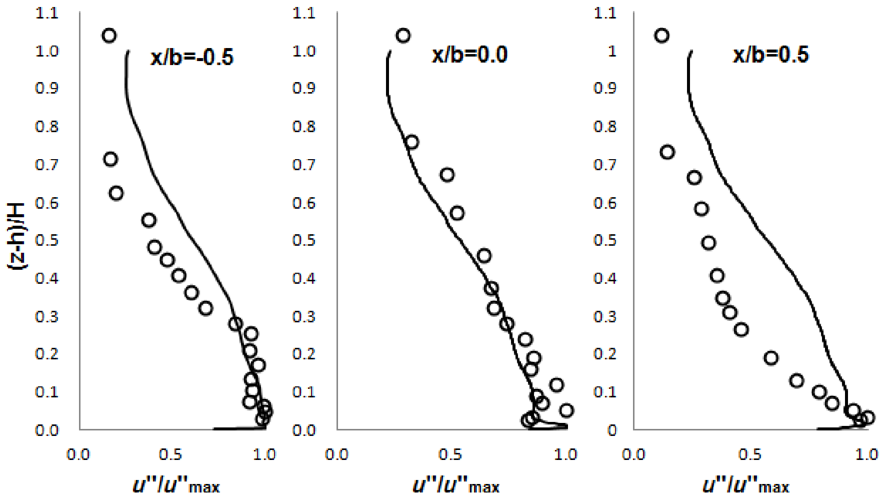

Fig.7. Vertical profile of the ensemble average streamwise velocity fluctuations u''/u''_{max}.
— : LES results and o : current experimental results

3.2. Preliminary results with x-wire senor

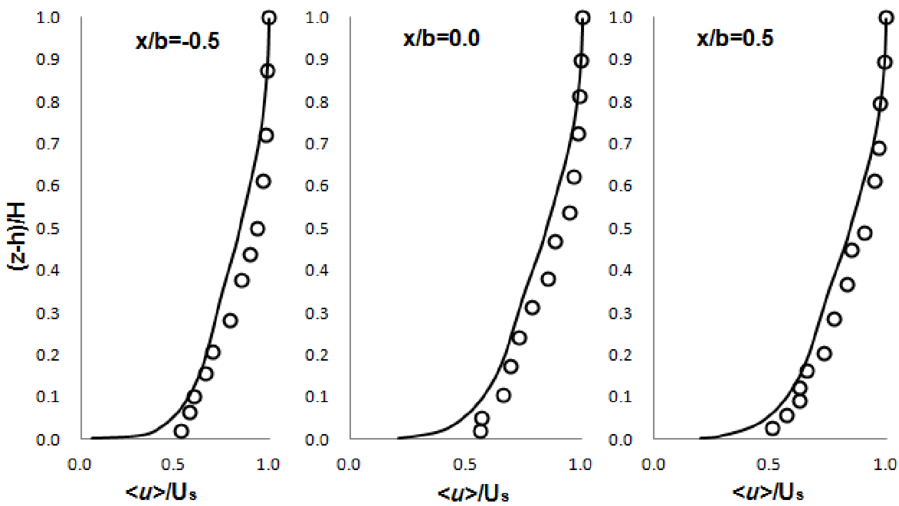

Fig.8. Vertical profile of the ensemble average streamwise velocity $\langle u \rangle /U_s$.
— : LES results and o : current experimental results

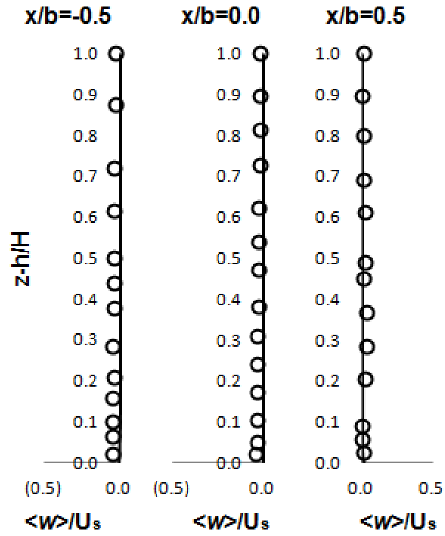

Fig.9. Vertical profile of the ensemble average vertical velocity <*w*> /U_s.
— : LES results and o : current experimental results

In this section, preliminary results (two component flow velocities and velocity fluctuation in streamwise and vertical directions) with X-wire senor are presented. Figures 8 and 9 show the vertical profiles of the ensemble averaged streamwise velocity <*u*> and the ensemble average vertical velocity <*w*>. In comparison with our LES calculations, similar to the single-wire results reported previously, both <*u*> and <*w*> are normalized by the maximum wind velocity, U_s along the segment and the characteristic length scale is the boundary layer thickness.

Compared with the single-wire results shown in figure 6, X-wire senor provides a more consistent measurement and the current X-wire results agree much better with our LES results than do our single-wire results. Owing to the size and orientation of the senor probe, it is hard to exactly measure at the surface of the building roof and resolve its corresponding flow structure. However, a typical boundary layer flow is revealed with a noticeable velocity gradient developed at the roof level due to the contribution of aerodynamic resistance of the buildings. A little bit higher value of streamwise velocity, <*u*> is observed in the current experiment work thatcould be caused by the difference in domain size between the LES model and the wind tunnel. The current wind tunnel domain height is around 11h while the LES model is 8h only, in addition to the horizontal direction, though the measurements are taken at the middle of the spanwise direction, the width of the building models are compared with the LES model which is of periodic boundary condition in spanwise direction. Other than this, this set of result does agree well with our LES works.

With the advantages of using X-wire sensor, a second velocity component is obtained which helps better resolve the flow field. Figure 9 shows the comparison of vertical profile of the ensemble vertical velocity, <*w*> of current and LES studies. Both results are of good agreement showing that vertical wind velocity should be of the least value (<*u*> >> <*w*>); otherwise the flow continuity will be violated.

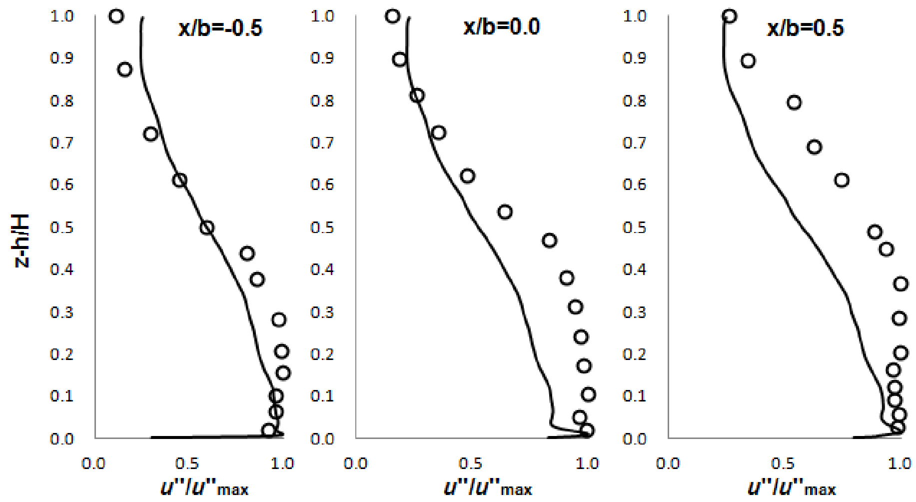

Fig. 10 Vertical profile of the ensemble average streamwise velocity fluctuations u''/u''_{max}. —: LES results and o : current experimental results

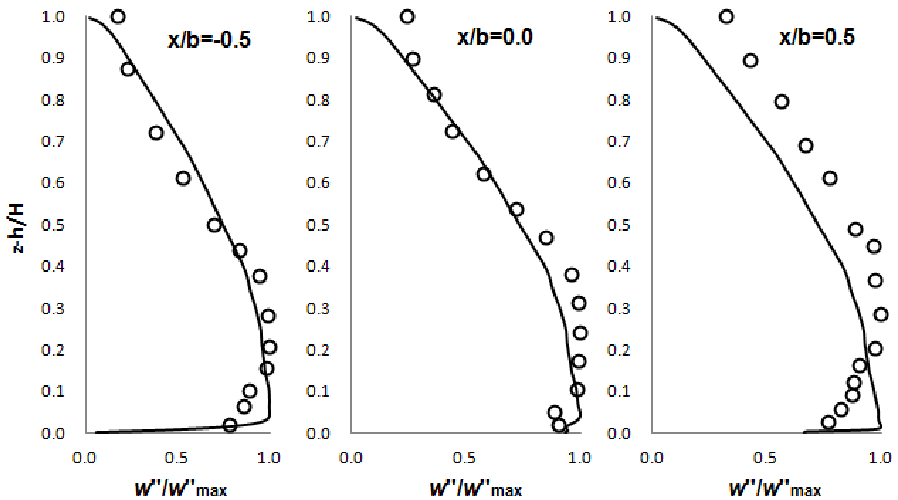

Fig. 11 Vertical profile of the ensemble average vertical velocity fluctuations w''/w''_{max}. —: LES results and o : current experimental results

Figures 10 and 11 show the vertical profiles of streamwise and vertical velocity fluctuations, *u"* and *w"*, along the windward, centre and leeward transects of the street canyon. It is noticeable that both the results of current experimental and LES studies generally agree well with each other. A local maximum is observed at the location slightly above roof level that tends to decrease with increasing height. Peak turbulence level along roof level is mainly due to aerodynamic resistance of the buildings which generate a shear layer that in turn creates a sharp velocity gradient and thus large turbulence production. In particular on the leeward side, the flow separation at the sharp corner of the building often create a huge amount of turbulence when compared with the position on the middle and windward side. This momentum transfer between street canyon cavity, building roof level and ABL thus plays an important role on the pollutant dispersion mechanism in and over urban canopy. At an elevated height over the street canyon, the velocity gradient decreases and approaches uniform inside the ABL and thus, less turbulence are produced. In addition to the comparison of the peak values of *u''* and *w'',* both current and LES studies show the trend that *w''* is peaked at a higher elevation when compared with the peak value of *u''* at around roof level. In addition to the profile of the vertical velocity fluctuations, LES results show a tendency to become zero at the top of the boundary while current experimental measurements do not. This observation could be due to the setting of the free-slip boundary condition at the top of the domain.

CONCLUSION

The flow fields over 2D idealized street canyons of unity aspect ratio are examined using reduced-scale model in a laboratory wind tunnel. Two sets of experiment are carried out with single- and X- hot-wire senor. Preliminary results on one component and two components velocities and the corresponding velocity fluctuations are presented. Results are also compared with our LES models which show a good agreement with each other. This is our objective to address the flow and pollutant dispersion problem with physical modeling approach to complement our numerical simulation. The data obtained could serve as a validation database as well as useful for future model development.

In most of the previous studies, both numerical and physical, focus had only put on the processes inside the canopy but overlooked the interaction between the shear layer, canopy cavity and the ABL. The urban canopy flow is basically a turbulent shear flow above a roughness. Concerning the shear layer induced by the aerodynamic resistance of the buildings that separate the canyons and the atmospheric flow, the high level of turbulence intensity observed along or slightly above the roof level in the experiments thus plays an essential role on the transfer of flow and other scalar properties, heat and pollutants between the canyons and free stream flow above.

It is our intention to study the pollutants dispersion mechanism over urban roughness by physical modeling approach. At this very beginning stage, we only work on the flow field; nonetheless, this could serve as a foundation and stepping stone for us to our most interest part, pollutant dispersion. A number of questions on flow field aspect still need to clarify through different experiments. Once we fully resolve the flow field structure over the urban roughness, we will proceed to the dispersion experiments to develop the relationship in-between in order to enrich our basic understanding of pollutant dispersion over urban roughness.

REFERENCES

Ahmad, K., Khare, M. and Chaudhry, K.K. (2005), “Wind tunnel simulation studies on dispersion at urban street canyons and intersections- a review.” *J. Wind Eng. Ind. Aerodyn.,* Vol. **93**, 697-717.

Brunn, H. (1976), “A note on static and dynamic calibration of constant-temperature hot-wire probes.” *J. Fluid Mech.,* Vol. **76**, Part 1, 145-155.

Canton, F., Britter, R.E. and Dalziel, S. (2003), “Dispersion mechanisms in a street canyon.” *Atmos. Environ.,* Vol. **37**, 693-702.

Chang, Cheng-Hsin and Meroney, Robert N. (2003), “Concentration and flow distributions in urban street canyons: wind tunnel and computational data.” *J. Wind Eng. Ind. Aerodyn.,* Vol. **91**, 1141-1154.

Cheng, W.C., Liu, Chun-Ho and Leung, Dennis Y.C. (2009), “On the correlation of air and pollutant exchange for street canyons in combined wind-buoyancy-driven flow.” *Atmos. Environ.,* Vol. **43**, 3682-3690.

Cheng, W.C. and Liu, Chun-Ho (2011), “Large-Eddy Simulaation of flow and pollutant transports in and above two-dimensional idealized street canyons.” *Boundary-Layer Meteorol.,* DOI 10.1007/s10546-010-9584-y.

Hoydysh, W.G., Griffiths, R.A. and Ogawa, Y. (1974), “A scale model study of the dispersion of pollution in street canyons.” APCA paper no. 74-157, *67th Annual Meeting of the Air pollution Control Association,* Denver, Colorado.

Liu, Chun-Ho, Leung, Dennis Y.C. and Barth, Mary C. (2005), “On the prediction of air and pollutant exchange rates in street canyons of different aspect ratios using large-eddy simulation.” *Atmos. Environ.,* Vol. **39**, 1567-1574.

Li, Xian-Xiang, Leung, Dennis Y.C., Liu, Chun-Ho and Lam, K.M. (2008), “Physical modeling of flow field inside urban street canyons.” *J. Appl. Meteor., and Climat.,* Vol. 47, 2058-2067.

Meroney, Robert N., Pavageau, Michel, Rafailidis, Stilianos and Schatzmann, Michael (1996) “Study of line source characteristics for 2-D physical modelling of pollutant dispersion in street canyons.” *J. Wind Eng. Ind. Aerodyn.,* Vol. **62**, 37-56.

Pavageau, Michel and Schatzmann, Michael (1999), “Wind tunnel measurements of concentration fluctuations in an urban street canyon.” *Atmos. Environ.,* Vol. **33**, 3961-3971.