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THE CALCULATION OF AIR INFILTRATION RATES CAUSED BY WIND AND STACK ACTION FOR TALL BUILDINGS

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The air that leaks through cracks and openings in a building envelope contributes to the heating and cooling loads of a building. Because its contribution to the total loads can be quite large, accurate estimates of infiltration rates are required for proper sizing of HVAC systems and analyzing the performance of various energy conservation measures. At present, methods for calculating infiltration rates are either over simplified with possible attendant large errors or very complicated involving the use of a computer model building.

A method for calculating the air infiltration rate caused by stack action was given in a previous ASHRAE paper[1] by the authors. For this paper, it was necessary to develop methods for calculating infiltration rates caused by wind action alone and in combination with stack action. A literature search for suitable wind pressures measurements for air infiltration calculations revealed that investigations of wind pressures on tall buildings have been directed almost exclusively to improving structural load calculations with measurements concentrated on those areas of the wall surfaces likely to be exposed to the greatest wind pressures. As air can leak through any part of exterior walls, detailed information on the distribution of wind pressures is required for infiltration calculation.

Recently, the National Aeronautical Establishment of the National Research Council of Canada (NRCC) conducted extensive pressure measurements on a tall building model in a boundary layer wind tunnel. Wind pressure data from this investigation were made available to the authors and, with the aid of a computer model building, procedures for calculating air infiltration rates were developed.

WIND TUNNEL PRESSURE MEASUREMENTS

Wind pressures on the surfaces of a plexiglass model representing a building 100 ft (31 m) by 150 ft (46 m) and 600 ft (183 m) high at a 1:400 scale, were measured in the 6 ft (1.83 m) by 9 ft (2.74 m) NRCC wind tunnel. The pressure taps on the model were distributed horizontally at the one-third and two-third heights for the four walls and vertically along the centerline of two adjacent walls (Fig. 1).

The wind velocity profile for a suburban boundary layer was simulated according to the following equation[2]

$$V_z = KZ^{1/3} \tag{1}$$

where V_z is the velocity at height Z above ground and K is constant. The velocity profile was developed in the tunnel using an upstream array of spires. No blocks were used to simulate ground roughness.

The model was placed on the turntable of the working section and was rotated 180 deg with a set of pressure readings taken at each 15-deg increment. They were converted to pressure

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Eq. 3 are also shown as dashed lines in Fig. 5. For wind angle of 0 deg (normal to the long wall) the C_p' curves are shifted to the right with values of C_p' greater than C_p for the windward wall and less for the leeward and side walls. For wind angle of 45 deg the values of C_p' and C_p are almost identical. The values of C_p' relative to those of C_p vary with wind direction as the former are referenced to the inside pressures which adjust to maintain a balance of air inflow and outflow.

At any level, the sum of the absolute values of C_p' of the windward and leeward or windward and side walls were about equal to those of C_p. Also, air flow inside the model building was mainly from the windward to the leeward and side walls with less than 5% of the total infiltration rate in the vertical direction from the central portion of the building to the upper and lower floors. It would appear that each floor behaved independently and can be treated separately when considering infiltration caused by wind action alone.

Fig. 6 shows the pressure differences across the four walls with changes in wind direction for the model building with width to length ratio of 1:1.5. They are expressed as the ratio of the pressure difference across the exterior wall over that of the long wall with wind acting normal to that wall (Side 1). The ratios can be estimated from the following equations obtained by curve fitting.

$$\text{Side 1} \qquad \frac{\Delta P_{\Theta,1}}{\Delta P_{o,1}} = -0.013\Theta + 1.0 \tag{4}$$

$$\text{Side 2} \qquad \frac{\Delta P_{\Theta,2}}{\Delta P_{o,1}} = 0.0165\Theta - 0.4 \tag{5}$$

$$\text{Side 3} \qquad \frac{\Delta P_{\Theta,3}}{\Delta P_{o,1}} = \begin{cases} -0.005\Theta - 0.14 & \text{for } 0 \le \Theta \le 45 \\ 0.003\Theta - 0.5 & \text{for } 45 \le \Theta \le 90 \end{cases} \tag{6}$$

$$\text{Side 4} \qquad \frac{\Delta P_{\Theta,4}}{\Delta P_{o,1}} = e^{(0.068\Theta - 6.914)} - 0.388 \tag{7}$$

where

Θ = wind angle measured counter clockwise from normal of Side 1, deg

$\Delta P_{o,1}$ = pressure difference across wall of Side 1 with Θ = 0 deg

$\Delta P_{\Theta,1}$, $\Delta P_{\Theta,2}$, $\Delta P_{\Theta,3}$, $\Delta P_{\Theta,4}$ = pressure differences across walls of Sides 1, 2, 3, and 4 for wind angle = Θ

The pressure difference across the long wall (Side 1) is maximum when Θ = 0 deg and decreases linearly with wind direction to zero at Θ = 75 deg. The pressure difference across the short wall (Side 2) is zero at Θ = 25 deg and increases linearly to a maximum value at Θ = 90 deg. Thus, as the wind angle changes from 0 to 90 deg, air infiltrates through the long wall from 0 to 25 deg, both the long and short walls from 25 to 75 deg and the short wall from 75 to 90 deg.

Fig. 7 shows the variation in infiltration rate with changes in wind angle and expressed as a ratio Q_Θ/Q_o where Q_Θ is the infiltration rate for a given wind angle Θ and Q_o is the long side infiltration rate with Θ = 0 deg. They are given for width to length ratios of 1:1, 1:1.5 and 1:2. Infiltration rates for any wind angle can be estimated from this figure knowing the infiltration rate of the long wall with Θ = 0 deg. It is seen that the maximum infiltration rate occurs when the wind direction is normal to the long wall.

Fig. 5 shows that the pressure difference coefficient, C_p', varies with height above ground. To simplify calculation of infiltration and exfiltration rates with wind acting normal to the long wall, mean pressure difference coefficients, C_{pm}', were calculated by solving for pressure difference, ΔP, in Eq 3 using the total infiltration rates obtained from the computer model results. The values are 0.96, - 0.13 and - 0.38 for the windward, leeward and side walls respectively.

$$Q_w = 5.375 \times 10^{-4} \alpha C_w LH^{1.435} V_s^{1.30} \quad (12)$$

where

Q_w = infiltration rate caused by wind, cfm (m^3/s)

α = Q_θ / Q_o (values from Fig. 7 for various wind angles)

C_w = flow coefficient, cfm/sq ft/(in. of water)$^{0.65}$ ($m^3/s/m^2$ $Pa^{0.65}$)

L = length of wall, ft (m)

H = building height, ft (m)

V_s = wind speed at weather station, mph (m/s)

Note: When SI units are used, replace constant 5.375×10^{-4} in Eq 12 by 0.0925.

Maximum infiltration rate occurs when wind is acting directly on the long wall with $\alpha = 1.0$.

Suggested values of C_w for curtain wall construction with sealed windows are as follows:[1]

	C_w	(SI Unit)
Tight wall	0.22	0.31×10^{-4}
Average wall	0.66	0.93×10^{-4}
Loose wall	1.30	1.83×10^{-4}
Masonry wall*	4.00	5.63×10^{-4}

* Measurement on one masonry wall building.[6]

The selection of the air tightness value for a curtain wall depends mainly on the joint design and workmanship during building construction. Air leakage tests on several buildings indicated that the exterior walls constructed with close supervision of workmanship can be expected to have low leakage rates.[1]

Example 1

Calculate total infiltration rate caused by 20 mph (8.94 m/s) wind measured at a weather station with wind acting directly on the long wall of a building 100 ft (31 m) by 150 ft (46 m) and 200 ft (61 m) high. The air leakage value of the exterior wall is $C_w = 0.66$ (0.93×10^{-4}). The building is located in a suburban terrain.

From Eq 12

$$Q_w = 5.375 \times 10^{-4} \times 1.0 \times 0.66 \times 150 \times (200)^{1.435} \times (20)^{1.30}$$
$$= 5240 \text{ cfm } (2.47\ m^3/s)$$

The corresponding leakage rate obtained from the full computer model was 5356 cfm.

The infiltration rate for other than wind acting normal to the long wall can be calculated using values of α in Fig. 7. For example, with wind angle of $\theta = 45$ deg the value of α for width to length ratio of 1:1.5 is 0.88.

Therefore

$$Q_w = 0.88 \times 5240 = 4611 \text{ cfm } (2.18\ m^3/s)$$

4690 cfm (computer result)

Nearby structures can affect wind pressures around a building. To investigate this effect on infiltration rate, wind pressure coefficients given by Bailey and Vincent[5] were applied to the computer model building. Results indicated that with the height of the shielding building of one-third, two-thirds and equal to the height of the shielded building and the distance between the buildings within 3 times the building width, the infiltration rate of the fully exposed building was reduced by 0, 20 and 60% respectively.

The graph was constructed to permit direct comparison of infiltration rates caused by wind and stack action. They are both expressed in cfm/sq ft of long wall area (Side 1 in Fig. [illegible]). To account for the variation in width to length ratio when considering stack action, the infiltration rates are plotted against an adjusted inside-outside temperature difference using the following equation which was deduced from Eq 13.

$$\Delta T_a = \left(\frac{1 + w/\ell}{1.67} \right)^{1.54} \Delta T \qquad (15)$$

where

ΔT_a = adjusted inside-outside temperature difference

ΔT = inside-outside temperature difference

w = width

ℓ = length

From Eq 15, ΔT_a equals ΔT for width to length ratio of 1:1.5.

In Fig. 8, any point on a constant building height line will give the wind velocity and ΔT_a required to produce equal infiltration rates. For example, for a building height of 200 ft (61 m), the infiltration rate caused by ΔT_a of 45 F (25 C) is equal to that caused by wind of 20 mph (8.94 m/s) as given by Point 1 of Fig. 8.

Air Infiltration Caused by the Combined Action of Wind and Stack Action

The computer results indicated that the air infiltration rates caused by stack action alone, Q_s, and wind action alone, Q_w, cannot be added to obtain the infiltration rate caused by the combination of both actions, Q_{ws}.

An equation was developed to calculate Q_{ws},

$$\frac{Q_{ws}}{Q_{lrg}} = 1 + 0.24 \left(\frac{Q_{sml}}{Q_{lrg}} \right)^{3.3} \qquad (16)$$

where

Q_{ws} = infiltration rate caused by combined wind and stack action

Q_{lrg} = larger value of Q_w and Q_s

Q_{sml} = smaller value of Q_w and Q_s

The two ratios in Eq 16 are plotted on Fig. 9. It shows that Q_{ws} is about equal to the infiltration rate caused by the larger of the two motive forces. When Q_w equals Q_s, Q_{sw} is 24% greater than either Q_w or Q_s.

Example 3

Calculate infiltration rate caused by both wind and stack action for the same building as in Examples 1 and 2 for wind speed of 20 mph (8.94 m/s), outside temperature of 0 F (-18 C) and inside temperature of 75 F (24 C).

From the results of Examples 1 and 2,

Q_w = 5240 cfm (2.45 m^3/s)

Q_s = 7180 cfm (3.39 m^3/s)

Windward Wall

From N = 0 to 0.7

ΔP_w = (0.72 to 0.48 N) $H^{2/3}$ V_s^2 x 10^{-5} (21)

Note - When SI units are used replace constant 10^{-5} by 0.0275

From N - 0.7 to 1.0

ΔP_w = 1.05 $H^{2/3}$ V_s^2 x 10^{-5} (22)

Note - When SI units are used replace constant 1.05 x 10^{-5} by 0.0289

Leeward Wall

ΔP_w = -1.27 $H^{2/3}$ V_s^2 x 10^{-6} (23)

Note - When SI units are used replace constant 1.27 x 10^{-6} by 0.0035.

Side Wall

ΔP_w = -3.64 $H^{2/3}$ V_s^2 x 10^{-6} (24)

Note - When SI units are used replace constant 3.64 x 10^{-6} by 0.010

For wind angles other than normal to the long wall apply factors from Eq 4, 5, 6 and 7 or Fig. 6 to pressure differences obtained from Eq 21.

Example 4

Calculate infiltration rates on the 5th floor of a 20-story building 100 ft (31 m) by 150 ft (46 m) and floor height of 10 ft (3.05 m) caused by a 20 mph (8.94 m/s) wind acting directly on the long wall and outside temperature of 0 F (-18 C) and inside temperature of 75 F (24 C). Y = 1; C_w = 0.66 (0.93x10^{-4}).

ΔP_s = 0.0143 x 1 (0.5 - $\frac{5}{20}$) 200 ($\frac{75}{460}$) (20)
= 0.116 in. of water (29.0 Pa)
0.123 in. of water (computer result)

Windward Wall

ΔP_w = (0.72 + 0.48 x $\frac{5}{20}$) $200^{2/3}$ 20^2 x 10^{-5} (21)
= 0.115 in. of water (28.6 Pa)
0.116 in. of water (computer result)

ΔP_{ws} = 0.115 + 0.116 (17)
= 0.231 in. of water (57.5 Pa)
0.223 in. of water (computer result)

Q_{ws} = 0.66 x 10 x 150 $(0.231)^{0.65}$ (11)
= 382 cfm (0.18 m^3/s)
378 cfm (computer result)

Leeward Wall

ΔP_w = -1.27 x $200^{2/3}$ 20^2 x 10^{-6} (23)
= -0.017 in. of water (4.32 Pa)
-0.015 in. of water (computer result)

ΔP_{ws} = -0.017 + 0.116 (17)
= 0.099 in. of water (24.6 Pa)
0.093 in. of water (computer result)

Tamura, G.T. and Wilson, A.G., "Pressure Differences Caused by Chimney Effect in Three High Buildings," ASHRAE Transactions, Vol. 73, Part II, 1967.

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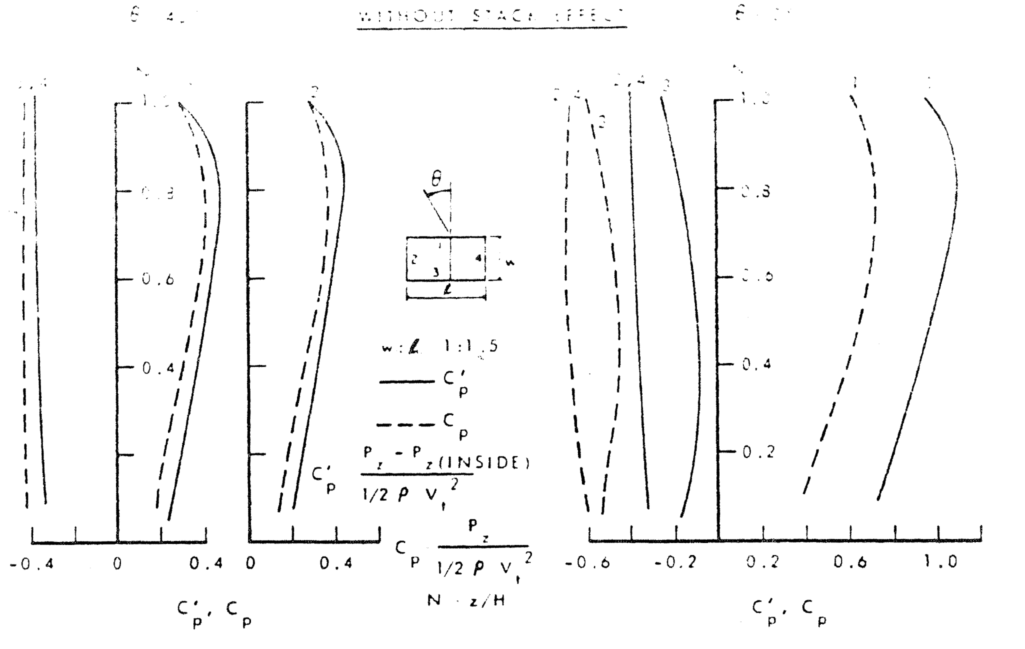

Fig. 5 Pressure difference coefficient, C_p', and wind pressure coefficient, C_p' vs height

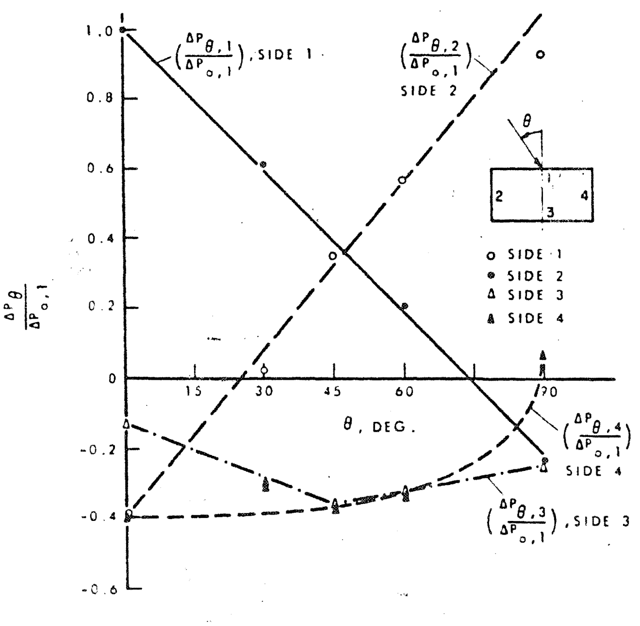

Fig. 6 Effect of wind direction on the mean pressure differences across exterior walls

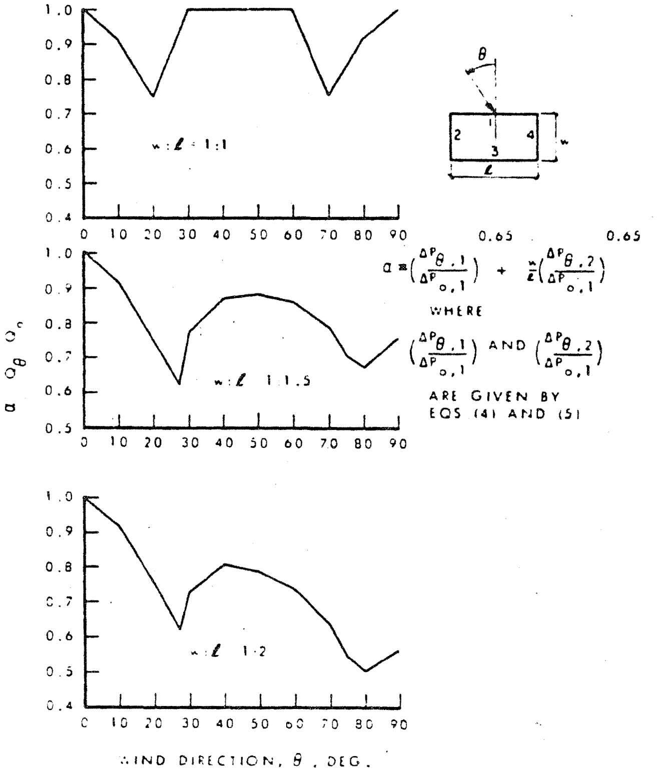

Fig. 7 Correction factor of air infiltration rate due to wind approaching at various directions