Wind-driven ventilation of buildings: models and wind tunnel tests

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Natural Ventilation for Energy Savings in California Commercial Buildings

- Funded by the California Energy Commission
- Organisations
  - UC San Diego
  - UC Berkeley
  - Lawrence Berkeley National Laboratory
  - Arup (San Francisco)
  - CPP Wind
- 3 Projects
  ① Potential benefits and risks
  ② Barriers to implementation
  ③ Tool development
- Implementation of wind-driven models in EnergyPlus
Typical buildings
Cross-Ventilation (CV)

Single Sided (SS)

12 meters

6 meters

6 meters
Single-sided model

- Ventilation rate due to 1 or more openings in same façade
- Dependence on wind angle and opening size and position
- Pursue empirical approach based on flow conditions near openings
CPP tests: model building

Pressure sensors around aperture positions

FID (concentration) sensors

2-story: approx 5:2:1, H = 10cm
Experimental set-up

Set-up

- Building: 2-story or 4-story
- Environment: isolated or blocks (low/high; close or wide spacing)
- Room on Floor 2 with 1 or 2 apertures open
- 2 aperture arrangements \( \times 3 \) building/environments

Types of run

- “Closed box” runs
  - Pressure, velocity
  - \( \Delta \phi = 0^\circ, 11.25^\circ, \ldots, 180^\circ \)
  - All building/environment combinations
- Ventilation runs
  - Concentration decay
  - \( \Delta \phi = 0^\circ, 22.5^\circ, \ldots, 180^\circ \)
  - Some building/environment combinations
- Flow visualization runs
Flow rate and pressure difference related

Flow rate

Pressure difference

Non-dimensional flow rate

Pressure difference (in H2O)

Wind angle (deg from North)

S1:S8

S3:S6

Wide, symm

Narrow, symm
Pumping through openings in the lee
Correlation model for flow Q

\[
\frac{Q}{A_{in}U_{ref}} = \left\{ a_p |\Delta c_p| + a_\sigma \sigma_{\Delta c_p} \right\}^{1/2} + a_s \left( \frac{U_L}{U_{ref}} \right)
\]

- Mean pressure difference term
- \( a_p \) is constant
- Pressure fluctuation term
- \( a_\sigma \) is constant
- Shear term
- \( a_s \) is constant
- is local velocity
Optimal fit using pressure data

Parameter values at optimum:

\[ a_p = 0.2, \sigma_a = 0.1, \sigma_s = 0 \]
Incorporation in EnergyPlus

\[
\frac{Q}{A_{in}U_{ref}} = \left[ a_p |\Delta c_p| + a_\sigma \sigma_{\Delta c_p} \right]^{1/2}
\]

- Model depends on parameters \( \Delta c_p \) and \( \sigma_{\Delta c_p} \)
- E+ currently has *average* \( c_p \) for façade, \( \overline{c_p} \)
  \( \Rightarrow \) Need additional modeling to obtain \( \Delta c_p \) and \( \sigma_{\Delta c_p} \)
- As a minimum require
  - Basic variation of \( c_p \) over façade
  - Dependence of \( c_p \) on wind angle \( \phi \) (already available in E+)
  - Approximation for \( \sigma_{\Delta c_p} \) as function of \( \phi \)
Pressure data analysis

• Pressure sensors, e.g. 2-story building

• Focused on South façade

• Analyzed $\Delta p_{ij}(t) = p_i(t) - p_j(t)$ for different $i, j$ for each wind angle $\phi$
  
  $\rightarrow \Delta c_p(s/W_B, \phi)$ and $\sigma_{\Delta c_p}(s/W_B, \phi)$
Digression: time resolution

Full resolution $\Delta t = 0.001s$

Coarsen data by averaging over consecutive ranges $n\Delta t$

$n=1$

$n=10$

$n=50$
S3:S6: $\Delta c_p$ power spectrum (90°-180°)

- Bigger low frequency peaks beyond 135° as for $\Delta c_p$(S1:S8)
- No significant peaks at $f_{Strouhal}$ (?)

Power Scale as for S1:S8
Relation to standard deviation

- Cumulative power ($\sum P_k$) related to standard deviation ($\sigma \propto \sum P_k$)
- Graph shows 80% of power for $\phi=180^\circ$ by $\sim 30$Hz, while only 40% for $0^\circ$
Optimal fit for Q

Mean error = 25%

Prediction

Experiment

Correlation

$R^2 = 0.52$
Single-sided 1-aperture

\[ Q = a_s A_{in} U_L \]

- Flow calculation available in EnergyPlus but
  - Lacking advice on choosing local velocity \( U_L \)
  - Not part of airflow network calculation
- Add capability to estimate \( U_L \)
Local velocity $U_L$: experimental evidence

Warren & Parkins (1985)

- Use combination of data, CFD and simple modeling (Bernoulli) to relate $U_L$ to wind angle and pressure differences over building
Single-sided, many openings

- When more than 2 openings, group together
- In group add areas, use same $c_p$
- Needs algorithm in EnergyPlus to handle aggregation
Corner ventilation: wind tunnel

- Corner office with 2 openings on adjacent walls
- Wind angles 0°, ..., 337.5°
- Expect mixture of CV and SS
Corner ventilation modeling

- Blend of CV and SS2 → model as 2 regimes
- Use data and CFD to establish applicability of CV and SS models

Corner office flow rates $Q'$

Wind angle (deg from North)

Non-dimensional flow rate

“SS” “CV” “SS”

S6:E2 S6:E4 SS
Conclusions

• Developed new correlations for single-sided and corner ventilation
• Single-sided, 2 apertures
  – Flow dependent on mean pressure difference
  – Pumping flow dependent on unsteady pressure differences
• Single-sided, 1 aperture
  – Local velocity important in determining flow rates
  – Angle dependent
• Corner ventilation
  – Combination of cross ventilation and single-sided depending on wind direction
• EnergyPlus implementation
  – Cross ventilation, single-sided and corner ventilation to be in next release (December 2013)