Mean and turbulent characteristics of the boundary layer under neutral and unstable conditions

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ABSTRACT

Prediction and visualisation of wind flow and pollutant dispersion in urban, densely built areas is necessary for city planners and engineers in order to regulate and monitor successfully the local air quality. Wind vortices, low pressure zones and channelling effects may affect the ventilation characteristics of street canyons under different meteorological conditions. In this respect physical and mathematical models are employed which are able to provide insight into passive cooling techniques for buildings located in densely built up areas. Experiments in a wind tunnel can be easily and quickly carried out since parameters such as the wind field and temperature can be controlled as opposed to field experiments. The purpose of the present work is to study the mean and turbulent characteristics of the two dimensional flow field developed under neutral and unstable stratification conditions, within and above an urban street canyon.

1. INTRODUCTION

The study of the effects of stability on flow in the atmospheric boundary layer is one of the most important topics of wind flow and urban dispersion research. Thermal stratification plays a major role in the wind flow and dispersion characteristics within the atmospheric boundary layer.

Wind tunnels have been used for many years in the study of pollutant dispersion and the wind field, but the large majority of these studies have been conducted under neutrally stratified conditions since stable or unstable boundary layer flows are both difficult and expensive to create. Oke, 1987 was one of the first to perform a systematic study of wind field characteristics between buildings forming street canyons along with the flow patterns established for different spacing. Jeong et al. 2002, added more data to this work. A large number of flow and tracer two-dimensional experiments have been performed for neutral conditions around single or clusters of buildings (Lee et al., 1991, Kastner-Klein et al., 2001). For two buildings the basic understanding of the flow in the urban street canyon has been obtained through tracer dispersion and smoke visualization experiments.

All wind tunnel experiments confirmed the presence of a large recirculating vortex within the urban canyon. A vertical upward and downward draught is observed on either sides of the street canyon. The wind speed is minimum in the middle of the street canyon. The vortex strength and flow orientation depends on the building height (Pearce et al., 1999, Garcia Sagrado et al., 2002, Chang, 2003) and affects the pollutant dispersion in the canyon (Hoydysh et al., 1988, Gerdes et al., 1998). The nature of the flow between two buildings of equal height is determined by the ratio of the width between buildings (W) to the building height (H) (Hussain et al., 1980). There is also a weak dependence on the cross-sectional length of the buildings. Smoke visualization studies showed that rooftop recirculation zones do not form on a series of buildings of equal height, except for the one furthest upstream (Meroney et al., 1996). Rafailidis et al., 1997 measured the flow above a series of street canyons and investigated the effects of the street width and the shapes of roofs on buildings around the street canyon. An extensive data base of two dimensional and three dimensional experiments is currently available from the University of Hamburg mainly for model validation purposes, (http://www.mi.uni-hamburg.de/EWTL-Homepage.315.0.html).

Mathematical models were also used to study the pollutant dispersion within different street canyon configurations and building height scenarios (Assimakopoulos et al., 2003, Xia et al., 2000). A comparison of computational results and field data showed that the wind field in urban areas is quite complex, presenting areas of very low wind speeds and convergence of vortices (Assimakopoulos et al., 2006). The influence of different roof shapes and ambient building structures on the wind field and the pollutant dispersion were also studied numerically (Xie et al., 2005).

Very few systematic studies have dealt with the effect of stability on flow and dispersion in urban areas, which is considered significant. A novel arrangement to simulate stably stratified atmospheric boundary layer flows in an empty wind tunnel using distributed electrical heaters is described by Grainger et al., 1994. The influence of thermal stratification on the size of the cavity wake length of a two dimensional fence was studied in a wind tunnel experiment (Ogawa et al., 1980). The cavity wake length decreases slightly as the thermal stability becomes more unstable in the wind tunnel. The effects of neutral, strongly unstable and strongly stable stabilities on the two dimensional flow in a single street canyon were also examined (Ogawa et al., 1981). Visualization by smoke tracer showed that in the stable case, the turbulence is damped near the canyon floor while for the unstable case large convective eddy motion is observed. The effects of stable stratification on the spread of a plume from a small ground level release in an empty wind tunnel were also examined (Ogawa et al., 1985). The wind tunnel test section surface was smooth and stability was changed by changing the temperature difference between the ambient air temperature and surface floor temperature. With increasing stability the flow field visualization showed that the turbulence was suppressed and the vertical plume spread was inhibited. A novel experiment for the study of the flow field and temperature within and above a single street canyon under stable and unstable conditions was conducted (Uehara et al., 2000) with the use of a Laser Doppler Anemometry along with a cold wire. Cavity eddies that arose in the street canyon tended to be weak when the atmosphere was stable and strong when unstable. When stability exceeded a certain threshold the wind speed in the street canyon dropped nearly to zero. However, the influence of adding buildings upwind and downwind the street canyon and altering the aspect ratio on the wind flow and the pollutant dispersion under different stability conditions has not yet been examined.

Within that frame the purpose of the present work is to study the characteristics of the flow field developed within and above urban street canyons, under neutral and unstable stratification conditions, with the aid of a wind tunnel in a two dimensional experimental set up.

2. EXPERIMENTAL SET-UP

The experiments took place in the neutrally stratified open circuit wind tunnel of the Department of Environmental Physics and Meteorology, University of Athens. The test section of the wind tunnel is 1.2 m long, 0.4 m wide and 0.23 m high. The wind tunnel is used primarily to simulate neutral flows.

Two cases were studied: (a) in the empty wind tunnel buildings with the same height H=20 mm were gradually placed in the test section spanning the width of the test section at equal distances, keeping the aspect ratio of building height (H) to canyon width (W) constant and equal to one, W/H=1. A total number of seven buildings forming six street canyons perpendicular to the flow were considered.

(b) The atmospheric boundary layer is generated with the use of a barrier, vortex generators and roughness elements placed in a staggered pattern (fig. 1). Downwind the elements the buildings were added gradually in the same way as in the first case.

The unstable conditions were simulated with the use of a copper floor which replaces the existing wind tunnel floor. The floor is equipped with a spiral like tube with hot water flowing constantly in order to achieve heating of the air giving rise to unstable stratification conditions.

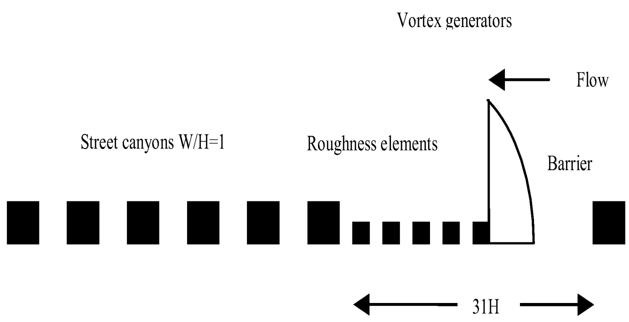

Figure 1. Experimental set up.

The mean wind velocities were measured with the use of a pitot static tube. The equipment was adjusted on a traverse system which can be placed in several horizontal and vertical positions. Vertical wind profiles upwind, above and downwind the buildings were taken at 1 mm intervals. The boundary layer thickness δ can be defined as the vertical location where the velocity is the 99% of the free stream velocity.

In the empty wind tunnel the forward face of the first building was located 700 mm from the entrance of the test section. All the measurements were made with a free stream velocity 3.1 m/sec. The Reynolds number based on the height of the building and the free stream velocity was above the critical value of 4000. A boundary layer 8 mm thick (δ/H=0.4) is developed in this distance with the use of a sand paper strip at the entrance of the test section which spanned the width of the tunnel.

In the open wind tunnel, in the absence of any model, with a 20 mm high barrier, 120 mm high vortex generators and 12 mm high wooden elements placed on the floor in a regular array following a staggered pattern as shown in figure 1 and for the same free stream velocity (3.1m/sec) the vertical wind profiles were taken at different horizontal positions above and downwind the roughness elements. The simulated boundary layer is about 130 mm thick at the distance (700 mm) were the first building is placed (δ/H=6.5). The vertical velocity distribution in this region can be described by a power law,

$$\frac{U(z)}{U_{ref}} = \left(\frac{z}{z_{ref}} \right)^{\alpha} \qquad (1)$$

where:
U(z): the mean velocity at elevation z,
U_{ref} : the mean velocity at the reference height z_{ref} .

The roughness length z_0, determined from a logarithmic profile above the floor was about 1.5 mm. The power law exponent α was estimated to 0.30. This arrangement corresponds to a simulation of the atmospheric surface layer at a scale of about 1: 500. Downwind the roughness elements buildings were placed gradually spanning the width of the test section simulating an urban environment. Wind velocity profiles were taken above and downwind the buildings and street canyons.

3. EXPERIMENTAL RESULTS

3.1 Neutral conditions

In the empty wind tunnel a boundary layer is developing right from the beginning of the test section floor. The boundary layer thickness δ is increasing with the distance. More specifically the boundary layer thickness at a distance of

400 mm from the entrance of the test section is 7 mm and reaches the value of 10 mm at a distance of 850 mm downwind the entrance.

A new boundary layer is developed with the addition of buildings. Figure 2 shows the normalized velocity profiles above the buildings placed in a boundary layer with thickness δ=8 mm. The wind speed is increasing rapidly above the obstacles due to convergence of the streamlines. This acceleration remains until the third building is added downwind as shown in figure 2. The wind speed is 1.12 times greater than the reference velocity above the first building, while for the second building the velocity is 1.04 greater. Downwind the first building an internal boundary layer is forming and the wind speed is decreasing. The wind profiles are similar for the last four buildings and the boundary layer is fully developed.

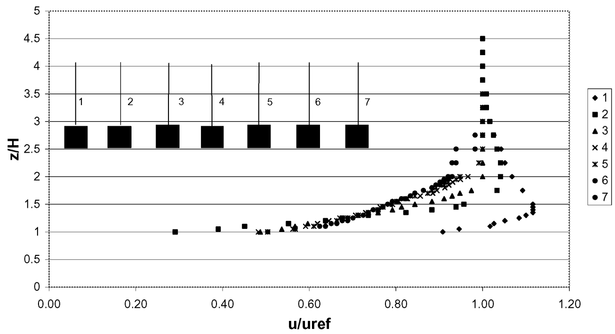

Figure 2. Wind profiles above the buildings (δ/H=0.4).

Figure 3 shows the normalized velocity profiles above the seven buildings placed in a thick boundary layer formed with the use of vortex generators and roughness elements. Since the buildings are placed within the fully developed boundary layer (δ/H=6.5) no acceleration of the wind speed is now observed above them (fig. 3). The velocity increases slightly with height reaching the value of the reference velocity. Downwind the first building the wind velocity decreases forming an internal boundary layer but maintains a profile characteristic of the upwind roughness.

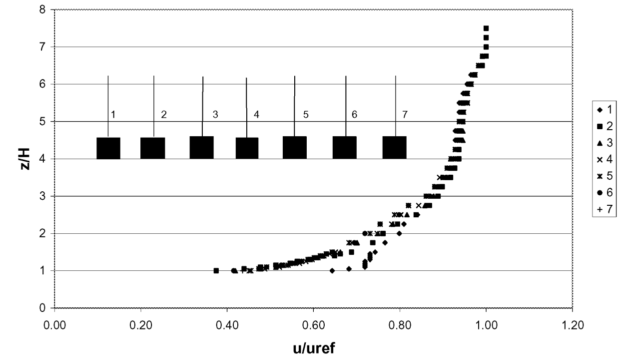

Figure 3. Wind profiles above the buildings (δ/H=6.5).

Figure 4 depicts the normalized velocity profiles downwind the roughness elements and downwind the buildings at the same longitudinal distance from the entrance of the test section (x=1000 mm). Downwind the buildings an internal boundary layer is formed as shown in figure 4. In the internal layer the wind velocity is reduced up to a level z=2.5*H. Above the top of the internal boundary layer the wind maintains a profile characteristic of the upwind roughness.

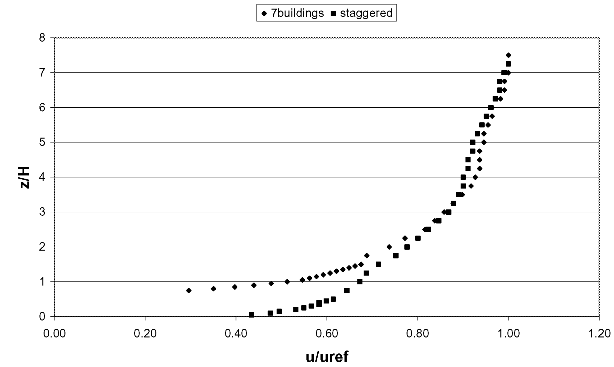

Figure 4. Wind profiles downwind the roughness elements and downwind the buildings.

3.2 Unstable stratification conditions

The same experiments were conducted under unstable stratification conditions. In the empty test section the boundary layer thickness δ is increased compared to the neutral case at all longitudinal positions. The forward face of the first building was located 700 mm from the entrance of the test section. As shown in figure 5 at this location the boundary layer thickness is 20 mm (δ/H=1), 2.5 times greater than in the neutral case.

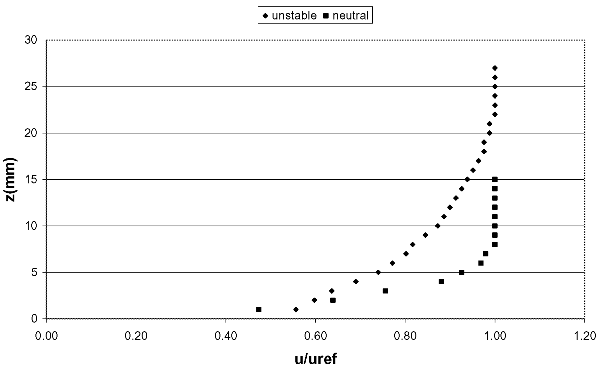

Figure 5. The development of the boundary layer under neutral and unstable stratification conditions at distance x= 700 mm.

Figure 6 shows the normalized velocity profiles above the buildings for the unstable conditions. The wind speed proved to be decreased being compared with the neutral case. The wind velocity increases above the buildings. This acceleration is weaker compared to the neutral case. The wind speed above the first and second building is 1.08 times greater than the reference velocity at a height z=1.5*H and then decreases reaching the reference velocity. An internal boundary layer downwind the first building is forming. The wind velocity decreases above the buildings while the wind profiles remain the same after the third building.

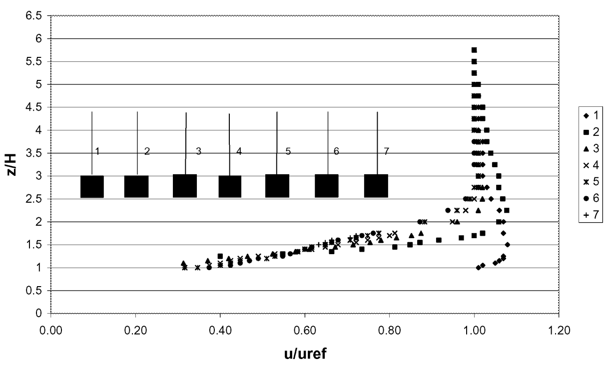

Figure 6. Normalized velocity profiles above the buildings under unstable stratification conditions (δ/H=1).

The normalized velocity profiles above the buildings placed downwind the roughness elements are presented in figure 7. The profiles retain the flow characteristics of the upwind roughness as observed in the neutral case.

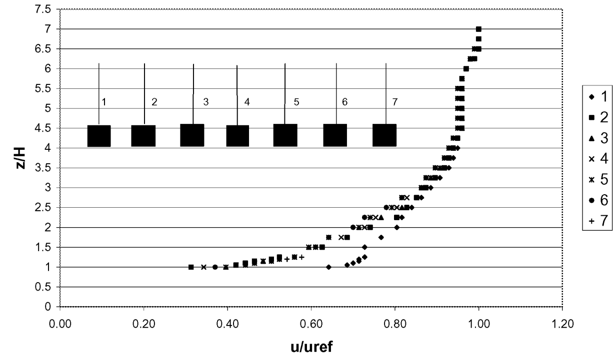

Figure 7. Normalized velocity profiles above the buildings under unstable stratification conditions (δ/H=6.5).

4. CONCLUSIONS

A wind tunnel experiment was conducted in order to study the wind field characteristics above an urban area under neutral and unstable stratification conditions. The buildings were added in the empty test section and in a boundary layer developed with the use of vortex generators and roughness elements.

- In the empty wind tunnel, in the absence of buildings the boundary layer thickness was greater under unstable stratification conditions indicating upward vertical movement of air.
- For the roughness elements case, placement of the buildings did not affect the general characteristics of the boundary layer for both the neutral and the unstable cases.
- For the unstable stratification conditions the temperature gradient may affect the wind velocity in the street canyons and this is an issue of further research.
- An internal boundary layer was formed

downwind the first building which reduces the wind speed above the downwind buildings and canyons.

- Low wind velocities were observed above the canyons for the two stratification cases. Further work is under way in order to identify how unstable and stable stratification conditions affect the wind speed and dispersion characteristics within the urban canopy in order to study implications of the building ventilation characteristics and indoor air quality.

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