3.1 TURBULENCE AND CHANNELING IN A SIMPLE URBAN ENVIRONMENT

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The flow through urban street canyon was simulated in a new water channel at the University of California, Riverside. The influences of the approach angle, flow velocity and building spacing were investigated. The resulting flow velocity field was measured using Particle Image Velocimetry. Two main flow patterns were observed: 1) flow channeling and 2) flow recirculation between the buildings. An attempt was made to establish the criterion for the occurrence of each pattern and to give the physical rationale which determines the resulting flow pattern.

1. INTRODUCTION

Urban boundary layer simulations were performed in the water channel at the University of California, Riverside (UCR), in the Laboratory for Environmental Flow Modeling (LEFM). A re-circulating water channel was utilized to create controlled flow field to model wind flows through simple mock urban environments. In particular, channeling effects in a two parallel building setup were studied (see Figure 1 for schematic). Motivation for this study was to understand simple interactions between urban elements. By hierarchically and systematically increasing the complexity of our mock urban settings we are building a fundamental knowledge much needed for the accurate dispersion modeling of the bio/chemical release and pollution in a full size urban environment.

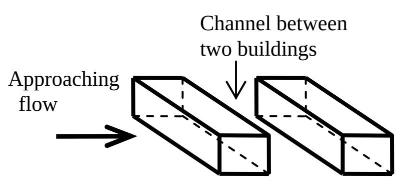

Figure 1. Schematic of two buildings and the approaching flow

2. RELATED PAST WORK

More recent 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), Rotach (2002); and Gavze *et al.* (2002) conducted field studies in which turbulent 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 ($H/S_L > 1$, H being the building height and S_L being the street width), a single vertically rotating horizontally-aligned in-canyon vortex develops, while a smaller counter-rotating vortex may develop next to the larger in-canyon vortex in a wider canyon ($H/S_L \sim 2/3$). Recent experiments (Baik *et al.* 2000; Eliasson *et al.* 2004) have tried to elucidate the vertical structure of the flow inside deep canyons ($H/S_L > 2$). Other studies have looked at the effect of roof shape and relative building heights on vertical transport and dispersion (e.g. Rafailidis and Shatzmann, 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 inflow wind direction (Wedding *et. al.* 1977; Hoydysh and Dabberdt, 1988; Kastner-Klein and Plate, 1999). Dabberdt and Hoydysh (1991) also found that concentrations within the street canyon vary significantly with block shape (rectangular vs. square) and with the relative width of street versus avenues.

Petra Kastner-Klein and co-workers have studied (Kastner-Klein *et al.* 2004, Kastner-Klein and Rotach 2004, etc.) the influence of street architecture on the wind and turbulence patterns in street canyons, and the associated effects on local air quality. Their results suggest that small-scale features of the building architecture (e.g. roof) may play an important role on large scale canyon flow patterns.

Schatzmann's wind-tunnel group at Hamburg (Schatzmann *et al.* 2000, Pavageau and Schatzmann 1999, etc.) has conducted extensive investigations of flows around single buildings, and flows in complex scaled city blocks. They measured the turbulent characteristics of the flows and statistical properties of concentration fields associated with steady releases at street level. They have also examined the dispersion of car exhaust in urban street canyons and pollutant emissions from underground parking garages. EPA's Fluid Modeling Facility (Research Triangle Park, NC) has conducted similar studies to examine flow and dispersion around buildings in selected US cities using scaled models (Brown *et al.* 2001).

Macdonald and co-workers (Macdonald *et al.* 2000a & b, Macdonald 2000, etc.) have used reduced-scale field experiments and water flumes to study the interaction of a tracer plume with the internal boundary layer created over the obstacle array. 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.

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In our newly initiated study at UCR's LEFM we are implementing a hierarchical approach starting from a simple model configuration whose complexity gradually increases.

3. EXPERIMENTAL SETUP

The water channel at the University of California, Riverside is a 6 m long re-circulating channel with a 1 m x 0.5 m test section. Two 0.5 m thick flow conditioners, in the form of honeycombs, placed at the entrance to the channel prevent the flow recirculation and reduce the turbulence level. The perforated screens are used for adjusting the flow to the desired logarithmic profile. The axial pump (Carry Manufacturing, Inc., 15HP, 8" in diameter) drives the flow from the settling tanks. Figure 2 gives the photo and schematic of the water channel.

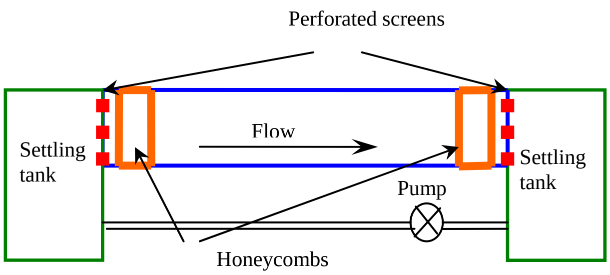

Figure 2a. Water channel schematic

Figure 2b. Water channel

The pump can produce a maximum mean velocity of 0.5 m/s in the test section. A variable frequency controller (AC Tech 20HP) allows pump control with a resolution of 1/100 Hz which corresponds to the mean velocity change of 0.1 mm/s. The water channel details and some examples of the dye flow visualizations can be seen at www.engr.ucr.edu/~marko.

For velocity measurements TSI's Particle Image Velocimetry (PIV) system was used. The PIV system includes a 400 mJ Nd-YAG laser (Big Sky Laser Technologies, Inc), a LASERPULSE Synchronizer (TSI Inc.), and a PowerView Plus 2M camera with CameraLink frame grabber (TSI Inc.). Particles used to seed the channel were Pliolite Ultra 100 (Eliokem). To make the particle (whose specific gravity is 1.02) neutrally buoyant food grade salt (Morton Culinox 999) was added to the tank. In addition to increasing the density, the salt brings the refractive index of the water as close as possible to the refractive index (Aly and Esmail, 1993) of the acrylic used to construct the model buildings. Insight 3G (TSI Inc.) software was utilized for data collection and TecPlot (Tecplot, Inc.) was used for the velocity vector field visualizations.

Building configurations simulating simple urban patterns were accomplished using highly polished acrylic models to minimize effects of refraction and attenuation of the laser sheet utilized for the PIV measurements. Using a simple two building configuration (see Figure 1 for the schematic) the effects of channeling were studied and distribution of the turbulent kinetic energy was measured. Flow velocity was varied from 2 cm/s to 10 cm/s, corresponding to Reynolds Numbers from 2,000 to 10,000. Flow approach angle was 1, 3, 5 and 7 degrees and the investigated ratios of street width to the building heights were 0.5, 1 and 1.5. By utilizing the PIV system (see Figure 3 for the schematic), resultant flow fields were measured over a period of up to 5 minutes. The occurrence of flow channeling vs. flow recirculation (Figure 4) was observed throughout experimentation. The criteria for channeling occurrence in this two building configuration was established.

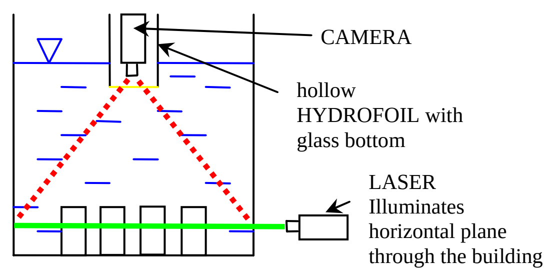

Figure 3. Schematic of the laser and camera configuration for the PIV measurements in the horizontal plane.

For each building separation (0.5H, 1H and 1.5H) the approach flow angle α was varied starting from 1 degrees. For each approach angle the approaching velocity was gradually increased until the channeling became evident. Flow images were collected at 2 frames per second (1Hz capture rate), the laser pulse delay was set to best resolve the flow velocity (ranging from 7000 to 15000 μs for flows between 2cm/s to 10cm/s), and the camera exposure set to 260 μs. The buildings were each 5cm deep, 20 cm wide, and 10cm tall. Spacing between buildings for each experiment was 5, 10, and 15 cm.

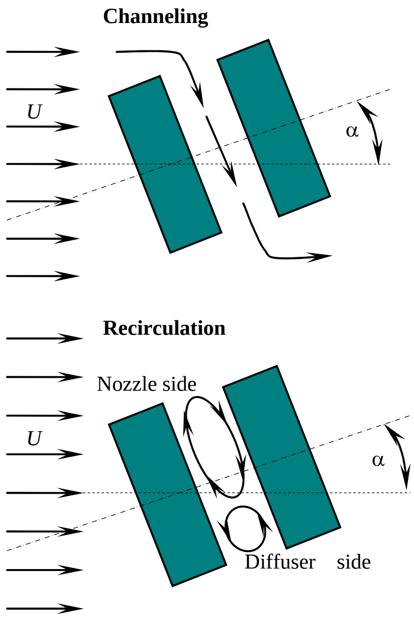

Figure 4. Two observed basic flow regimes within the urban canyon (Top view is given): channeling and flow recirculation. Variations of these basic flows are observed as described in Section 4. This figure serves as a definition diagram for the flow approach angle α, nozzle side and diffuser side of the setup.

4. EXPERIMENTAL RESULTS

For the qualification of different flow regimes we used the mean flow pattern together with the distribution of turbulent kinetic energy (TKE) calculated as

$$TKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right), \qquad (1)$$

where *u'* and *v'* are velocity fluctuations in x (along the mean flow) and y (perpendicular to the mean flow) direction, respectively.

For convenience, the building side where to the approach angle causes flow to decelerate and separate we will refer as a *diffuser side*, and the other side where the flow is accelerating we will refer as a *nozzle side*. See Figure 4 for schematic.

In each experiment flow followed one of the four distinct patterns: 1) no channeling, 2) partial flushing, 3) full flushing, and 4) recirculation. See Figure 5 for the schematic of each flow and the corresponding turbulence modifications in the flow. Each regime is discussed bellow.

4.1. No Channeling

This flow pattern occurs when the boundary layer at the nozzle side of the lead building grows enough to displace the flow past the leading edge of the second building ("skimming"). Although channeling does not occur, the minor flow on the leading edge of the second building may "leak" into the channel.

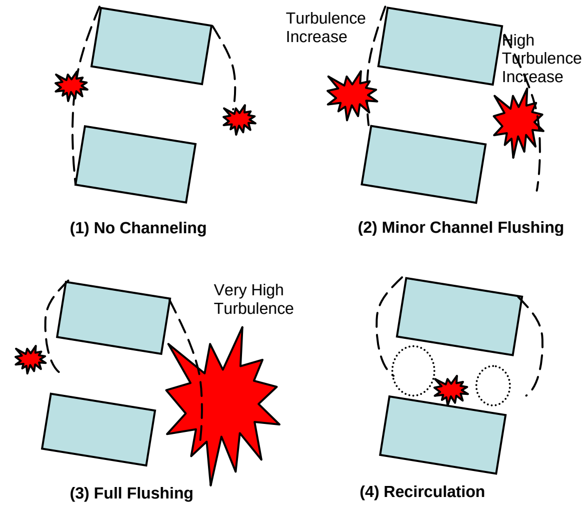

Figure 5. Observed flow types. Dashed line represents the boundary layer development. Doted line represent major vortex. Red marks represent the regions of increased turbulence. The size of red marks is proportional to the relative increase in turbulence with respect to the free stream. See text for details.

Despite the possible "leak" into the channel", the channeling is not present since the leaked fluid does not carry through the channel, but rather drives a very weak recirculation at the nozzle side of the channel. There is no significant flow on the diffuser side of the channel except the local recirculation caused by the boundary layer growth. The clear distinction between "skimming" and "leaking" regime exists, however once fluid penetrates the street there is no clear cut between the regimes (2) and (3) on Figure 5. This regime is typical for small approach angles, low velocities and small street width. Figure 6 gives the typical no channeling regime observed at the mean approach velocity of 1.5 cm/s, approach angle 1^{o}, and building spacing of 0.5H.

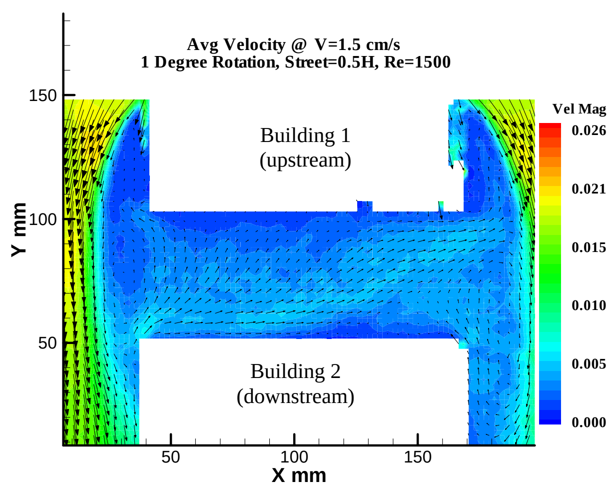

Figure 6a. No channeling regime observed at the mean approach velocity of 1.5 cm/s, approach angle 1^{o}, and building spacing of 0.5H - mean flow pattern.

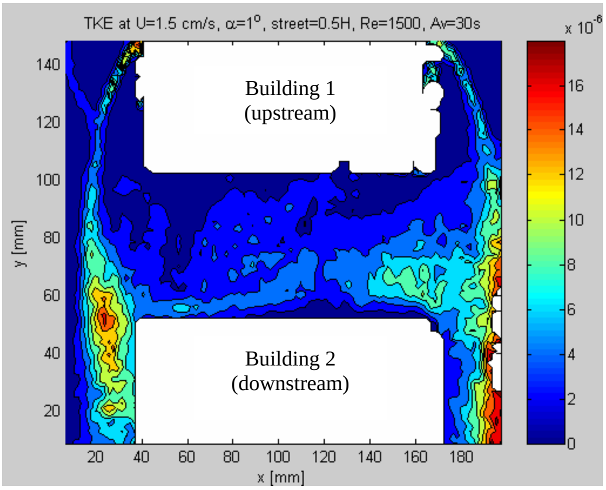

Figure 6b. No channeling regime observed at the mean approach velocity of 1.5 cm/s, approach angle 1°, and building spacing of 0.5H - TKE distribution.

4.2. Channeling - Channel Flushing

The flow deflected by the first building may not skim the second building (see Figure 5(2)). If this happens the deflected flow will impinge the leading edge of the second building and it will be directed in the street. This flow can lead to different types of recirculation between the building depending on the relative width of this flow with respect to the street width. Typically, this flow enters the channel at the leading edge of the second building, travels along the second building until it is being sucked by the low pressure at the trailing edge of the first building where it exits the channel at the diffuser side,mixing with the incoming flow. Figure 7 gives the typical minor flushing regime observed at the mean approach velocity of 5.1 cm/s, approach angle 3°, and building spacing of 0.5H.

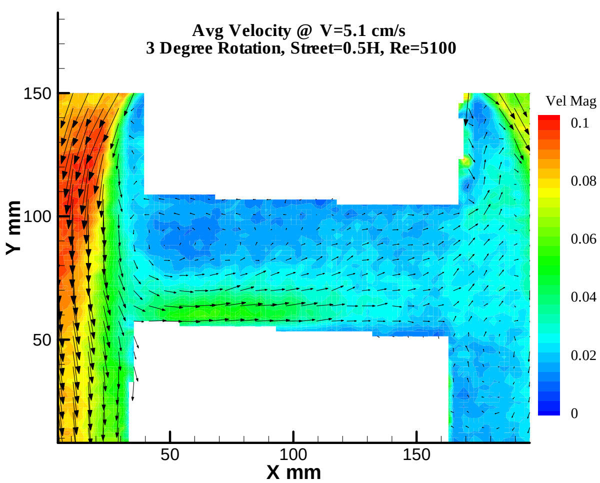

Figure 7a. Minor flushing regime observed at the mean approach velocity of 5.1 cm/s, approach angle 3°, and building spacing of 0.5H - mean flow pattern

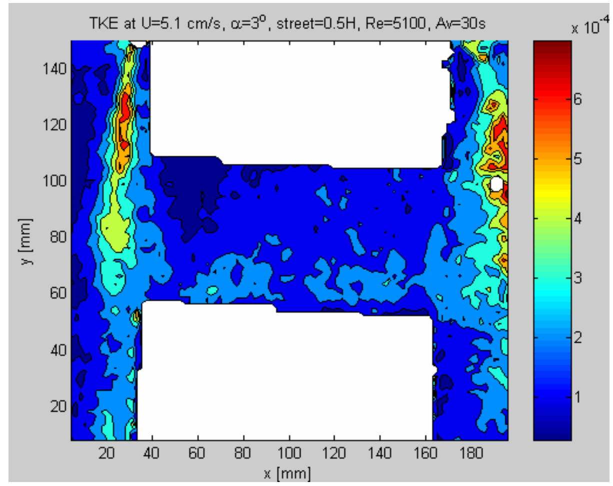

Figure 7b. Minor flushing regime observed at the mean approach velocity of 5.1 cm/s, approach angle 3°, and building spacing of 0.5H - TKE distribution.

If the mean flow within the channel intensifies enough it will lead to the full flushing. In the full flushing regime the flow within the channel follows the leading edge of the second building throughout the whole length or may separate from it, but will not reach the trailing edge of the first building. At the channel exit, this flow mixes with the flow on the diffuser side causing major turbulence increase (see Figure 5(3)). The full street flushing can already be observed at the street width of 0.5H, approaching velocity 4 cm/s, and approach angle of 3°. Increasing the velocity and angle intensifies this effect. For the approach angles smaller than 7°, increase of velocity will lead to the interruption of flushing and formation of recirculating regime. For the approach angles larger that 7°, full flushing will persist for all velocities and building separations. Figure 8 gives the typical full flushing regime observed at the mean approach velocity of 1.5 cm/s, approach angle 5°, and building spacing of 1.5H.

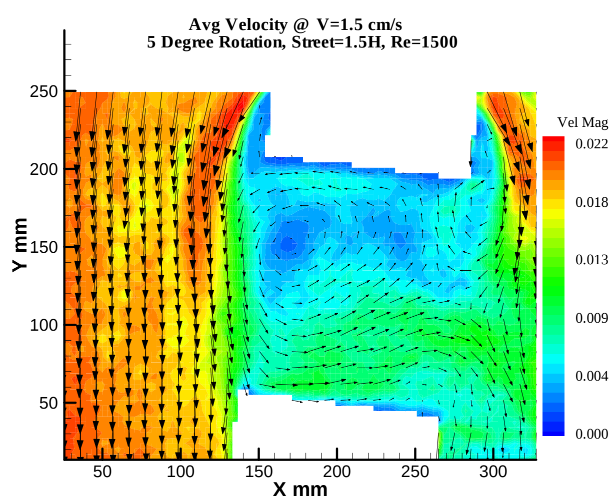

Figure 8a. Full flushing regime observed at the mean approach velocity of 1.5 cm/s, approach angle 5°, and building spacing of 1.5H - mean flow pattern

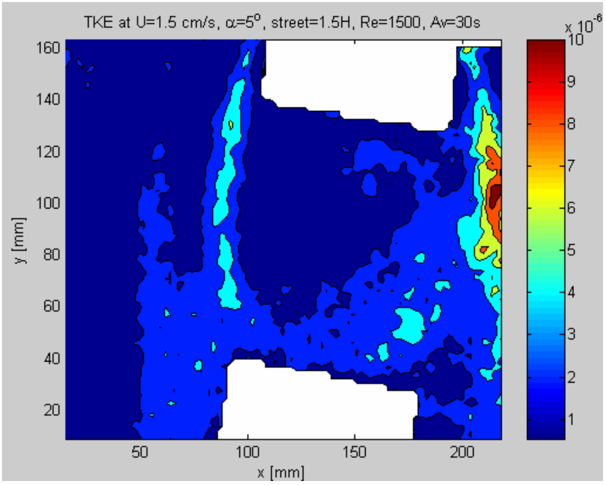

Figure 8b. Full flushing regime observed at the mean approach velocity of 1.5 cm/s, approach angle 5°, and building spacing of 1.5H - TKE distribution.

4.3. Speed Driven Recirculation Regime

Speed up from full flushing can lead to recirculation (see Figure 5(4)). Increased velocity produces two competing tendencies – pressure drop in the leading building wake which is preferable for the recirculation occurrence and the increased momentum at the channel entrance preferable to full flushing. At a certain point, any increase in speed causes channeling to halt. Here, the blocking effects of the second building is not enough to cause channeling in the wake of the first building. Figure 9 gives the typical recirculation regime caused by the high velocity and driven by the high pressure drop in the building wake. This is observed at the mean approach velocity of 3.7 cm/s, approach angle 5°, and building spacing of 1.5H.

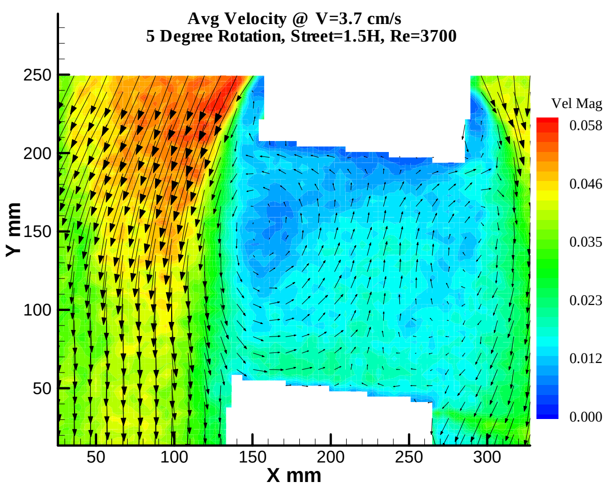

Figure 9a. Recirculation regime observed at the mean approach velocity of 3.7 cm/s, approach angle 5°, and building spacing of 1.5H - mean flow pattern

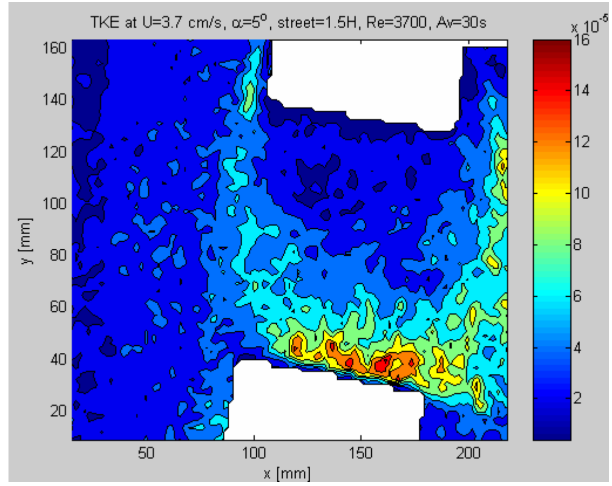

Figure 9b. Recirculation regime observed at the mean approach velocity of 3.7 cm/s, approach angle 5°, and building spacing of 1.5H - TKE distribution.

The major turbulence increase in this regime occurs at the leading edge of the second building where two opposing vortices meet (Figure 9b).

5. SUMMARY

The systematical and hierarchical laboratory modeling of the urban flows is initiated at the University of California, Riverside, in the Laboratory for Environmental Flow Modeling (http://www.engr.ucr.edu/~marko). As a first step in this long-term study the interaction of two simple buildings was investigated. Resulting flow interactions were categorized based on the mean flow pattern and turbulence distribution. It was found that when the flow approach angle is greater than the critical value of ~7° the flow velocity no longer affects the channeling occurrence and channeling is always observed for all street widths. In future experiments, critical approach angle will be precisely defined by refining the angle step size for each street width. For the approach angles smaller than ~7° the channeling occurrence is a function of the incoming flow velocity and building spacing. Once the flow velocity reaches a critical value the channeling will occur. Further increase of velocity will eventually halt channeling and replace it with a strong recirculation within the street. The parameterization of resulting flows and turbulence with respect to the geometry and incoming flow and development of dimensionless criteria which can be scaled for the use in the real urban environment is currently under the development.

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