12.1 # Evaluation of the QUIC-URB Wind Model using Wind Tunnel Data for Step-Up Street Canyons

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1. INTRODUCTION

The possibility of accidental or deliberate release of contaminants in urban areas has been the driving force behind pursuing fast response modeling for urban dispersion problems during the last decade. Field experiments have been conducted to better understand the flow and dispersion patterns in urban downtowns (URBAN 2000, JU2003, MSG05, UDP Midtown etc). Numerous models and CFD codes (CFD-Urban, FEFLO-URBAN, FLACS etc) have been developed to predict dispersion characteristics in urban centres. Evaluation of these diagnostic models and CFD codes with the field experiment data has illustrated the complex nature of urban street canyon flows. These complexities can be associated to many parameters such as varying wind directions, complex building geometries, solar insolation etc. Wind tunnel modeling provides a way to systematically control and vary the aforementioned parameters. Therefore, in this paper, results from wind tunnel simulations have been used to better understand the effect of the building geometry on the flow characteristics in a simple two-building step-up street canyon. Measurements were acquired along the vertical symmetry plane of the model buildings. Results predicted by QUIC-URB are compared with the experimental results and areas of improvement in the parameterizations are suggested.

A step-up street canyon is defined as a street canyon in which the height of the upwind building (H_u) is less than the height of the downwind building (H_d). Step-up street canyons are typical of any real world city. The presence of a tall building in a cluster of relatively shorter buildings can significantly alter the street level flow patterns.

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Such flow behavior has been observed and reported for the MSG05 and UDP Midtown field experiments (Coirier & Kim, 2006). This behavior can be attributed to the increased downdraft induced by the tall building and could have a significant impact on the downwash of pollutants / contaminants in the event of an accidental / deliberate release. Additionally, the enhanced vertical motions near the windward face of the tall building could also influence the pedestrian wind comfort and street-level pollution due to vehicle-induced emissions.

Emergency response wind models such as QUIC-URB (Pardyjak & Brown, 2001) owe their fast response nature to empirical parameterizations. The parameterizations in QUIC-URB have been developed using wind tunnel data for simple building arrangements and basic flow regimes (isolated roughness flow and skimming flow). For relatively complex building configurations, the absence of data / parameterizations requires extrapolating results of simple building arrangements, thereby impeding the performance of the model. Hence, this paper endeavors to not only shed light on the flow characteristics of step-up street canyons, but also contribute to the parameterization database for fast response modeling.

2. QUIC-URB BACKGROUND

The Quick Urban & Industrial Complex (QUIC) dispersion modeling system consists of an urban wind model QUIC-URB (Pardyjak & Brown, 2001), a Lagrangian dispersion model QUIC-PLUME (Williams et al., 2002) and a graphical user interface QUIC-GUI (Nelson et al., 2006). QUIC-URB is based on the dissertation of Röckle (1990) and the subsequent work of Kaplan and Dinar (1996). It computes spatially-resolved mean wind fields in urban domains and is based on empirical flow parameterizations and mass conservation. The basic parameterizations in QUIC-URB have been developed using existing wind-tunnel data sets for simple buildings arrangements such as isolated buildings and street canyons. For more complex building configurations, these parameterizations are applied by dividing a complex building configuration into series of simple (rectangular parallelepiped-shaped) building configurations and superimposing the resulting flow fields. The various building parameterizations in QUIC-URB and the order in which they are applied and over-written are (Top-Down parameterization precedence):

a. Upwind cavity
b. Rooftop recirculation
c. Near wake
d. Far wake
e. Street canyon
f. Vegetation
g. Street Intersection

The manner in which these parameterizations are applied for a simple step-up street canyon is shown in Fig. 1.

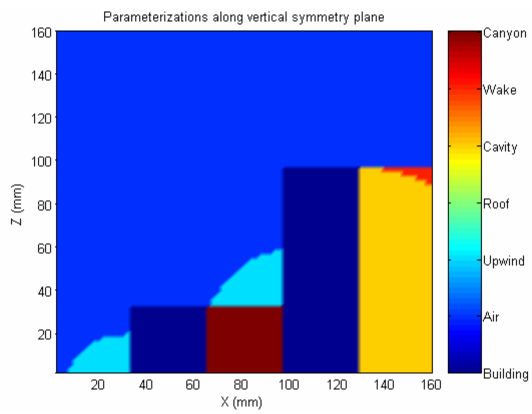

Fig. 1: Schematic showing the various parameterizations applied for a step-up canyon

It can be seen be seen that QUIC-URB predicts the flow structure for a step-up street canyon by imposing the parameterization for skimming flow in the canyon. Above the roof height of the upwind building, it determines the flow pattern by applying the upwind cavity algorithm for the downwind building.

3. EXPERIMENTAL METHOD

3.1 Flow conditions and setup

The experiments were performed at the Physical Fluid Dynamics Laboratory at the University of Utah at an atmospheric pressure of 648.5mm Hg, at a temperature of 21.5°C in a 7.9 m long boundary layer wind tunnel facility having a working cross section of 0.61m × 0.91 m. LEGO sheets with circular dimples of height 2mm lined the floor of the tunnel and were used to produce rough walled turbulent flow. The experiments were run at a free stream velocity of ~ 5 m/s with a corresponding boundary layer depth (δ) and power law exponent (η) at the measurement location of δ / H_d ~ 2.5 and η ~ 0.19. The inflow velocity and turbulence intensity profiles are shown in Figs. 2 & 3 below.

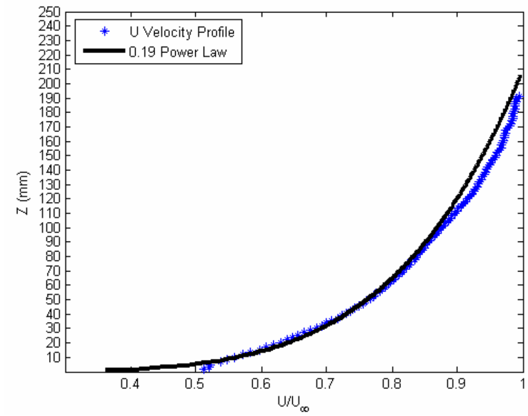

Fig. 2: Inflow velocity profile

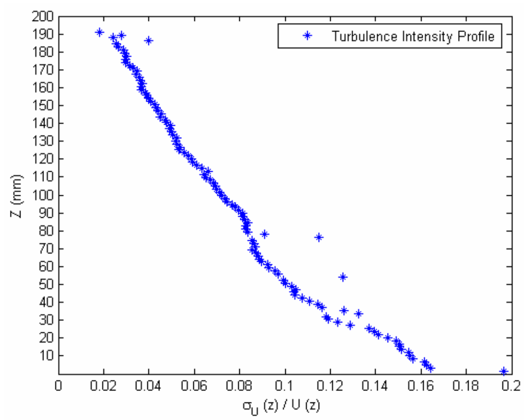

Fig. 3: Inflow turbulence intensity profile

3.2 Canyon Configurations Investigated

Two sets of experiments were performed. The first experiment investigated the flow field around a step-up street canyon with H_d / H_u ~ 3. The second experiment explored the flow structure in a step-up street canyon with H_d / H_u ~ 1.67. These experiments were performed for four different upwind and downwind building widths (W) (both varied by the same factor) and for a constant street canyon width (S). The cross-wind widths of the buildings were varied systematically from W=1L to W=4L (where L is the along-wind length of the building and was kept constant). This resulted in a total of 8 cases for both the experiments.

For better understanding, the building arrangement for the first experiment (H_d / H_u ~ 3) is shown in Fig. 5.

3.3 Notation

The following notation will be used to address the different canyon configurations and the various parameters used to describe the flow physics. Some of these parameters are shown in Fig. 4.

- H_u Height of the upwind building; (= 32 mm for the 1st experiment; =57.6mm for the 2nd experiment)
- H_d Height of the downwind building; (= 96mm)
- L Along-wind length of the building; (= 32mm)
- S Street canyon width; (S=L)
- U_H Velocity at downwind building height; (= 4.34 m/s)
- W Cross-wind width of the building; (varied from W=1L to W=4L in increments of 1L for both the buildings)
- X distance of a given profile from the upwind building
- X_V Vortex core distance from the leeward face of the upwind building
- Z_{St} Stagnation point height on the downwind building
- Z_V Vortex core distance from the ground

The following example explains the notation used to describe the various canyon configurations. **H_d / H_u ~ 3; H_u ~ 1L; W / S (=L) ~ 1** represents a step-up street canyon with H_d / H_u ~ 3, the height of the upwind building (H_u) being equal to the length of either of the buildings (L) and the width of the buildings (W) being equal to the length of the buildings (L).

3.4 Measurement Technique

2D PIV was used as the measurement technique. The measurements were taken along the center plane (symmetry plane; X-Z plane) of the model buildings. The flow was seeded with olive oil particles generated using two Laskin Nozzles. The aerosols were illuminated with a 532nm wavelength laser sheet (1.5mm thick) generated using a 50mJ NewWave Research (Fremont, CA) Solo PIV III Nd-Yag Laser. A 4.0MP (2048×2048pixels) CCD camera manufactured by TSI Inc. (Shoreview, MN) having a frame rate of 17fps was used in conjunction with a frame grabber for image acquisition. A LASERPULSE synchronizer was used to control the timing between the laser pulses and the camera shutter open time through a PC desktop computer. Analysis of the acquired image pairs was done using TSI INSIGHT3G analysis software. FFT based cross-correlation analysis was performed on the conditioned image pairs by dividing them into 32×32 pixel interrogation regions. 1000 image pairs were considered for computing the average velocity and turbulence fields. The spatial resolution of the final data sets obtained was ~ 2.35mm.

4. QUIC-URB SIMULATIONS

The experimental cases were simulated in QUIC-URB for model evaluation. The domain size chosen was 160×160×160 mm^3 with a grid resolution of 2mm. The experimental inflow profile (Fig. 2) was used as the inflow profile for the simulations. Lego sheets used in the experiment for generating uniform rough wall turbulent flow were not accounted for in the simulations. The parameterizations implemented were the upwind cavity, street canyon, rooftop recirculation, cavity and the wake parameterizations.

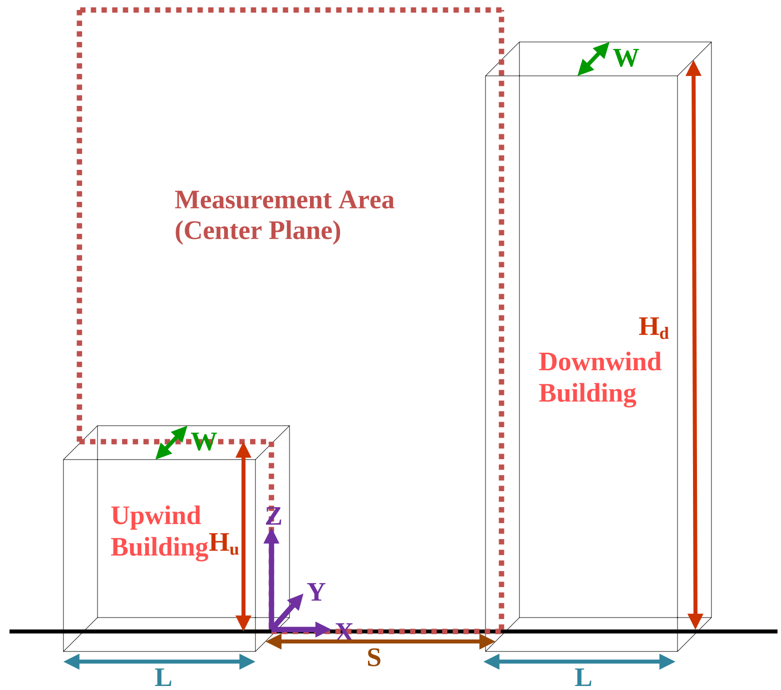

Fig. 4: Schematic showing the notation used

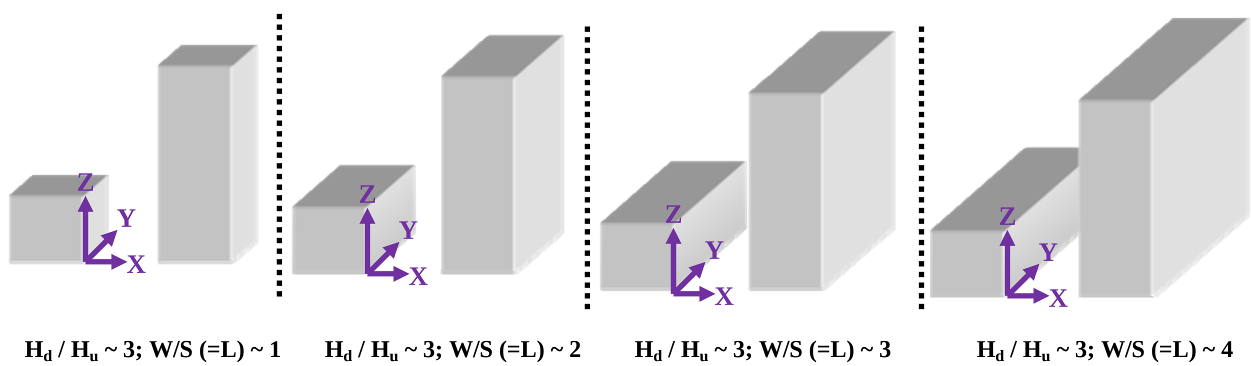

Fig. 5: Schematic showing the various cases of the first experiment (H_d = 96mm; H_u = 32mm)

QUIC-URB vs. Experiments for Step-up Street Canyons

Experiments | **QUIC-URB**

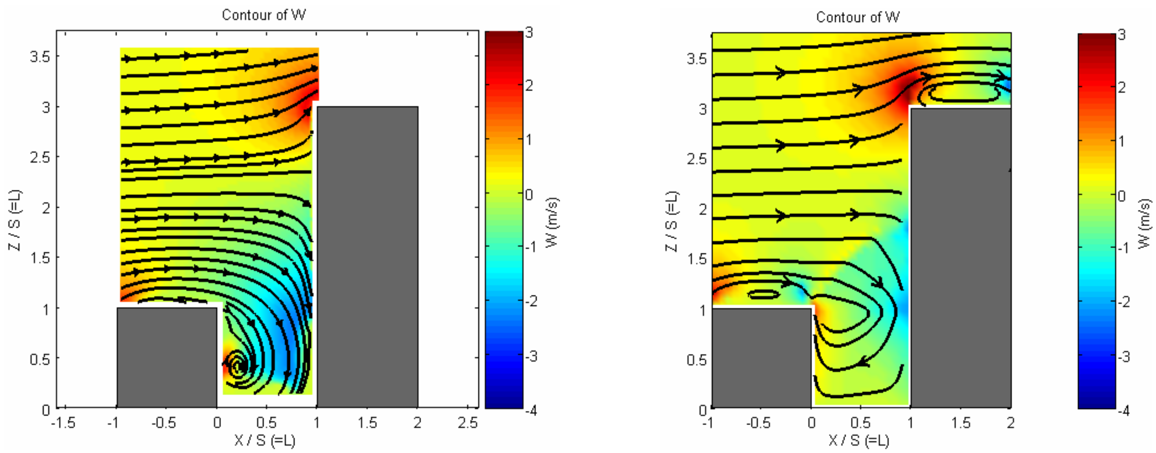

Fig. 6: H_d / H_u ~ 3; H_u ~ 1L; W / S (=L) ~ 1

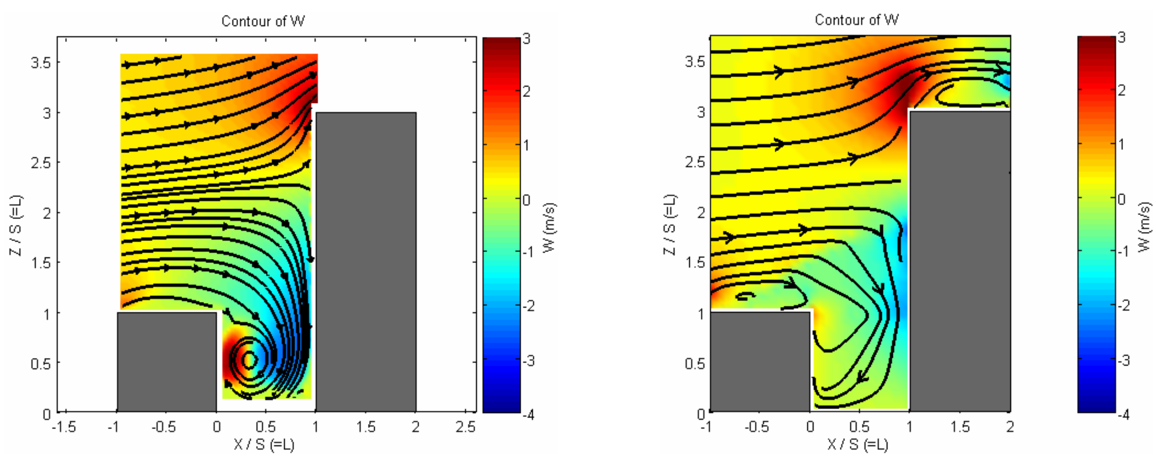

Fig. 7: H_d / H_u ~ 3; H_u ~ 1L; W / S (=L) ~ 2

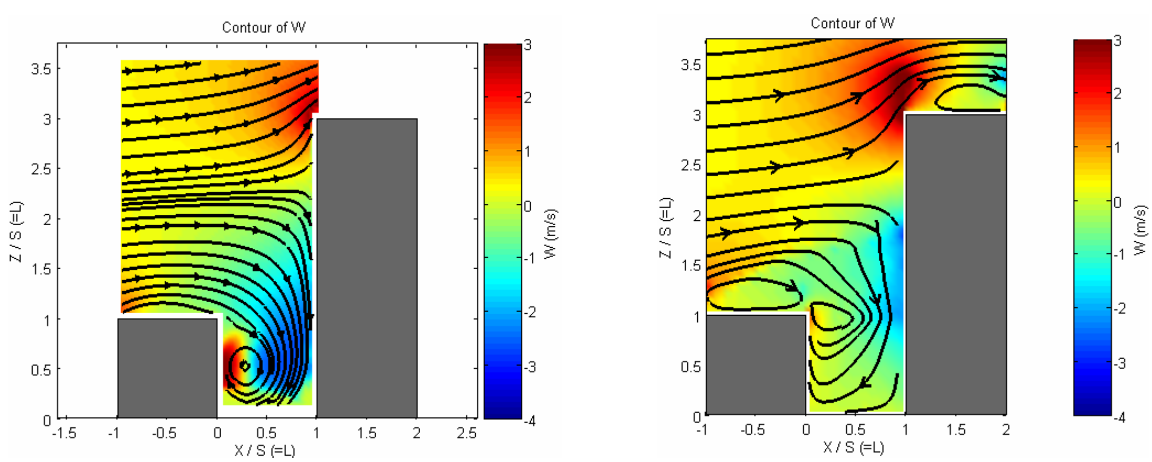

Fig. 8: H_d / H_u ~ 3; H_u ~ 1L; W / S (=L) ~ 3

QUIC-URB vs. Experiments for Step-up Street Canyons

Experiments **QUIC-URB**

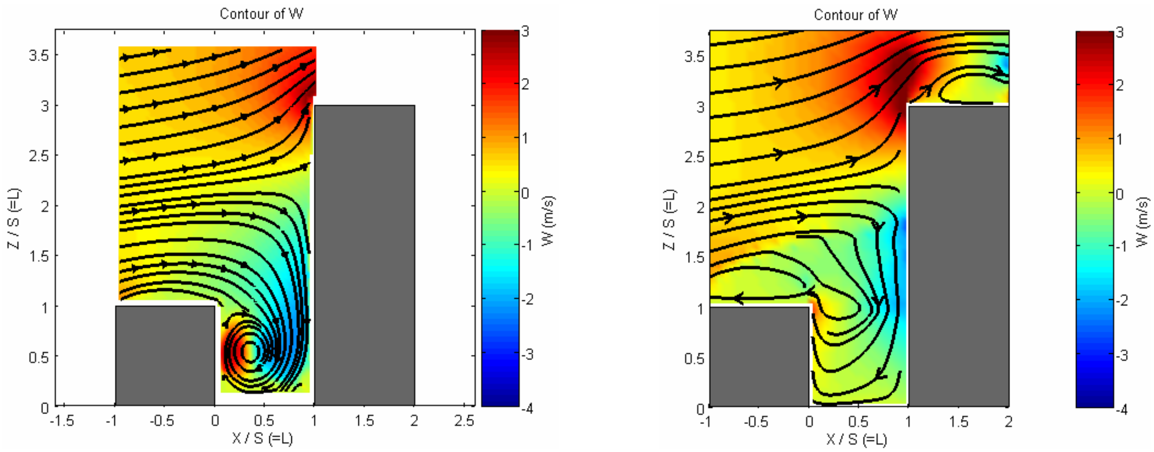

Fig. 9: H_d / H_u ~ 3; H_u ~ 1L; W / S (=L) ~ 4

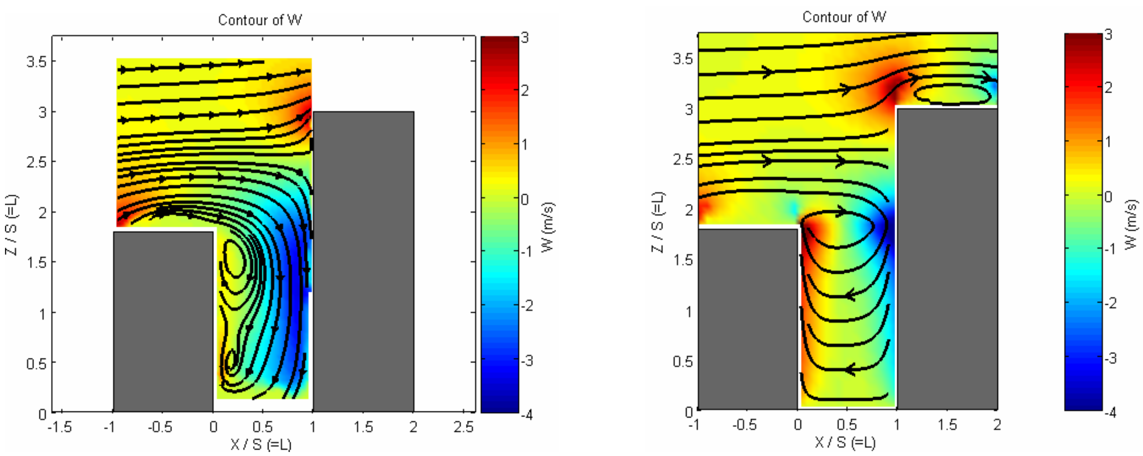

Fig. 10: H_d / H_u ~ 1.67; H_u ~ 1.8L; W / S (=L) ~ 1

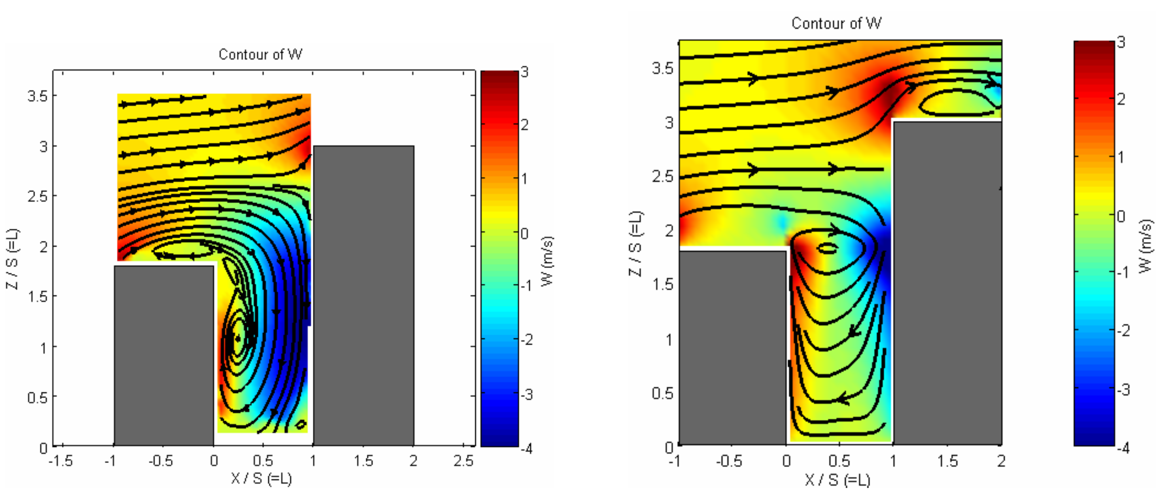

Fig. 11: H_d / H_u ~ 1.67; H_u ~ 1.8L; W / S (=L) ~ 2

QUIC-URB vs. Experiments for Step-up Street Canyons

Experiments **QUIC-URB**

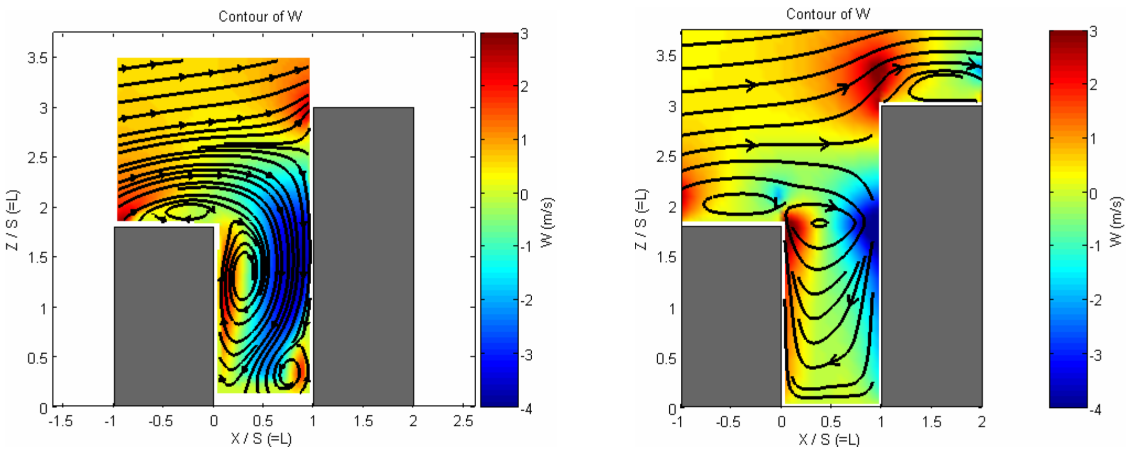

Fig. 12: H_d / H_u ~ 1.67; H_u ~ 1.8L; W / S (=L) ~ 3

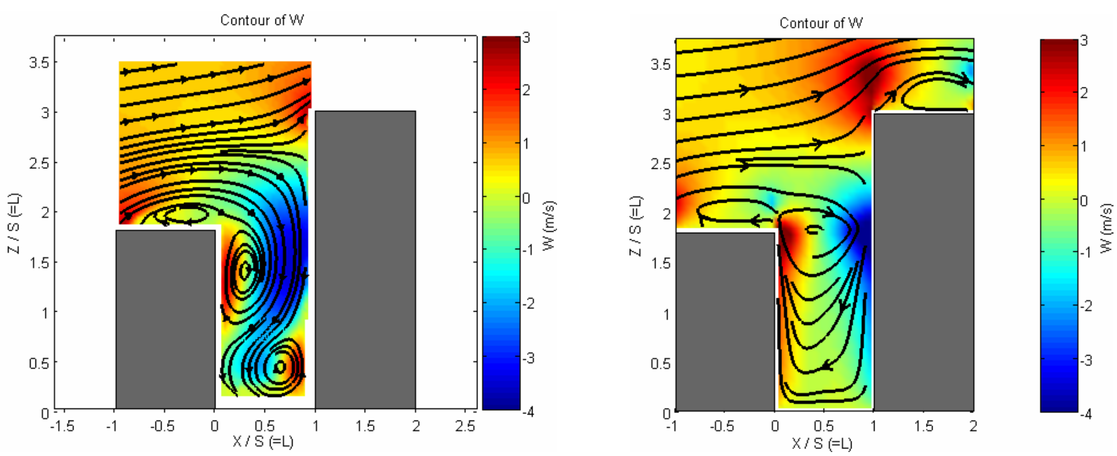

Fig. 13: H_d / H_u ~ 1.67; H_u ~ 1.8L; W / S (=L) ~ 4

5. RESULTS

5.1 Mean vertical velocities (W) & streamline patterns

Figures 6 to 13 compare the results predicted by QUIC-URB and those obtained from experiments.

5.1.1 H_d / H_u ~ 3

For cases with H_d / H_u ~ 3, the following observations can be made:

The flow structure in the canyon predicted by QUIC is markedly different from that observed in the experiments. The flow patterns predicted by QUIC are a result of the upwind cavity algorithm for the downwind building being over-written by the street canyon algorithm. Consequently, a sharp discontinuity is seen in the flow structure at the upwind building roof height. Above this, QUIC predicts downdrafts that are in agreement with the experimental results. But within the canyon (below the upwind building roof height), since the street canyon algorithm is imposed, a relatively weaker vortical structure is predicted by QUIC with significantly lower downdrafts and updrafts. These downdrafts could have a strong impact on the vertical & lateral dispersion patterns in the canyon given that stronger downdrafts improve the ventilation in the canyon. Additionally, the simulations in QUIC were run with the assumption that a rooftop recirculation region would exist on the upwind building. Therefore, we see an exaggerated rooftop recirculation region in the results predicted by QUIC. However, the experimental results show weak or no recirculation on the upwind building.

To better understand the differences in the downdrafts and updrafts between the results predicted by QUIC and those obtained from experiments, the mean vertical velocity values (W_m) were plotted at heights $0.5H_u$, $1H_u$ and $1.5H_u$.

Figure 14 shows the vertical velocities plotted at $1.5H_u$. It can be see that at this height, the results predicted by QUIC and those obtained from experiments are in very good agreement. For the case W / S (=L) ~ 1, QUIC predicts positive vertical velocities until S ~ 0.3L. This is because these data points are outside the upwind cavity for the downwind building in QUIC-URB.

Figure 15 shows the vertical velocities plotted at height $1H_u$. It is seen that at this height, QUIC-URB predicts positive and negative vertical velocities at the canyon height. However, experimental results show only strong negative velocities at the canyon height suggesting a different flow structure (street canyon vortex compressed towards the leeward face of the upwind building) in the canyon than that predicted by QUIC-URB (a regular street canyon vortex).

Figure 16 shows the vertical velocities plotted at height $0.5H_u$. The differences in results can be seen through the difference in the velocity magnitudes. It can be seen that QUIC-URB under-predicts the updrafts and downdrafts at the center of the canyon. Also, QUIC-URB predicts almost similar vertical velocities at this height for the various building widths. A close inspection of the experimental results suggests that for H_d / H_u ~ 3, as the building width is increased, the negative vertical velocities in the canyon decrease and the vortex core moves more towards the center of the canyon. This is because as the width of the buildings is increased, the incoming flow experiences greater blockage. This causes the flow to accelerate and go over the top of the downwind building rather than move into the canyon. Hence, increase in building widths results in a more stable vortex in the canyon with weaker downdrafts.

5.1.2 H_d / H_u ~ 1.67

The flow structure predicted by QUIC-URB for these cases is very different from those observed through experiments. The results obtained from experiments are quite unique and have not been reported before in street canyon literature. It is observed that for building width W ~ S (=L), the streamline patterns suggest the simultaneous existence of two co-rotating vortices near the leeward face of the upwind building. This unusual flow structure can be attributed to the near-zero velocities near the leeward face (often near-zero wind velocities could result in indiscernible flow patterns in urban street canyons). It is seen that as the building width is increased, the primary vortex moves closer to the roof of the upwind building and we see the formation of secondary counter-rotating vortex at the bottom of the canyon near the windward face of the downwind building. This secondary vortex could be imagined to be a result of a more stable primary vortex formed at higher building widths (due to less entrainment of incoming flow in to the canyon).

6. CONCLUSION

The experiments conducted reveal several unique flow patterns that have not been reported before in the street canyon literature. These flow patterns can significantly alter the overall dispersion characteristics in step-up street canyon configurations. Hence, a new parameterization for step-up street canyons is recommended for the QUIC-URB wind model and is currently under development.

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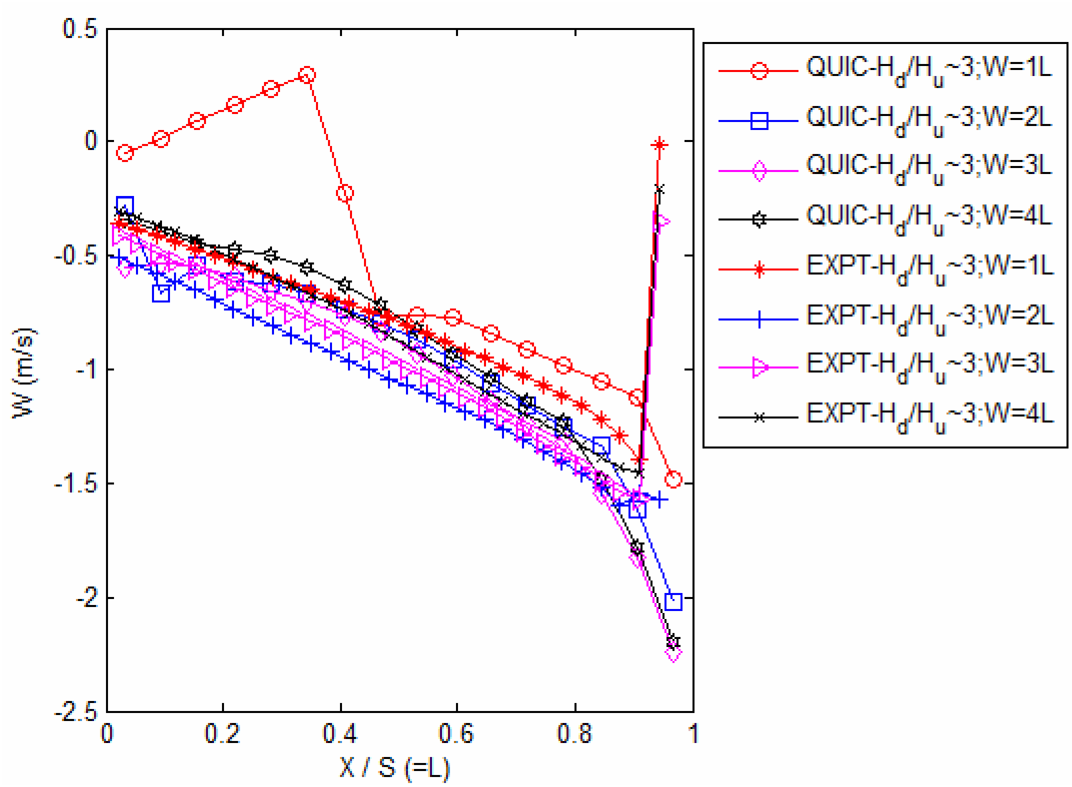

Fig. 14: Mean vertical velocities (W_m) at $1.5H_u$

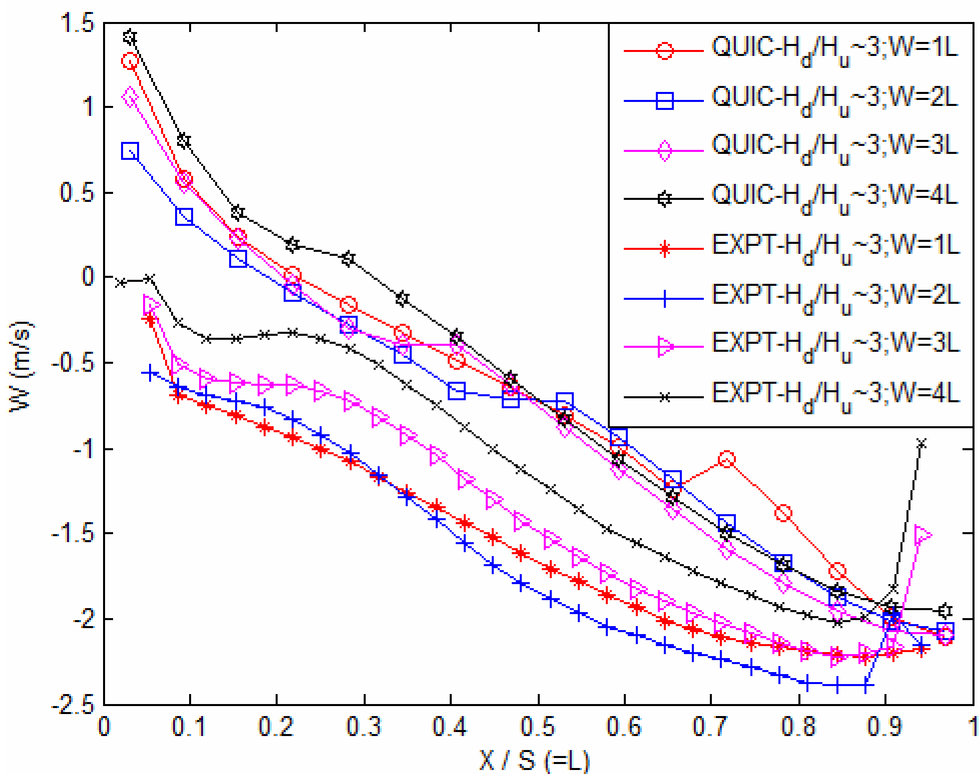

Fig. 15: Mean vertical velocities (W_m) at $1H_u$

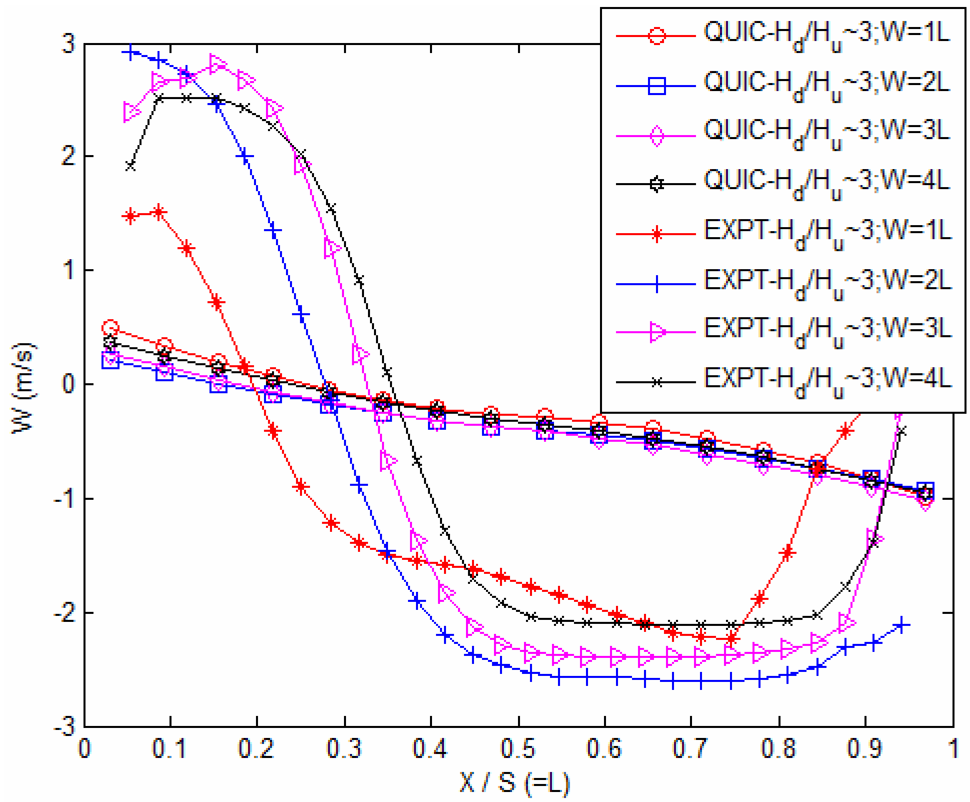

Fig. 16: Mean vertical velocities (W_m) at $0.5H_u$