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Lateral channeling within rectangular arrays of cubical obstacles

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ABSTRACT

Water channel experiments were conducted with the goal of obtaining better understanding of flows through urban-like arrays of buildings. Particle Image Velocimetry (PIV) was used for comprehensive flow measurements within a modeled simple urban setup. Building arrays were modeled using acrylic blocks whose refractive index is the same as that of salty water. Such a setup allowed for undisturbed laser sheet illumination through the obstacles enabling detailed flow measurements between the obstacles/buildings. Building array size, measurement plane and flow conditions were varied. A novel flow feature, lateral channeling, observed and quantitatively measured, within regular 3×3 and 5×5 arrays of cubes is reported here. A sideways mean outflow from the building array is observed behind the first row of buildings followed by the mean inflow in the lee of all succeeding rows of buildings. When the central building in a 3×3 array is replaced by a building of double height, due to the strong downdraft caused by this tall building, the lateral outflow becomes significantly more intense. When the central building in a 5×5 array is replaced by a building of double height, the building downdraft blocks the lateral inflow to the array. This is the first time that such detailed measurements are available for a mock urban array of finite size—a real three-dimensional case. The newly identified mean flow pattern may be accountable for the initial plume spread within an array of obstacles.

1. Introduction

Urban areas of the world are experiencing rapid growth which raises concerns of environmental deterioration, degradation of life quality and possibility of a deliberate toxic release. One of the central urban problems is the dynamics of environmental flows, their nature and transport and mixing capabilities (Fernando et al., 2001). Although significant progress has been made on understanding urban flow phenomena, a variety of issues remain to be understood. Most of the past studies on urban flow and dispersion can be classified in several groups: studies on flow above roughness elements, studies related to flows around individual buildings, street canyon flow studies and studies on urban canopy flow as a whole. There are numerous field, laboratory and numerical agriculture-related studies dealing with flows above and inside the vegetative canopy (e.g. Shavit and Brandon, 2001; Takahashi and Hiyama, 2004; Finnigan and Belcher, 2004) which may have similarities with flows inside and above the urban canopy. Some relevant urban oriented studies are given next.

Detailed laboratory experiments with a focus on the flow readjustment to a different surface roughness were conducted by Cheng and Castro (2002a). Using wind-tunnel experiments, Cheng and Castro (2002b) investigated the spatially averaged mean velocity and turbulent stresses above an urban-like surface. This study pointed out some difficulties in applying the fore mentioned results of flows over vegetative canopies to flows above urban canopies.

Hosker (1980) provided a review of studies related to isolated buildings. Extensive investigations of flows around single building and flows in complex scaled city blocks were conducted in a wind tunnel (e.g. Pavageau and Schatzmann, 1999; Schatzmann et al., 2000). Those studies examined the turbulent characteristics of the flows and the statistical properties of concentration fields associated with steady releases at street level. Similar studies were conducted to examine flow and dispersion around scaled model buildings using EPA's fluid modeling facility (Brown et al., 2001).

Some studies of flow and dispersion within the urban canopy have modeled the canopy as a series of urban street canyons. Oke (1987) summarized the nature of this flow in terms of the ratio of the spacing between buildings, S, to the building height, H. Based on past studies conducted in wind tunnels and water flumes, Oke defines three types of flow regimes depending on S/H: isolated roughness flow regime for $S/H > 4$, wake

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interference flow regime for $2<S/H<4$, and the skimming flow regime for $S/H<2$.

Other studies have focused on individual street canyons and street intersections, where complex flow patterns can occur. Kastner-Klein et al. (2001) used a wind tunnel, while Macdonald et al. (2002) used a water flume to study the details of such flows. Yamartino and Wiegand (1986), Gavze et al. (2002), and Rotach et al. (2005) conducted field studies in which turbulence intensities and flow velocities were measured with sonic anemometers, and the associated concentration patterns were studied using tracer releases. Such studies have provided useful insight into urban street canyon flows. In a narrow street canyon ($S/H\sim 1$), a single horizontally aligned in-canyon vortex develops, while a smaller counter-rotating vortex may develop next to it in a wider canyon ($S/H\sim 1.5$). Baik et al. (2000) and Eliasson et al. (2006) tried to elucidate the vertical structure of the flow inside deep canyons ($S/H<0.5$). Different studies have looked at the effect of roof shape and relative building heights on vertical transport and dispersion (e.g. Rafailidis and Schatzmann, 1995; Kastner-Klein et al., 1997; Macdonald et al., 1998). A number of wind tunnel tracer experiments have shown that concentrations for releases in the street canyon are particularly sensitive to the approaching wind direction (Wedding et al., 1977; Hoydysh and Dabberdt, 1988; Kastner-Klein and Plate, 1999). Dabberdt and Hoydysh (1991) found that concentrations within the street canyon vary significantly with block shape (rectangular vs. square) and with the relative width of streets vs. avenues.

The influence of street architecture on the wind and turbulence patterns in street canyons and the associated effects on local air quality were also studied (Kastner-Klein et al., 2004; Kastner-Klein and Rotach, 2004, etc.). The results suggest that small-scale features of the building architecture (e.g. roof) may play an important role in determining canyon flow patterns.

Reduced-scale field experiments and water flumes were used to study the interaction of a tracer plume with the internal boundary layer created over the obstacle array (Macdonald et al., 2000a, b; Macdonald, 2000). Compared to plumes in the open terrain, the plumes in the arrays were typically wider, and the plume width was closely related to the width of the obstacles. It was found that the lateral concentration profiles were Gaussian in all cases when the wind was perpendicular to the obstacle array. However, plumes were deflected along street canyons when the wind direction was not normal to the array.

Yee et al. (2006) compared results from field tracer measurements with corresponding simulations using a water channel and a wind tunnel. They found that the field measurements agree better with the water channel measurements than with the wind tunnel results. The better performance of the water channel might be related to the more precise flow control and conditioning that is possible in the water channel.

Coceal et al. (2006) performed the direct numerical simulations (DNS), while Lien and Yee (2004) deployed the $k-\varepsilon$ model to study flows through regular arrays. Lien et al. (2005) presented the mathematical foundation for modeling the flow within three-dimensional building arrays. Theurer et al. (1996) made the wind tunnel investigation of several hierarchical, idealized, arrangements of buildings to obtain the parameters required in a semi-empirical urban dispersion model. The wind tunnel experiments showed that the influence of individual obstacles becomes negligible at downwind distances larger than the radius of homogenization (ROH). At distances larger than ROH, for the dispersion calculation, buildings can be considered as homogeneous roughness. It should be mentioned that one of the motivations for the present laboratory study was validation and improvements of another semi-empirical model, the Quick Urban and Industrial Complex (QUIC) model. Theurer (1999) proposed a classification scheme for urban environments which consists of nine typical building arrangements. The effect of each building arrangement on local concentration of pollutants was investigated through wind tunnel experiments and numerical modeling. However, due to the complex interactions of the flow and buildings no explicit formula for the concentration in terms of different building parameters was possible.

Several major field measurements related to the urban flows and dispersion were conducted. These field campaigns include the Urban 2000 (Salt Lake City, Utah, Allwine et al. 2002), Mock Urban Setting Test-MUST (Biltoft, 2001), Joint Urban 2003 (JU2003, Oklahoma City, Oklahoma, Allwine et al., 2004), and the New York City Urban Dispersion Program (Allwine and Flaherty, 2006). Similar field measurements were conducted in European cities, e.g. the Basel Urban Boundary Layer Experiment (BUBBLE, Rotach et al., 2005). These campaigns resulted in invaluable data sets but measurements are site specific and due to the complexity of urban morphology it is not trivial to generalize them.

Over the past several years, a group at the University of California at Riverside (UCR) has conducted several tracer studies to understand flow and dispersion in urban areas. In one of them, a model urban area was constructed on the Dugway Proving Ground using meter high drums (Yuan and Venkatram, 2005). Tracer sampling on several arcs within the model canopy was supplemented with turbulence measurements. The study showed that tracer concentrations could be estimated well if flow and turbulence within the canopy were measured. In another study (Venkatram et al., 2005) a tracer was released from the top of a trailer surrounded by buildings. The major finding from this study was that surrounding buildings induce large horizontal fluctuations leading to dispersion that could not be estimated using conventional dispersion models. All studies pointed to the need to understand the details of the interaction of the mean flow with urban morphology.

What is lacking is a systematic study of flow in building clusters of varying complexity. To address this gap we initiated a systematic experimental program in the newly established Laboratory for Environmental Flow Modeling (LEFM) at UCR. As a part of the study, in this communication we present a new mean flow pattern through regular arrays of cubical obstacles in the skimming regime. The laboratory setup and its capabilities are described in Section 2 followed by the experimental results in Section 3. Results are summarized in Section 4.

2. Laboratory setup

A custom-designed circulating water channel, with a test section that is 1.5 m long, 1 m wide and 0.5 m deep (Fig. 1), was utilized for the experiments. Water is circulated through the test section using a 20 HP axial pump, which produces a maximum mean velocity of $0.5\,\mathrm{m\,s^{-1}}$ in the test section. A variable frequency controller allows flow control with a resolution of 1/100 Hz (from 0 to 60 Hz) which corresponds to the mean velocity change resolution of only $0.08\,\mathrm{mm\,s^{-1}}$. Flow conditioning is achieved with the profiled honeycombs and the custom-built perforated screens. The perforated screens are used to generate desired inflow velocity profiles as a part of the flow conditioning. The channel flow is steady and becomes fully developed before reaching the test section.

The LEFM is equipped with the Particle Image Velocimetry (PIV) system for velocity measurements. Detailed velocity field can be measured in the vertical or horizontal plane. PIV measurement technique is well established and widely used for fluid flow investigations (Adrian, 1988, 1991, 1997; Prasad et al., 1992).