Fast Pressure Calculations on Buildings to Improve Outdoor-to-Indoor Transport & Dispersion

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Presentation Outline

• Why Pressure Important for T&D Applications
  - Pressure Distribution on Buildings Influences Air Exchange Rate

• Modeling Tools
  - QUIC-URB Wind Model
  - QUIC Pressure Solver

• Model Evaluation

• How the fast wind & pressure models could be used to improve Indoor T&D calculations
Motivation

• Outdoor Releases
Infiltrate into Buildings

5 minute duration outdoor release

½ hour QUIC Salt Lake City simulation
Motivation

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**Motivation**

- **Outdoor Releases Infiltrate into Buildings**
- **Population mostly resides Indoors**

**LANL USA Day-Night Indoor-Outdoor Pop DB**

McPherson, T., A. Ivey, and M. Brown, 2004: Determination of the spatial and temporal distribution of population for air toxics exposure assessments, AMS 5th Symp on Urban Environment, Vancouver, BC.
Motivation

• Outdoor Releases Infiltrate into Buildings

• Population mostly resides Indoors

• Exposure estimates can be much smaller if building “protection” considered

Gadgil, 2005
GMU T&D Workshop

Outdoor Prediction

Indoor Prediction

Acute Exposure Guideline Levels
Motivation

• Outdoor Releases
  Infiltrate into Buildings

• Population mostly resides Indoors

• Exposure estimates sensitive to building “protection”

• Air exchange for naturally-ventilated buildings is proportional to wind-induced pressure on building walls
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Chan et al. (2005) – Most residential buildings in US do not have mechanical ventilation systems
Motivation

- **Outdoor Releases**
  Infiltrate into Buildings

- **Population mostly resides indoors**

- **Air exchange for naturally-ventilated buildings is proportional to wind-induced pressure on building walls**

Pressures on surface used as boundary conditions in CFD and multi-zone models, e.g., **COMIS**

Orifice equation

\[
Q_f = ELA_{bldg} \times (2 \times \frac{\Delta P_{bldg}}{\rho})^{1/2}
\]

\(Q_f\) = volumetric airflow rate
\(ELA_{bldg}\) = effective leakage area of bldg

In practice

\[
Q_f = k \times \Delta P^n \quad 0.6 < n < 0.7
\]
The Urban Dispersion Model (UDM)

The Air Exchange Rate (AER) is due to a Buoyancy ("stack") Pressure and a Wind-Induced Pressure.

Ignoring the stack pressure effect (e.g., $T_{\text{indoor}} = T_{\text{outdoor}}$)

$$AER_{\text{bldg}} = \left( \frac{AER_{\text{ref}}}{\Delta P_{\text{ref}}^{2/3}} \right) \cdot \Delta P_{\text{bldg}}^{2/3}$$

Indoor Concentration

$$\chi_i(t) = e^\tau \left[ \chi_{out}(t_s) + \int_{t_s}^{t} \frac{\chi_{out}(t')}{\tau} e^{-\frac{t'}{\tau}} dt' \right]$$

where

$$\tau = \frac{3600}{AER}$$
Idea:
Use Fast Solvers To Compute Pressure Field on Buildings and Provide as Input to Indoor Models.
QUIC-URB Wind Solver

- Based on dissertation of Röckle (1990)
- 3D winds obtained from diagnostic/empirical method
- Initial winds based on building spacing and geometry
- Then mass conservation imposed (Sherman, 1978)
QUIC-URB Wind Solver

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QUIC Pressure Solver (Gowardhan et al., 2006)

Momentum Equation:

\[
\frac{\partial U_i^0}{\partial t} = -\frac{\partial (U_i U_j)}{\partial x_j} - \frac{1}{\rho} \frac{\partial P}{\partial x_j} - \frac{\partial (u'_i u'_j)}{\partial x_j} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j}
\]  

where,

I - Adveotive terms

II - Reynolds stress terms

III - Diffusive terms

Assuming **steady state** and taking **divergence** of Eqn. 1
QUIC Pressure Solver

\[
\frac{\partial}{\partial x_i} \left( \frac{\partial P}{\partial x_i} \right) = \rho \frac{\partial}{\partial x_i} \left( \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} - \frac{\partial (U_i U_j)}{\partial x_j} - \frac{\partial (u_j') u_j'}{\partial x_j} \right)
\]

(2)

• The pressure Poisson equation is solved by iterative method with \( \partial p/\partial n = 0 \)

• Reynolds Stresses are neglected due to lack of information

• Coefficient of Pressure is calculated using the following formula:

\[
C_p = \frac{\overline{P} - \overline{P}_o}{\left( \frac{1}{2} \rho V_o^2 \right)}
\]
QUIC Wind & Pressure Solvers

Salt Lake City Downtown
(Domain: 200 x 200 x 50 cells)

Computation Time:
QUIC-URB = 67 s
Pressure = 46 s

Pentium 4
2.5 GHz
Model Evaluation Cases

Cube (90 deg)

Cube (45 deg)

Squat

U-shaped

L-shaped
Model Evaluation Cases

High-Rise

7x1 Wide Building Array
QUIC vs. Experimental Data: Cube (90 deg.)

Cube

\[ C_p = \frac{P - P_0}{\left( \frac{1}{2} \rho V_o^2 \right)} \]

Adapted from Richards & Hoxey (2006)
QUIC vs. Experimental Data: L-Shaped Building

Adapted from Gomes et al (2005)
QUIC vs. Experimental Data: L-Shaped Building

Adapted from Gomes et al (2005)
QUIC vs. Experimental Data: U-Shaped Building

Front Face C  Side Face D

U-Shape

Adapted from Gomes et al (2005)
QUIC vs. Experimental Data: U-Shaped Building

Adapted from Gomes et al (2005)
\[ \Delta C_p = \text{Max } C_p \text{ Front Face } - \text{Min } C_p \text{ Back Face} \]

\[ C_p = \frac{\bar{P} - \overline{P_o}}{\left(\frac{1}{2} \rho V_o^2\right)} \]
**QUIC vs. Experimental Data**

The Maximum $C_p$ on the Front Face

\[
C_p = \frac{\bar{P} - \bar{P}_o}{\left(\frac{1}{2} \rho V_o^2\right)}
\]
QUIC vs. Experimental Data

The Minimum $C_p$ on the Back Face

$$C_p = \frac{P - P_o}{\frac{1}{2} \rho V_o^2}$$
Where the Combined Wind & Pressure Solvers Could Make a Difference

• Off-angle winds

• Dense Urban Areas - Sheltering effects of surrounding buildings

• Detailed analyses of building of interest (where locations of vents, windows, doors are known)
Off-Angle Winds

CFD simulations of Gomes et al. (2005)
Detailed Analyses of Buildings of Interest

Specify pressure boundary conditions at inlets and outlets for control volume codes.

e.g., COMIS
Dense Urban Areas – Sheltering Effect

In city centers, buildings will have much lower natural ventilation rates due to obstruction of wind by surrounding buildings.
Dense Urban Areas – Sheltering Effect

In city centers, buildings will have much lower natural ventilation rates due to obstruction of wind by surrounding buildings.

Bauman et al (1988) “Studies show wind pressure reductions of up to 90% resulting from wind blockage by upwind buildings. However, there is a variability of 80% depending on the configuration of the buildings.”

CFD simulations of Yang et al. (2005)
Dense Urban Areas – Sheltering Effect

Indoor models often have sheltering correction factors, e.g.,

UDM reduces the $\Delta P$ by a fixed amount if the building plan area density is above a specific threshold.
Dense Urban Areas – Sheltering Effect

Pressures computed for Madison Square Garden, NYC.
Summary

• Wind-induced pressure information on buildings can be used to improve indoor dosage calculations (for outdoor and indoor releases)

• The QUIC wind and pressure solvers are relatively computationally inexpensive and would fit into a fast-response T&D modeling system

• Preliminary evaluation studies indicate that the QUIC wind and pressure solvers generally provide reasonable agreement with experimental studies
Technical Challenges

• Rooftop pressures on flat roofs difficult to match

• How about pitched roofs?

• Lack of experimental data in complex building environments

• Is turbulence important?
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CFD vs. Experimental Data

Rooftop Pressure

Adapted from Richards & Hoxey (2006)