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# EVALUATION OF A FAST-RESPONSE PRESSURE SOLVER FOR A VARIETY OF BUILDING SHAPES AND LAYOUTS

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## 1. INTRODUCTION

For naturally-ventilated buildings, the infiltration of outside air into a building is proportional to the pressure difference across the building (e.g., Feustel, 1998). Hence, knowledge of the pressure drop across a building is needed to help determine the indoor concentration from outdoor air pollutants. Many indoor dispersion models require the pressure difference across the building envelope as an input boundary condition in order to determine the naturally-generated component of the air flow within the building (e.g., Dols, 2002).

A pressure solver developed by Gowardhan et al. (2007) has recently been added to the Quick Urban & Industrial Complex (QUIC) fast response dispersion modeling system. QUIC produces high-resolution mean wind and concentration fields around buildings (Pardyjak and Brown, 2001; Gowardhan et al., 2006). The pressure solver produces 3D pressure fields around building complexes using the mean wind field produced by the QUIC wind solver. The pressure field is generated by solving the pressure Poisson equation, obtained by taking the spatial divergence of the steady-state Navier-Stokes equations for incompressible flow. Figure 1 shows pressures computed on building surfaces in downtown Salt Lake City.

The QUIC wind solver is an empirically-based diagnostic wind model based on the ideas of Röckle (1990). The wind solver generates a mass consistent mean wind field around buildings by using various empirical relationships based on the building height, width, and length, and the spacing between buildings to initialize the velocity fields in the regions around buildings (e.g., upwind rotor, downwind cavity and wake, street canyon vortex, and rooftop vortex). This initial flow field is then forced to satisfy mass conservation. For the 2 million grid cell downtown simulation shown in Fig. 1, the wind field was generated in approximately one minute on a single processor PC, while the pressure field took less than a minute to obtain.

In principle, the QUIC model could be used to rapidly provide pressure boundary conditions for indoor flow and dispersion models. The QUIC wind solver, however, is an approximated model and it is not clear if the pressure field generated from the QUIC-produced wind fields will be accurate enough for indoor model applications. In order to answer this question, the pressure drop produced by QUIC across a building is evaluated against pressure measurements taken around a variety of building shapes and layouts. Before presenting the comparisons, we begin by describing the pressure solver followed by a short description of the wind-tunnel experiments.

## 2. PRESSURE SOLVER DESCRIPTION

The pressure Poisson equation is derived from the Reynolds-averaged Navier-Stokes (RANS) equations for incompressible flow without body forces, expressed here using Einsteinian notation as:

$$\frac{\partial \overline{U_i}}{\partial t} = -\frac{\partial(\overline{U_i}\,\overline{U_j})}{\partial x_j} - \frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} - \frac{\partial(\overline{u'_i u'_j})}{\partial x_j} + \nu \frac{\partial^2 \overline{U_i}}{\partial x_j \partial x_j}, \qquad (1)$$

where $\overline{U_i}$ is the mean velocity in the $x_i$ direction, $u'_i$ is the turbulent fluctuating velocity, $\overline{P}$ is the mean pressure, $\rho$ is the average density, $\overline{u'_i u'_j}$ is the Reynolds stress, and $\nu$ is the kinematic viscosity.

Assuming steady-state conditions and taking the divergence of Eqn. (1), we obtain

$$\frac{\partial}{\partial x_i}\left(\frac{\partial \overline{P}}{\partial x_i}\right) = \rho \frac{\partial}{\partial x_i}\left(\nu \frac{\partial^2 \overline{U_i}}{\partial x_j \partial x_j} - \frac{\partial(\overline{U_i}\,\overline{U_j})}{\partial x_j} - \frac{\partial(\overline{u'_i u'_j})}{\partial x_j}\right). \qquad (2)$$

Equation (2) is the pressure Poisson equation. Since the QUIC wind model only produces the mean wind field and produces no information on the turbulence, for the time being, we simplify the equation further by neglecting the Reynolds stresses. As will be discussed later, differences between the model-computed and measured pressure may be due to neglecting these terms. In the future, the Reynolds stresses will be included in the calculation to study the effect of turbulence on the mean pressure distribution on building surfaces.

The QUIC pressure solver uses the successive over-relaxation (SOR) method to iteratively solve the pressure Poisson equation on a staggered finite difference mesh. A second-order accurate central-differencing scheme has been used to obtain the

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source term for the pressure Poisson equation (R.H.S. of Eqn. (2)) at each grid point in the solution domain. A no-slip boundary condition was applied at the wall surfaces. The pressure boundary conditions are zero gradient in the wall normal direction on solid surface faces and atmospheric pressure at the faces of the domain (inlet and outlets). The initial value of pressure at each grid point inside the solution domain is specified as the ambient atmospheric pressure.

The computed pressure field is normalized by subtracting the ambient atmospheric pressure ($P_o$) and then by dividing by the free stream velocity ($V_o$) at the reference height to obtain the coefficient of pressure ($C_p$):

$$C_p = \frac{\overline{P} - \overline{P_o}}{\left(\frac{1}{2}\rho V_o^2\right)} \qquad (3)$$

The QUIC pressure solver will be evaluated using $\Delta C_p$, the difference between the maximum $C_p$ found on the front face of a building and the minimum $C_p$ found on the back face of the building. $\Delta C_p$ is proportional to the pressure drop across a building.

## 3. SUMMARY OF EXPERIMENTS

The cases that have been used for evaluation of the QUIC pressure solver include a cube, a tall building, a low building with large footprint, a U-shaped building, an L-shaped building and a 7x1 array of low wide buildings. For all cases the inflow was perpendicular to the building face, i.e., 90° inflow. For the cube, measurements were obtained for 45° inflow as well.

Pressure measurements for the cubical building with normal incident flow and the tall building are from Baines (1963). The experiments were performed in a wind tunnel with a fully-developed turbulent boundary layer and a shear inflow profile. The wind tunnel was a low-speed open-return type with a cross-sectional area of 1.33 m by 2.67 m. The inflow velocity profile was described by a power-law with exponent 0.25. For the tall building, the height-to-width-to-length ratio was 8:1:1 with a height of 0.46 m. In addition, data from an outdoor experiment performed by Richards et al. (2001) for a cube with normal incident inflow was included in order to show the spread in the $\Delta C_p$ measurements.

For the cubical building with 45° inflow, pressure data from the ASHRAE Handbook (1985) were used. The experiments were performed using a uniform inflow velocity profile and low turbulence intensity. The pressure data for the low building (H-to-W-to-L ratio of 0.5:1:1) were obtained from an Architectural Institute of Japan (AIJ) report (1998). Details of the experimental work were not documented in the reports, but it was mentioned that the inflow velocity profile had a power-law shape with exponent of 0.25.

The U-shaped and L-shaped building experiments were conducted by Gomes et al. (2005) in a closed-circuit wind tunnel with cross-sectional area of 1.25 x 1.0 m$^2$. The buildings were 0.3 m high and embedded in a uniform flow with low turbulence intensity. Measurements were taken at different incident angles. Pressure taps were not placed on all building faces, so the pressure drop across the buildings was approximated by looking at the maximum Cp for the 0 degree inflow case and the minimum Cp for the 180 degree inflow case.

The experimental data for the array of seven rows of wide buildings were obtained from the U.S. Environmental Protection Agency's Fluid Modeling Facility wind tunnel (Brown et al., 2001). The wind tunnel is an open return(4) type and is 3.7 m wide by 2.1 m high by 18.3 m long. The buildings were 0.15 m high x 3.7 m wide x 0.15 m long with one building height spacing between the buildings. With building spacing-to-height ratios of one, the 2D arrays should be somewhere between the skimming and wake interference flow regimes (Oke 1987). The building models were placed in a simulated neutral atmospheric boundary layer with a depth of 1.8 m, a roughness length of 1 mm, and a velocity profile with a power-law exponent of 0.16.

## 4. RESULTS AND DISCUSSION

The QUIC wind solver was run for all the cases described in Section 3. The inflow wind profile was matched to the experiment. The simulations were run with a grid resolution that allowed the minimum building dimension to be described by 10 grid cells. The resultant wind fields were then utilized by the QUIC pressure solver to produce 3D pressure fields around the buildings.

Figure 2 shows the $\Delta C_p$ computed by the QUIC pressure solver and measured in the experiments for all the cases. All of the single building cases reveal that the model-computed $\Delta C_p$ is within 10% of the experimentally measured value, except for the low-squat case which was overestimated by 20% and the high-rise case which was overestimated by about 50%. The model-computed maximum $C_p$ for the high-rise was significantly overestimated and was the main reason for the overestimated $\Delta C_p$. In general, the maximum $C_p$ on the front face of the isolated buildings was better estimated than the minimum $C_p$ on the backface, with the one exception being the high-rise case.

The model-computed value for the first building in the 7x1 array was identical to the measured $\Delta C_p$. The trend of decreasing $\Delta C_p$ was captured by the model for the buildings in the 2$^{nd}$ and 7$^{th}$ rows. This is due to the sheltering effect provided by the upwind building(s), so that the 2$^{nd}$ and 7$^{th}$ row buildings actually had negative $C_p$ values on their front faces similar to that found in the experiments. However, for the last row the magnitude of the negative $C_p$ value was much too large and the sign of $\Delta C_p$ computed by the model was wrong.

The difference between the measurements and the model-computed maximum $C_p$ on the front face of the high-rise surprise us. In general, the pressure on the front face is determined by the strength of the wind that hits the front face and this is fairly well characterized in the wind solver. The reason for the difference will need to be further investigated. The problem encountered in the last row of the 7x1 wide building array is most likely due to the overestimation of the canyon winds in the street canyon. The QUIC wind solver has been shown to overestimate the street-level winds in idealized building arrays by 50% or more. Although this doesn't have a significant impact on dispersion of contaminants from a street-level release, we believe it does play a role in overpredicting the suction on the front wall of the last building.

## 5. CONCLUSION

The QUIC pressure solver has been evaluated using pressure measurements on buildings from wind-tunnel experiments. The $\Delta C_p$, the difference between the maximum pressure coefficient $C_p$ measured on the upwind face of a building and the minimum pressure coefficient measured on the downwind face, has been used in the evaluation. The model-computed $\Delta C_p$ was within 10% of the experimental measurements for a cube, a U-shaped building, and an L-shaped building. The $\Delta C_p$ was overestimated by about 50% for a high-rise building and by about 20% for the low squat building. For a seven row array of wide buildings, the $\Delta C_p$ computed for the first building was identical to the measurements, the 2$^{nd}$ row had a small $\Delta C_p$ within the uncertainty of the pressure measurements, while the last row building actually had the wrong sign of $\Delta C_p$.

Since the leakiness of a naturally-ventilated building is proportional to the pressure difference across the front and back faces, the QUIC modeling system could be used to provide boundary conditions to indoor dispersion models. For complex urban environments, QUIC would be able to account for the sheltering effect of upwind buildings and may be able to provide credible estimates of the $\Delta P$ across the building envelope. However, the large error in the last row of the 7x1 building array indicates that more evaluation studies are necessary for groups of buildings.

Evaluation of the QUIC wind solver for high rise cases is ongoing (see paper by Addepalli et al. (2007) at this same conference) and improvements in the wind field may improve the pressure field for the high-rise case. The pressure solver will also be further tested for cases with multiple buildings of different shapes and sizes to look at the impact of sheltering on the pressure field. Finally, the importance of the Reynolds stresses – which we have neglected – in the pressure Poisson equation are being evaluated through large eddy simulations.

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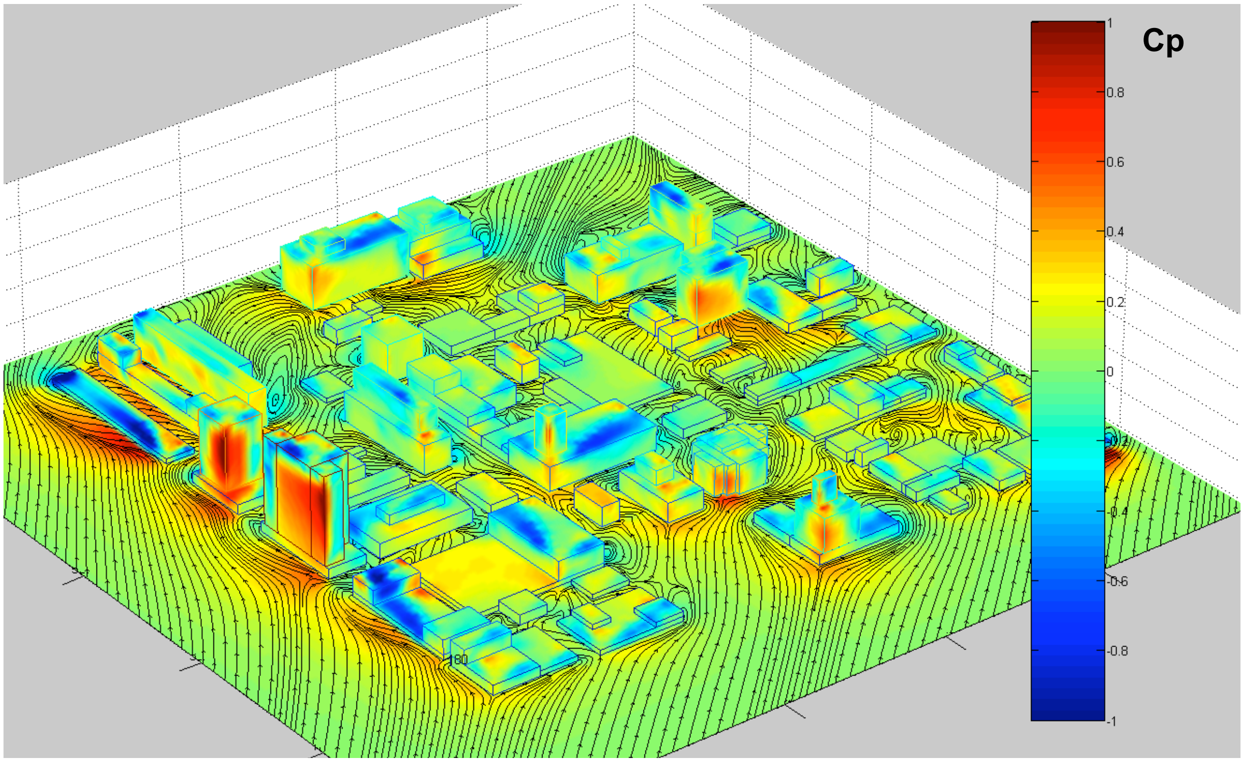


Figure 1. A QUIC simulation showing streamlines and surface pressures for downtown Salt Lake City. The red colors show regions of high pressure and the blue colors regions of low pressure. The computation was performed on a 2.5 GHz Pentium 4 processor and took 67 s for the wind solver and 46 s for the pressure solver. The domain is 200 x 200 x 50 grid cells.


Figure 2. Comparison of the model-computed $\Delta C_p$ and the experimentally-measured $\Delta C_p$ for different buildings. $\Delta C_p$ is defined by the maximum $C_p$ on the front face and the minimum $C_p$ on the backface. Note that the cube case with normal inflow includes two experimental data sets.