6.2 FLOW AND TURBULENCE IN URBAN CANOPIES

D. Zajic*, H.J.S. Fernando, M. Princevac and R. Calhoun
Environmental Fluid Dynamics Program
Mechanical & Aerospace Engineering, Arizona State University, Tempe, AZ 85287-9809

1. INTRODUCTION

Rapid urbanization and associated issues such as urban security and deteriorating air quality have necessitated a better understanding of airflow, turbulence and heat/mass transfer in urban canopies. Such knowledge is central to the development of detailed predictive models as well as parameterization of urban effects in meso-scale models. To this end, as a part of an Urban Fluid Mechanics initiative at Arizona State University, field and laboratory experiments were conducted to improve our understanding of urban flows, and the results presented herein reflects some recent results of this work.

The influence of a city on flow within and around is twofold. A city typically represents a heat island (i.e. an area with temperatures higher than its rural surroundings) and an isolated area with increased mechanical and thermal roughness. The formation of a heat island is a consequence of different thermal properties of rural and urban surfaces as well as the existence of additional anthropogenic heat flux in the latter. Urban areas cool much slower due to larger heat capacities of materials used to modify the land surface as well as due to heat flux from buildings, vehicles and industrial facilities. Also, urban canyons trap radiation from different sources. Increased urban drag in urban areas is important in near-surface transport parameterizations, and in certain meso-scale models the city influence is included through an additional drag term in the momentum equation (Brown, 2000). Interaction of flow with buildings induces higher turbulence levels, especially at the building top level. Jetting of flow thorough urban canyons can cause anomalous wind speeds compared to the surrounding non-urban areas. Flow characteristics in urban canyons depend on the angle of incoming wind, canyon geometry and the shape and size distribution of buildings. Traffic also represents a significant turbulence source at the pedestrian level. Turbulence and flow properties at the street level and at low altitudes are very important in predicting the distribution of vehicular and roof-top (chimney) pollutants.

Data presented in this work were collected during the Joint Urban 2003 (JU 2003) field campaign in Oklahoma City during the period from June 28 to July 31, 2003. A large number of investigators from government laboratories, universities and private firms participated in this experiment, which was hosted by the U.S. Defense Threat Reduction Agency (DTRA), Army Research Office (ARO) and the U.S. Department of Homeland Security (DHS) (Allwine et.al., 2004). Arizona State University (ASU) Environmental Fluid Dynamics Program (EFD) was one of the participants, and a part of their efforts is described in this paper.

2. EXPERIMENTAL SETUP

The purpose of the JU 2003 field campaign was to gather data that help better understand flow, heat transfer and dispersion of contaminants in urban environments. Knowledge gained from this study will be used to improve, refine and validate computer models that simulate flow and dispersion in urban areas. The JU 2003 was conducted in a real urban area, and the data were collected in different parts of the urban domain, including in the Central Business District (CBD), in commercial/industrial areas as well as in suburbs. This wide distribution of measurements sites enabled a comprehensive understanding of flow and its stability and their local variations.

The instrumentation deployed by the ASU-EFD team consisted of four 3-D ultrasonic anemometers, radiation sensors, infrared temperature sensors, thermistors, a soil heat flux plate, a soil water content sensor and a Doppler LiDAR (Light Detection And Ranging). The instruments were located at three different sites, dubbed: energy budget station, sonic tower and the LiDAR location. The Energy budget station was located near the intersection of the N Walker Avenue and NW 11th Street, 1.3 km northwest outside of the CBD on a grassy surface surrounded by low-level buildings and some vegetation. This tower was instrumented with the following: Kipp and Zonen Net Radiometer at 9.2 m above ground level (agl), two cup anemometers at 8.9 m and 1.5 m agl, two thermistors at 8.3 m and 1.1 m agl, an IR thermometer, an upward facing pyranometer and a downward facing pyrgeometer at 3.5 m agl, a 3D Sonic anemometer (Campbell Sci.) and a Krypton Hydrometer at 2.5 m agl. A soil heat flux plate (6.5 cm below the ground level), six thermistors (2 x 2 cm, 3 cm, 4 cm, 5 cm and 8 cm below the ground level) and a soil water content reflectometer were added on July 13. Data from the net radiometer, cup anemometers, thermistors, pyranometer, pyrgeometer and soil heat flux plate were stored as five-minute averages. Data from the IR thermometer, sonic anemometer, Krypton hydrometer and soil water content reflectometer were stored as one minute averages.

* Corresponding author address: Dragan Zajic, Dept. of Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ 85287-6106. E-mail: zajic@asu.edu

The sonic tower was located in the CBD, approximately 20 meters from the northeastern edge of the east-west oriented Park Avenue, delimited by Broadway Avenue at the east end and Robinson Avenue at the west end. This section of Park Avenue is 157 m long. The tower was equipped with three sonic anemometers with a sampling rate of 10Hz: the Applied Technology sonic was at 2.5 m agl, Young at 5 m agl, and Metek at 8.5 m agl. The IR sensor (sampling rate 8 Hz) was mounted on the same tower to measure the street surface temperature. Data loggers and laptop computers stored raw data from sonic anemometers (three velocity components and temperature) and one-minute averaged *rms* surface IR temperature. The Young sonic and the IR thermometer were operated continuously during the whole campaign. During the first part of the campaign, two sonics were operational only during IOPs. Starting with IOP 6, all three sonics operated continuously. The ASU-EFD sonic tower was just one of the large number of meteorological towers located on the street level of this section of Park Avenue. A number of sonics were also located on the roof tops. It is expected that the high density placement of wind sensors will provide detailed flow field characteristics that are necessary to better understand transport and dispersion in the street canyon. Also, it will provide street level turbulence statistics that significantly influence the comfort of pedestrians. In the Park Avenue canyon, buildings on the southern side are fairly uniform in height (50 m), except one 120 m tall building at the western end. Buildings on the northern side are also approximately of the same height except for a small group of shorter buildings and a narrow passage near the middle of the eastern half of Park Avenue. Since the width of the street canyon is close to 25 m, canyon height to width ratio is approximately 2, which indicates a skimming flow regime (Hussain and Lee, 1980). The LiDAR was located approximately four kilometers to the south-southeast from the CBD, on the southwest corner of 25th Street and Amin Drive. The LiDAR operated during IOPs and non-IOPs, as necessary. Most of the scanning strategies were coordinated with the Army Research Laboratory (ARL) LiDAR group to capitalize the opportunity for Dual-Doppler scanning.

3. RESULTS

Flow properties in urban areas are significantly affected by the thermal properties of the surface material. Asphalt and concrete surfaces prevalent in urban areas have different heat storage capacities than characteristic rural surfaces, and the daytime thermal storage influences stability conditions inside the urban canyons. Surface temperatures measured at two sites, the downtown (street canyon) site and the energy tower site (open grassy field), are presented in Figure 1 for a

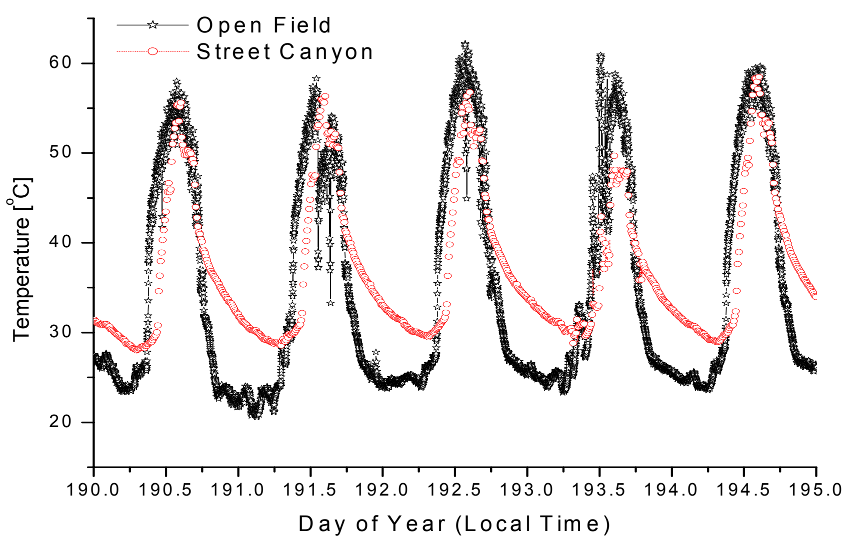

Figure 1. Surface temperatures measured in Park Avenue street canyon and in an open grassy field.

five day period (190 to 195 Day of Year*; July 10 to July 15). A warming trend throughout these five days can be noted. A sharp increase of temperature above the open grassy field occurs several hours after sunrise (~ 6:30 AM local time). The surface temperature begins to rise around 8:30 AM. Morning heating in the urban canyon is sluggish due to shading effects of the buildings. The skin temperature starts its fastest growth around 10:30 AM, as solar energy begins to penetrate the urban canyon. During the daytime, the surface temperature in the urban canyon is slightly lower, again due to the shading effects of buildings and trees located on the sidewalk. Temperature begins to drop rapidly around 4:00 PM in both sites. However, after about one hour, the temperature drop in the urban canyon slows down, but it continues to cool steadily throughout the night until warming takes place in the morning. Conversely, the surface temperature in the open field drops rapidly (~ 9 ^{o}C/hour) until it reaches a state with a very low cooling rate (~ 0.17 ^{o}C/hour)) that lasts until morning. The nocturnal temperature difference between these two sites, which are located only 1.3 km apart, was on the average ~ 7 ^{o}C, and this disparity clearly points to the urban heat island effect.

Different surface properties as well as shading effects have an influence on the air temperature as well. Figure 2a shows air temperature at 8.5 m for the two sites for a period of 11 days and figure 2b gives the temperature difference between these two sites. During the daytime, the air temperature is lower inside the urban canyon due to the shading effect of tall buildings while during the nighttime it is higher due to heat emitted by buildings and other anthropogenic heat sources (e.g. heat from the buildings).

Figure 3 shows a time series of 30-min. averaged wind direction for a two day period. In most of the days, between early morning to early afternoon, the winds inside the canyon were westerly while during the other periods the winds were coming from the east. There were periods where the wind direction was persistently from the west or east for a period of 48 hours or more. This behavior can be attributed to the

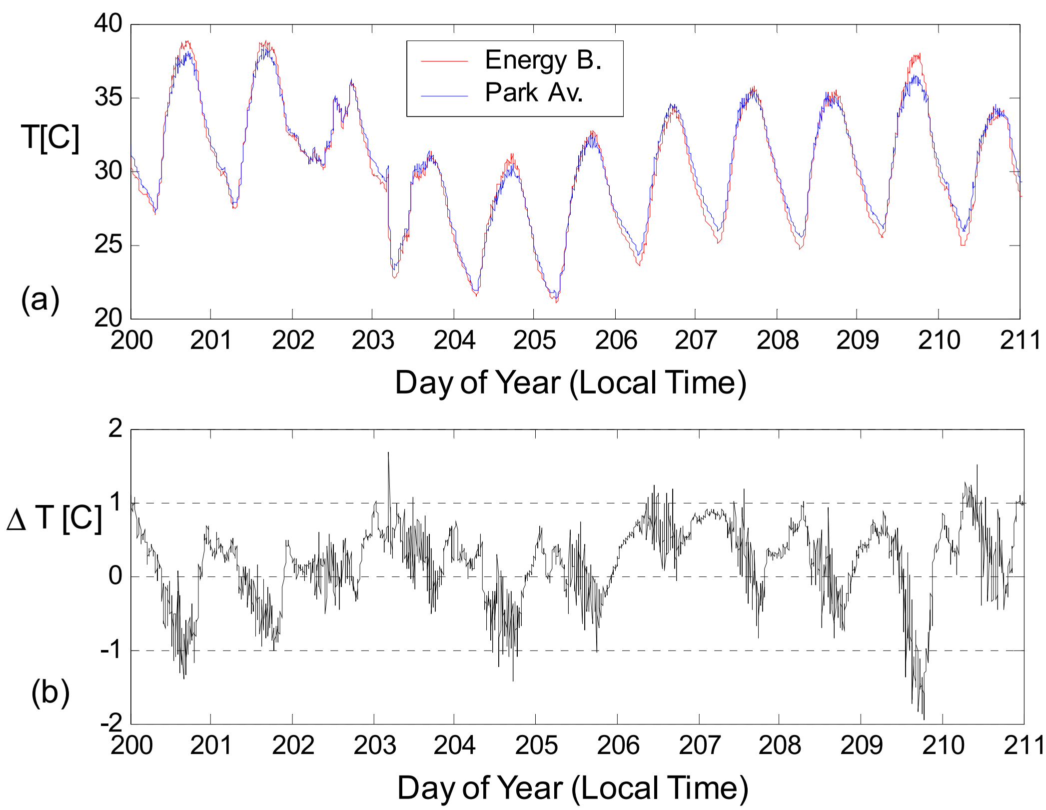

Figure 2. (a) Air temperatures at 8.5m measured in the street canyon and in an open grassy field (b) The temperature difference between the two locations.

* January 1st at 0:00 (midnight December 31st) is 0.0 Day of Year. This means that January 1st at noon is 0.5 DofY.

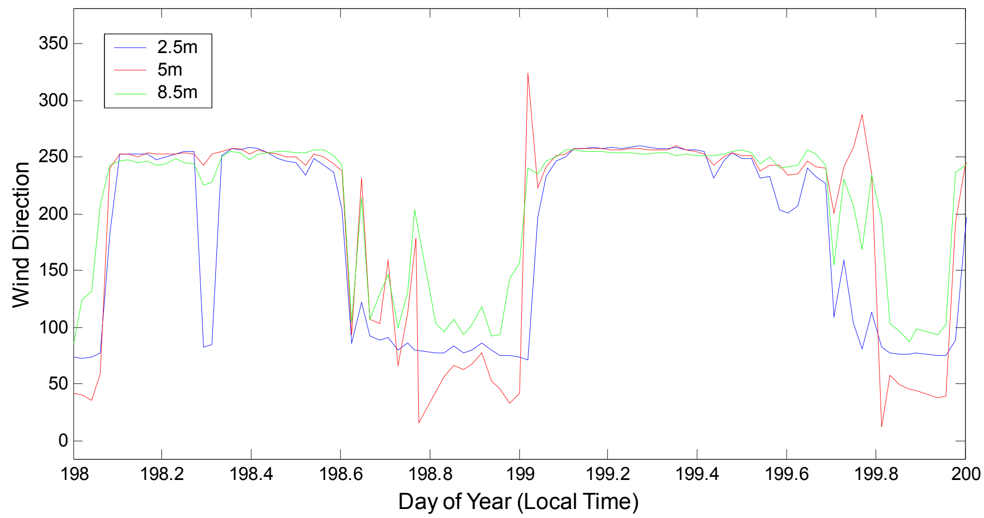

Figure 3. Time series of wind direction measured in street canyon.

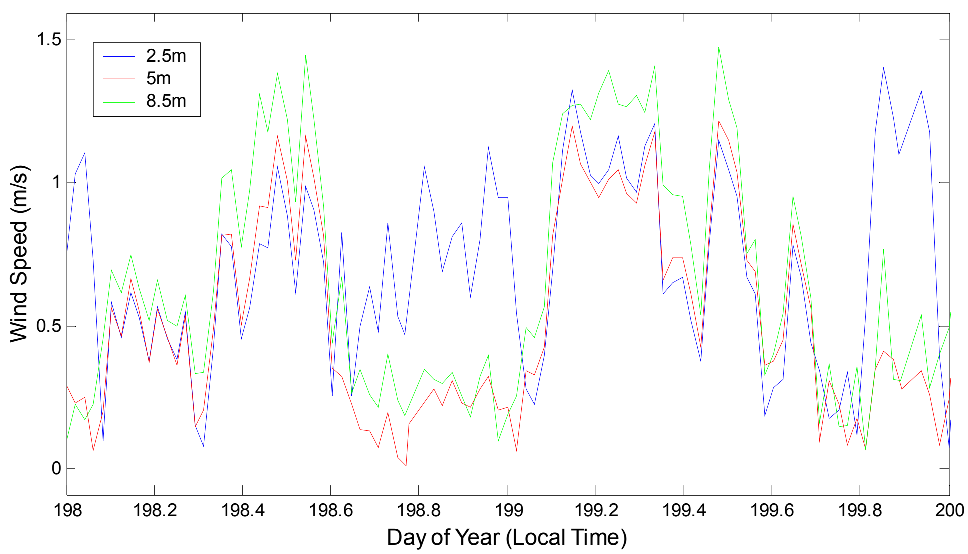

Figure 4. Time series of wind speed measured in the street canyon.

slow change of large-scale wind forcing and the constrained nature of the flow due to the east-west oriented urban canyon. Also, wind direction fluctuations are much stronger for winds coming from the east than from the west, which is a consequence of the tower location. The west end of the urban canyon is approximately 130 m away from the tower and the flow in between is smoothly channeled, but for easterly winds the flow arrives at the tower upon traveling only 20 m from a street intersection. Sudden shift of wind direction at the lowest sonic at 198.3 occurs at the same time as a significant drop in wind speed. Due to the low speed of the incoming wind at this time, local perturbations caused by traffic might have dominated air motion and corresponding directional shift during this period.

Wind speed profiles show that the wind speed in the middle sonic (located 5 m agl) is often lower than the other two sonics, which can be explained as an influence of a tree canopy located very close to the tower at this level. The wind speed is characterized by large fluctuations (Figure 4), which are expected to be due to the traffic and presence of buildings and vegetation. Analysis of 5, 30 and 60 minutes average velocity profiles shows that wind speed at the highest sonic is not necessarily higher than at the lowest ones, and especially during the evening the wind speed at the lowest sonic recorded a higher speed than the highest sonic. Nonetheless, the highest sonic measured the highest turbulent kinetic energy most of the time. Smaller wind speeds at higher levels were also observed in the middle of the urban canyon for certain periods (Oklahoma University tower, see Brown et. al. 2004). Some interesting flow features were detected on the southern side in the middle of the urban canyon during 15.00-16.30 (local time), where it was observed a shift of wind direction by 180 degrees slightly above 8 m, wherein the wind speed is close to zero. All these observations point to the immense complexity of flow field inside a typical urban canyon. To obtain a better picture of the flow field in the Park Avenue urban canyon, it is necessary to simultaneously consider wind speed and direction from all sensors located therein.

The ASU LiDAR deployed in JU 2003 was used to collect data on the “inflow” boundary condition in the urban core, with the intention of capturing eventual coherent structures. Dominant winds during JU 2003 were southerly/southeasterly and the LiDAR site was toward south-southeast from the CBD. LiDAR measurements allowed upstream identification of features embedded in the boundary layer, for example, a microfront or an advecting microburst-like feature (Princevac et al. 2004). Figure 5 shows a RHI plot of the ASU Doppler LiDAR data, showing alternating regions of high and low speed wind at the inflow toward the CBD. A plume-like structure of higher velocity (radial) fluid emanating over the CBD can be seen here. Another interesting interpretation would be due to the deflection of flow by CBD. This type of feature identification provides deeper insight on the flow around and approaching the urban core. For example, does the major acceleration occur above the urban core (roof level) or to the sides of it? Additionally, these identifications have to be correlated with the atmospheric stability conditions and other parameters such as sub-urban (entrance) roughness and urban canopy height. Note that the laser beam impacts a building on the lower part of the scan at approximately 3.8 kilometers.

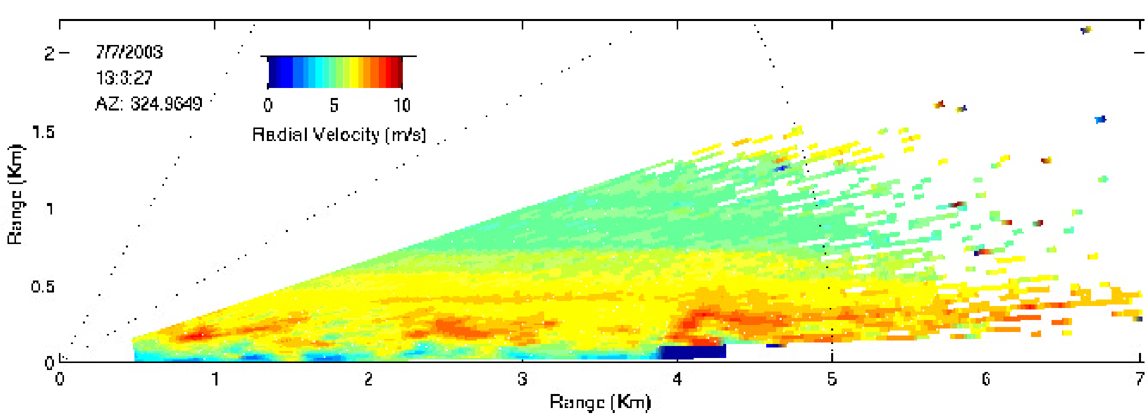

Figure 5. RHI (azimuth fixed at 324.96°, elevation changes from 0 to 20°) LiDAR scan towards CBD

4. CONCLUSIONS

The JU 2003 field campaign provided a good opportunity for many researchers to study flow and dispersion in urban areas on realistic scales. ASU-EFD team collected a large set of data that is being thoroughly analyzed and compared with laboratory and modeling results. Preliminary analyses show that the nature of the local site has a significant influence on flow and its stability. Larger heat capacity of urban surfaces and anthropogenic heat fluxes cause the city surface to be much warmer than the suburban landscape located just 1.3 km away. The levels of turbulence and wind speed and direction are strongly influenced by presence of vegetation and traffic, and their variation within the urban canyon is pronounced. Data from different research groups have recently become available, and a detailed study of canyon flow field is currently underway.

5. REFERENCES

Allwine K.J., M. J. Leach, L. W. Stockham, J. S. Shinn, R. P. Hosker, J. F. Bowers, and J. C. Pace 2004: Overview of Joint Urban 2003 - An atmospheric dispersion study in Oklahoma City, *84th Annual Meeting American Meteorological Society meeting*, Seattle, WA, Amer. Meteor. Soc. J7.1

Brown M.J. 2000: Urban parameterizations for mesoscale meteorological models, Chapter 5 in *Mesoscale Atmospheric dispersion*, Z Boybeyi, Eds, WIT Press, Ashurst Lodge, Ashurst, Southhampton S0407AA UK, pp 193

Brown M.J., D. Boswell, G. Streit, M. Nelson, T. McPherson, T. Hilton, E. R. Pardyjak, S. Pol, P. Ramamurthy, B. Hansen, P. Kastner-Klein, J. Clark, A. Moore, D. Walker, N. Felton, D. Strickland, D. Brook, M. Princevac, D. Zajic, R. Wayson, J. MacDonald, G. Fleming, and D. Storwold, 2004: Joint Urban 2003 Street Canyon Experiment, *84th Annual Meeting American Meteorological Society meeting*, Seattle, WA, Amer. Meteor. Soc. J7.3

Hussain M. and B.E. Lee 1980: A wind tunnel study of the mean pressure forces acting on large groups of low-rise buildings, *J Wind. Eng. Indust. Aero.*, 6, 207-225.

Princevac M., R.J. Calhoun and H.J.S. Fernando 2004: Doppler-Lidar deployment during JU 2003 experiment, XXI *International Congress of Theoretical and Applied Mechanics*, August 2004, Warsaw, Poland, EU.