How To Determine Building Infiltration Rates at Low Reynolds Numbers

An easy-to-use procedure, more realistic than the broad approximations usually applied, is likely to result in cost savings.

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THE PREDICTION of infiltration rates for buildings exposed to variable wind impingement is a complex task at best, presently handled in design by the broadest of approximations. Many experimenters[1] have likened the placing of a stationary building in a moving air stream to the partial immersion of an object in a shallow moving stream of water, with the water level made analogous to the static pressure head.

Analyzing Wind Impingement

Referring to Fig. 1, note that the impinging wind sets up a velocity head along the windward wall illustrated. At any crack or opening along this wall, this velocity head will cause air to enter the building, provided the internal static pressure is less than the velocity head at a point immediately upstream of the opening. If we arbitrarily assign to the difference between these two pressures at any instant of time, t, a value of ΔP, then the resulting velocity, V, in feet per minute, of air moving through the opening is given by:

$$V = 4005 C_d (\Delta P)^{1/2} \qquad (1)$$

This relationship can be shown to be equivalent to the following equation, which expresses incompressible fluid flow through an orifice:

$$V' = K[2g(P_1 - P_2)/\rho]^{1/2} \qquad (2)$$

The term $(P_1 - P_2)$ is by definition the head loss, with P_1 and P_2 representing inlet and outlet pressures respectively. For air infiltration, it is reasonable to assume a negligible change in density, ρ, from inlet to outlet, along with standard conditions for air, and therefore use the simplified, more useful relationship represented by Equation 1.

Calculating Infiltration Rates

Until recently, it has been common practice to treat the so-called coefficient of discharge, C_d, as a constant, which one would naturally expect for turbulent flow. Ordinary orifice flow is easily calcu-

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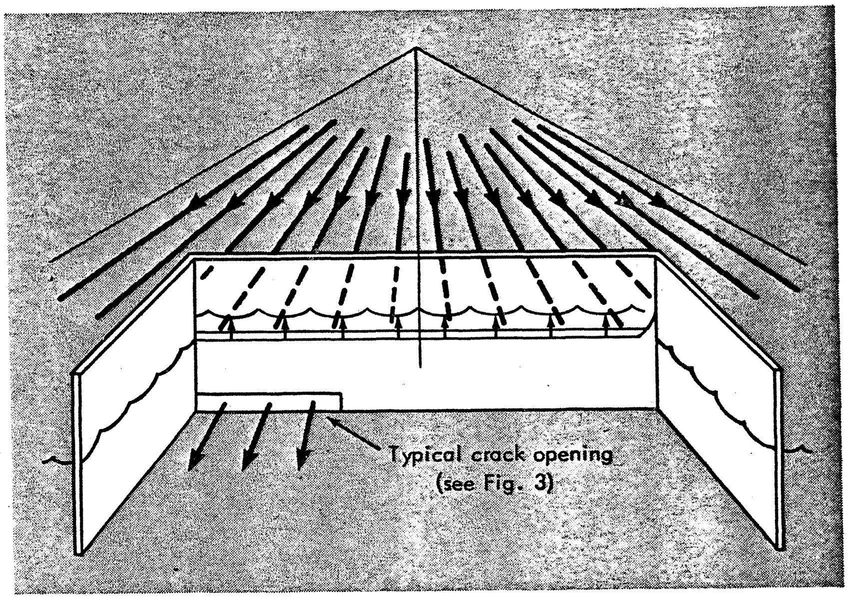
[1] Superscript numerals indicate references at end of article.



1 **PROFILE** of impingement on windward wall is illustrated.

lated on this basis. But when the restriction is too long for pure orifice flow and too short for assumption of linear flow, the solution of Equation 2 with C_d treated as a constant independent of flow regime parameters will lead to substantially erroneous results. This results from the following characteristics of close clearance orifices:

1) The velocity profile varies from uniform flow at the entrance to parabolic flow at the exit as side wall friction progressively retards the outer fluid layers along the passage.

2) The flow passages through minute cracks in building walls are rarely uniform; the configuration can be expected to vary significantly along the length of any such opening.

3) Laminar or boundary flow occurs when clearances are extremely close, and its characteristics differ significantly from those of turbulent flow.

Boundary Layer Phenomenon

It has been known for some time that the pressure drop of a fluid under laminar flow conditions in a short tube is significantly greater than values predicted by Poiseville's law, because of changes in the velocity profile near the tube entrance. In essence, when a fluid enters a small opening, the fluid particles at the interface with the inside surface are decelerated by the resulting viscous forces while the particles in the inner portions of the air stream remain unaffected for some distance from the

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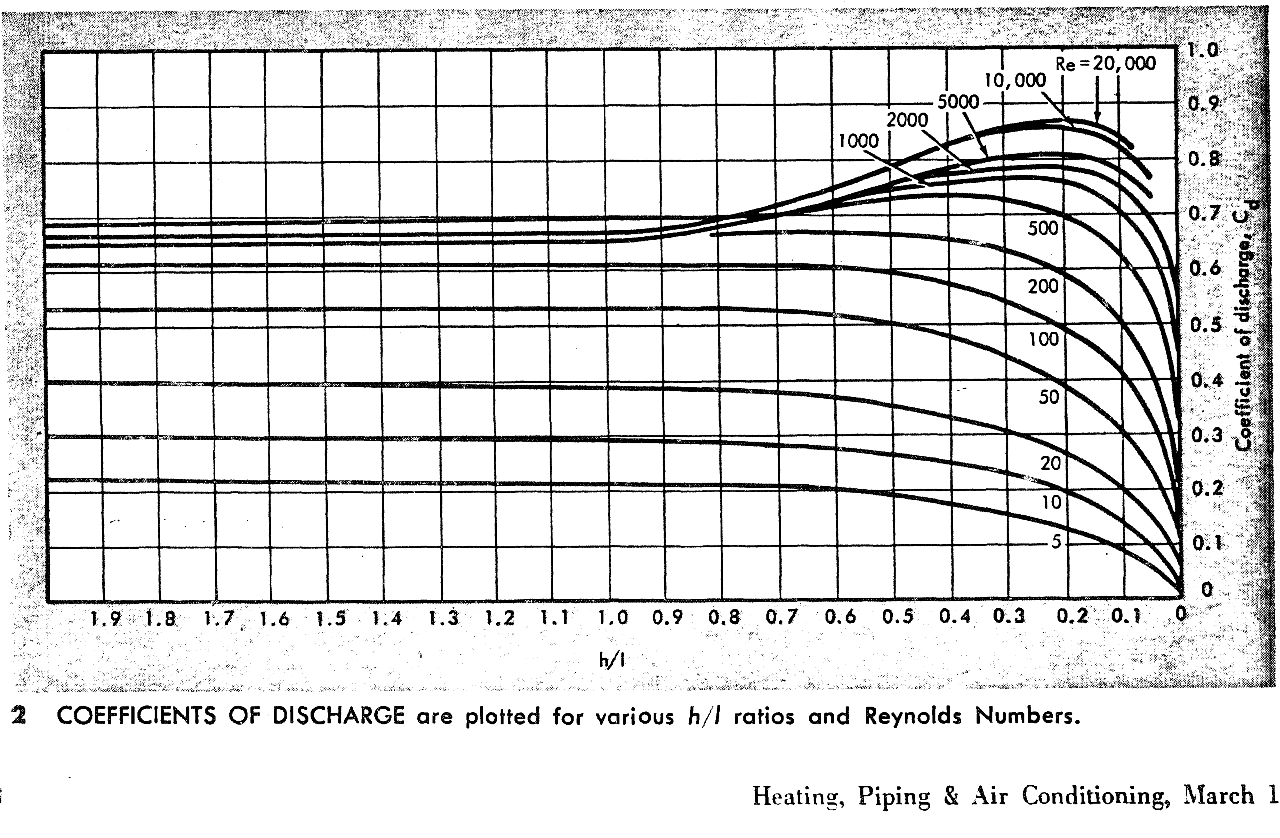


2 **COEFFICIENTS OF DISCHARGE** are plotted for various h/l ratios and Reynolds Numbers.

Nomenclature

K = orifice coefficient, dimensionless
C_d = coefficient of discharge, dimensionless
g = gravitational constant, 32.2 ft per sec^2
l = flow length, ft
w = equivalent width of opening, ft
h = equivalent height of opening, ft
P_1 = inlet pressure, lb per sq ft
P_2 = outlet pressure, lb per sq ft
ΔP = differential pressure across opening, in. WG
R_h = hydraulic radius, ft
D_e = equivalent diameter, ft
R_e = Reynolds Number, dimensionless
ρ = density of fluid, lb per cu ft
μ = absolute viscosity of fluid, lb per cu ft per sec
V = fluid velocity, fpm
V' = fluid velocity, fps

point of entry. Since the mass flow rate remains constant, the fluid in the inner portions of the air stream must speed up until the familiar velocity profile is reached at some distance from the point of entry.

The change in the momentum of the fluid in the inner portions of the air stream can only be provided by a force beyond that required to overcome the friction drag along the inner walls of the opening. This force appears as an increase in the pressure difference required to move a given quantity of fluid through a short tube. On this basis, experiments have been conducted[2] to correlate flows through short, close clearance openings, similar to tiny cracks in exterior building walls, with various length-to-equivalent diameter ratios characteristic of such openings.

These data are presented in a useful arrangement in Fig. 2.[3]

Using Reynolds Numbers

The key to using Fig. 2 to determine accurate values of C_d is the determination of the Reynolds Number. It will be recalled that for noncircular openings one can apply the concept of the hydraulic radius, R_h, with $4R_h$ being equivalent to the diameter of an opening for which the Reynolds Number analogy can be employed.

Recalling that R_h is by definition equal to the "area of the fluid flowing/wetted perimeter" and referring to Fig. 3, representing a slot type wall crack, we note that:

$$R_h = wh/2(w + h) \qquad (3)$$

Since D_e, the equivalent diameter, is equal to $4R_h$, we can write:

$$D_e = 2wh/(w + h) \qquad (4)$$

By definition $R_e = D_eV'\rho/g\mu$, and by variable substitution using Equation 4 and appropriate conversion factors, it can be shown that:

$$R_e = V\rho(wh)/30\mu(w + h) \qquad (5)$$

Using Equation 5 and Fig. 2 in a method of successive approximation, it is now possible to determine an accurate estimate of infiltration rates. This will be illustrated by example.

How To Estimate Infiltration Rate

Suppose we want to determine the velocity, V, of 70 F air entering a narrow crack in the curtain wall panel of a building facade, with approximate dimensions of $w = 2$ ft, $l = 1/16$ in., and $h = 1/64$ in., under the influence of 1.0 in. WG pressure differential.

At 70 F, $\mu = 4.79 \times 10^{-7}$ lb per sq ft per sec, and $\rho = 0.075$ lb per cu ft. Substituting all known quantities into Equation 1, we find that:

$$V = 4005C_d(1.0)^{1/2} = 4005C_d \text{ fpm}$$

Now substituting all known quantities into Equation 5, we obtain:

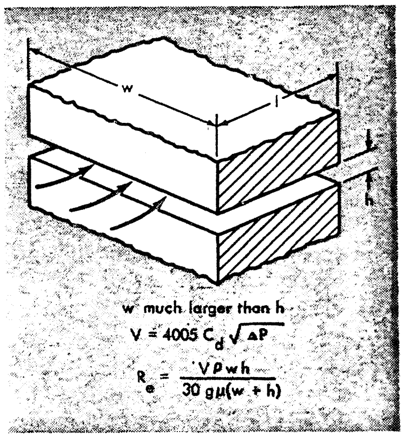
$$R_e = V \times 0.075 \times 2 \times 0.0013/30 \times 4.79 \times 10^{-7} \times 32.2 \times 2.0013 = 0.021V$$

But since $V = 4005C_d$, we know that:

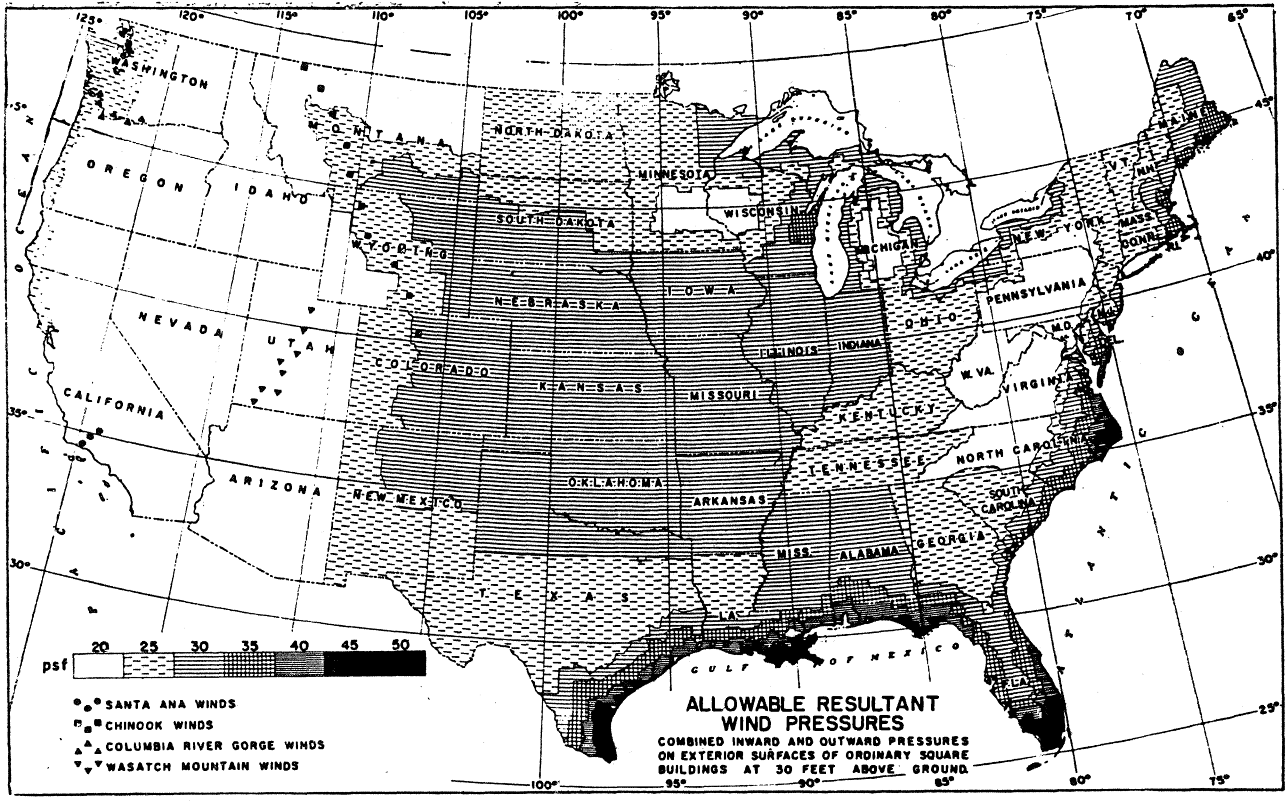
$$R_e = 84C_d$$

For our first trial, we will assume that $C_d = 0.4$, in which case $R_e = 33.6$ from the above relationship. Checking this against Fig. 2, however, we find that for $h/l = 0.25$ and $C_d = 0.4$, $R_e = 45$.

For the second trial, we will assume that $C_d = 0.3$, in which case $R_e = 25$. Referring again to Fig. 2, we find that for $h/l = 0.25$ and $C_d = 0.3$, $R_e = 25$, which checks. We now return to Equation 1 and substitute 0.3 for C_d:



3 TYPICAL CRACK in exterior building wall is depicted.



Courtesy International Conference of Building Officials

4 WIND PRESSURE MAP of United States is used with Table 1 to determine design wind pressures. Table 1 indicates wind pressures for various area key numbers, shown at lower left on the map.

TABLE 1—DESIGN WIND PRESSURES are tabulated for various areas of the country (area key numbers are obtained from Fig. 4) and various building height zones.

Building height zones, ft	Design wind pressure, in. WG for area key no.						
	20	25	30	35	40	45	50
Less than 30	0.41	0.54	0.67	0.67	0.81	0.95	1.08
30 to 49	0.54	0.67	0.81	0.95	1.08	1.21	2.02
50 to 99	0.67	0.81	1.08	1.21	2.02	1.48	1.62
100 to 499	0.81	1.08	1.21	1.48	1.62	1.88	2.02
500 to 1199	0.95	1.21	1.48	1.62	1.88	2.16	2.42
1200 and over	1.08	2.02	1.62	1.88	2.16	2.42	2.69

$$V = 4005 \times 0.3 = 120 \text{ fpm}$$

Now let us assume turbulent flow and a nominal value of C_d = 0.61. Repeating the above calculation, we find that:

$$V = 4005 \times 0.61 = 244 \text{ fpm}$$

This results in an error of 104 percent for this example.

Design Wind Pressures

Fig. 4 is a map of the United States with various wind pressure zones indicated.[4] To determine the applicable design wind pressure for calculating infiltration rates for a building located in a specific locality, refer to Fig. 4 and determine the appropriate area key number in the lower left hand corner. Refer next to Table 1 and determine the design wind pressure for the appropriate key number and building height zone. Table 1 was developed by assuming that 20 percent of the recommended Uniform Building Code[4] wind pressure loads for structural design, adjusted for the effect of flow around a building, represents a reasonable approximation for estimating average wind impingement pressures at coincident building cooling or heating loads.

To illustrate use of the map and table, assume that we wish to determine the wind impingement pressure at a window crack on the 11th floor (approximately 130 ft above grade) of a building in Los Angeles. Referring to Fig. 4, the area key number is seen to be 20. Referring next to Table 1, for this key number and a height zone of 100 to 499 ft the wind impingement pressure is seen to be 0.81 in. WG. The algebraic difference between this value and the internal static pressure (above ambient) maintained at the 11th floor would be equal to ΔP for the direct solution of Equation 1.

ΔP Distribution

A proper estimate of ΔP requires a full evaluation of the distribution of pressure differences across the entire building and not just the exterior wall alone. This distribution is dependent on the action of the impinging wind, the stack effect, the effect of air handling systems on the air leakage characteristics of the building enclosure, and the internal separations. This relationship is graphically portrayed in Fig. 5.

Note that a uniform vertical distribution of exterior openings and a linear relationship between flows through all such openings has been assumed for the purpose of simplicity. The actual pressure profile for a building as a function of height is often difficult to predict accurately since:

1) Excess ventilation air is not normally introduced uniformly on all floors.

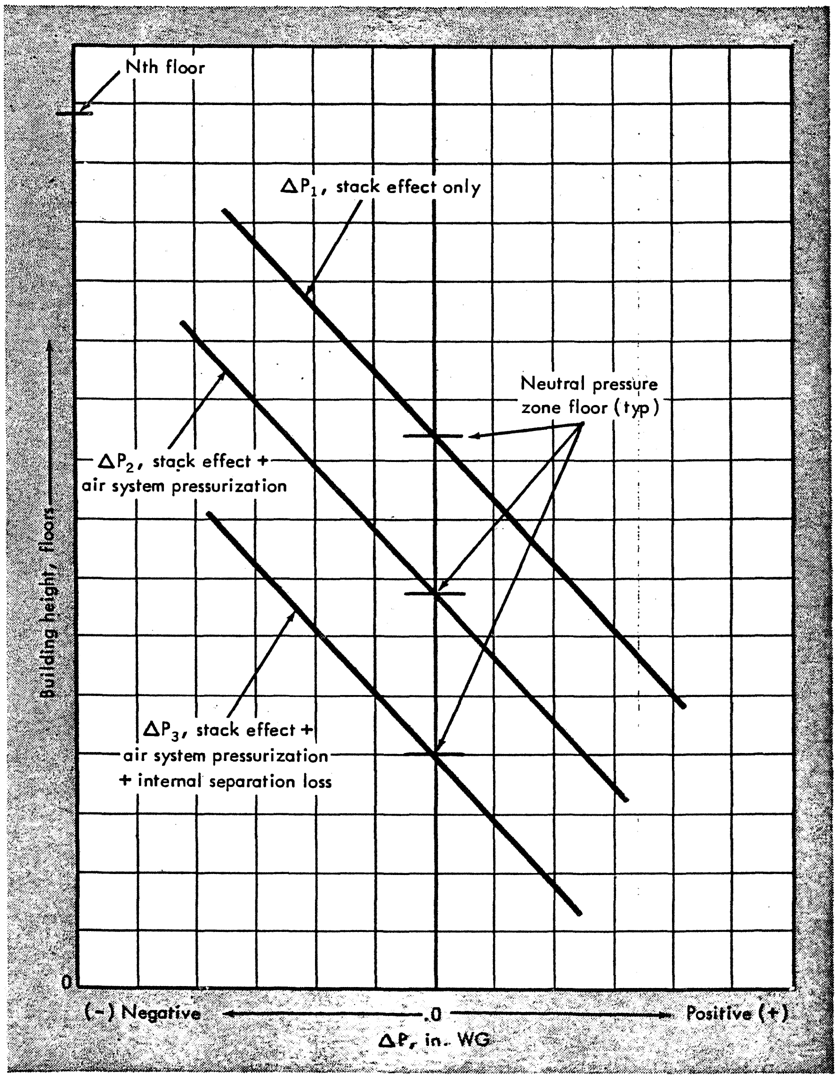
2) Pressure differences between floors may be variable.

3) Few data are available on the pressure drop through internal separations.

Further, air flows enter a building on the windward side and exit on the leeward side. For this reason, the pressure differential across a windward wall could be lower than those on other walls (unless interior construction permits pressure isolation of various spaces), and would have to be considered in estimating the maintained space static pressure adjacent to each wall section under study.

The pressurization increment for a sealed building depends on the volume of the building and is fixed by the pressure ratio established by the atmospheric datum pressure to the atmospheric datum plus velocity pressure. For a leaky building, the pressure increment is a function of the leak orifice,[1] and continuous replenishing is required.

In any event, the equilibrium static pressure within a building depends on the relative sizes and discharge coefficients of leak openings in the available paths from windward to leeward facades. The resulting variation in exterior wall pressure differential for most buildings will be on the order of ±0.10 in. WG, and the procedure outlined previously can be expected to provide reasonably conservative results.



5 EXTERIOR WALL pressure difference is plotted against building height. Effects of stack effect, air system pressurization, and internal separation are illustrated.

In Summary...

The assumption of higher than probable values of C_d for openings and cracks in calculating infiltration rates for buildings has resulted in excessive allowances for heating and cooling capacity to offset such effects. It has sometimes been argued that pressurization of perimeter building areas can all but eliminate infiltration. Offsetting the impingement velocities normally encountered, however, may result in excessive pressurization costs and waste of installed fan horsepower.

With today's widespread use of close tolerance construction materials, the assumption of turbulent flow coefficients of discharge in infiltration calculations is quite unrealistic, as was illustrated in the example presented earlier. Use of the methods described herein for determining infiltration rates will result in reduced internal pressurization requirements to offset wind impingement. ‡

References

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4) *Uniform Building Code*, 1961 Ed., Vol. 1, International Conference of Building Officials, pp. 101-104.