Estimating Air Leakage Through Doors for Smoke Control

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Abstract

A generalized, nondimensional relationship for flow through defined narrow gaps is used to predict leakage flow past closed door assemblies. Typical gap shapes considered include straight-through; single or double sharp (90°) bends; baffle at leading edge; comb-type labyrinth; and filament brush seal. Applications for prediction and design appropriate to smoke control systems are indicated.

Introduction

One of the most difficult design problems in maintaining the firesafe integrity of separating elements deals with joint and penetration details. Doors within walls represent a major challenge, in terms of both flame penetration and the passage of smoke and gases. With the increased attention now being given to the design of buildings to control smoke movement and to maintain smoke-free areas of refuge, better information on the flow of air and smoke-air mixtures through closed door assemblies is needed.

A method for predicting air leakage rates through defined narrow gaps around door edges over wide pressure and temperature ranges has been developed.[1] The analysis that formed the basis for the prediction method demonstrated that even for simple rectangular-shaped gaps, the conventional flow equation appropriate for sharp-edged orifices, $Q = C A (\Delta p)^{1/2}$, does not apply over the entire flow range of interest. In particular, the exponent varies continuously from 0.5 for high values of pressure difference and flow to 1.0 for low values of pressure difference and flow. The corresponding Reynolds number range goes from over 20,000 down to 10 or less. The analysis also takes into account the

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pressure drops experienced at sharp (90°) bends, sudden enlargements and contractions, and the effects of elevated temperature on the density and viscosity of the flowing air. For example, it has been found that the flow rate may increase or decrease with temperature depending on gap size and flow region. No account is taken in this method of the presence of smoke particulates or of the effects of transients or of variations in pressure difference. However, solid or liquid smoke particulates generally move along with heated air as a fluid mixture, and variable pressures and pressure gradients can be treated readily by averaging or integral approaches.

Since the published analysis uses generalized, nondimensional relationships, the purpose of this article is to provide simpler, more convenient techniques for prediction and design. It is hoped that such predictions will be of general use in the analysis of flow through closed door assemblies and specifically in the design of smoke control systems. It is also anticipated that the analytical method will allow door suppliers and users to estimate the performance in the test method standard[2] specified in NFPA 105 for the installation of smoke-control door assemblies[3] and will suggest ways in which door edge details may be modified to meet the established criteria. However, this method should not be considered a substitute for the standard test, particularly where very complex gaps and/or flexible sealing devices are employed, and where thermal effects such as deformations of door members or seals will occur.

Narrow Gaps and Labyrinths

Narrow gaps between doors and frames provide leakage paths of simple, defined geometrical shape. They provide a certain degree of control of air and smoke leakage by restricting the flow to narrow passages of appreciable depth and usually with one or more sharp bends. For such arrangements, the leakage flow rate may be calculated readily from previously established nondimensional relationships.[1] For a typical single-leaf swinging door with straight-through gaps of uniform thickness, Figure 1 provides leakage flow rate directly for a range of pressure differences. Similarly, Figure 2 gives flow rates for gaps with zero, one and two sharp (90°) bends. These graphs apply to constant pressure flow through gaps at the top and two sides only, an arrangement specified in the standard test method to simulate a common field condition. For flow through uniform thickness gaps along the top, sides, and bottom, multiply the flow rate by 1.18. As may be seen, the reduction in air leakage from the use of multiple bends may be appreciable, especially in comparison to a typical 0.91 m by 2.13 m by 44.5 mm (3 ft by 7 ft by 1-3/4 in.) unimproved door with nominal clearances. However, in order to derive long-term benefit from the special designs, the fixed

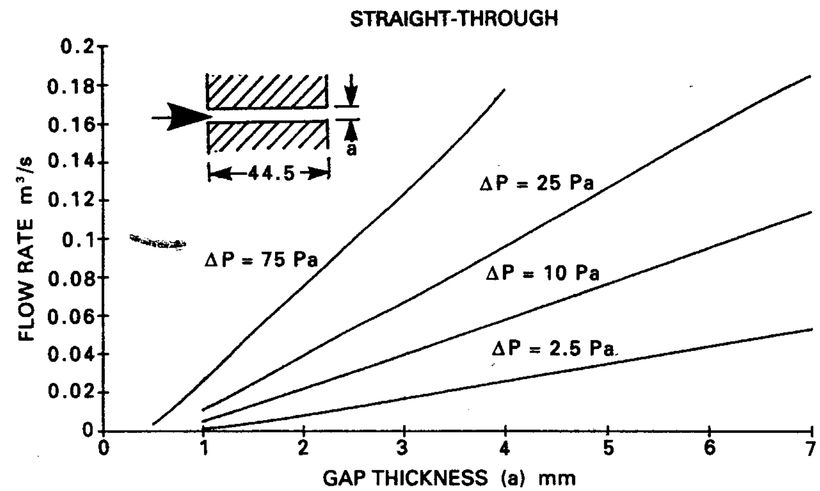

Figure 1. Straight-through gaps of uniform thickness (0.91 m by 2.13 m by 44.5 mm door).

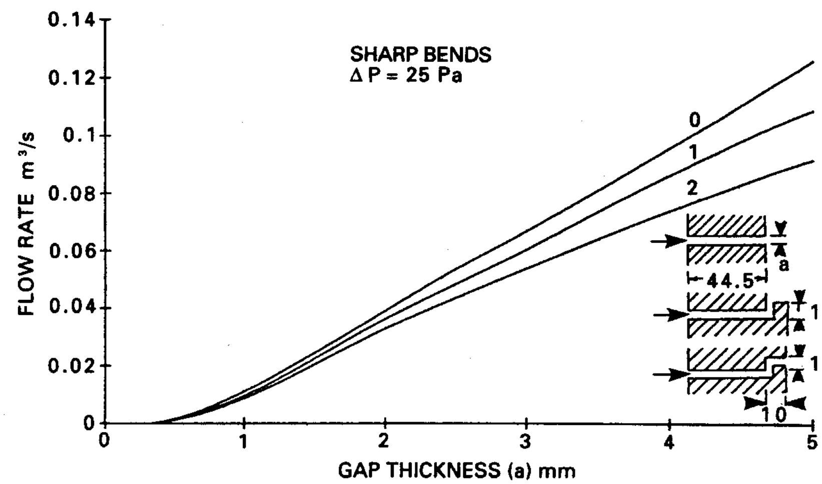

Figure 2. Gaps with 0, 1, and 2 sharp (90°) bends.

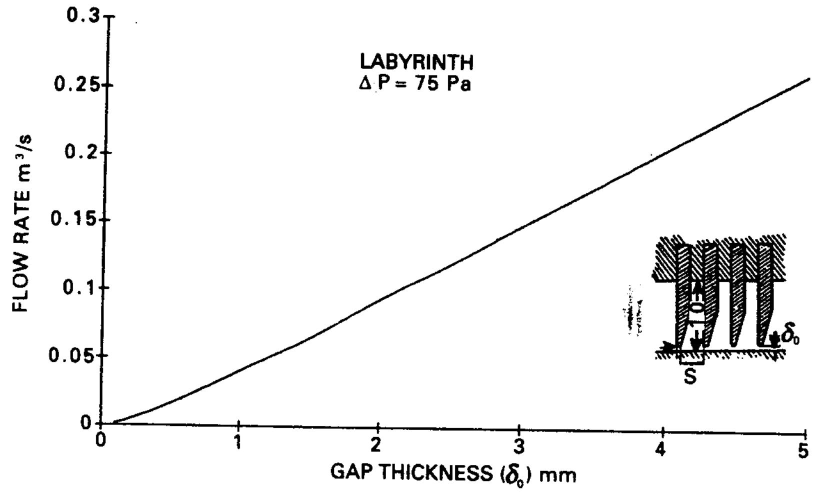

Figure 3. Comb-type labyrinth seal.

narrow passages need to be maintained without distortion or deformation.

A labyrinth makes use of more complex shapes and surfaces to restrict flow in the gap between the door leaf and the frame. These may consist of a simple series of comblike baffles or of combinations of staggered baffles, protuberances, and sudden expansions, contractions and bends all of which serve to increase flow resistance by lengthening the flow path and by forming energy dissipating eddies. Figure 3, based on design data from Idelchik,[4] shows results for a simple comb-type labyrinth seal composed of Z (=15) multiple cells, with a spacing distance S (=1 mm) and a gap δ_0 ranging from 0.1 to 5.0 mm.

Gaps with Flexible Seals

A wide range of flexible gaskets, strips, and fiber brushes may be used to provide contact between the door leaf and the frame. In this case, the geometry of the leakage path is not very clearly defined and usually varies depending on degree of flexibility, wear, and localized deformations or irregularities. Thus, prediction of leakage through such gaps may not be feasible unless it is assumed that the sealing device deforms so as to provide a fixed orientation and defined flow passages upon closure of the door.

Some information is available from standard sources for laminar flow past regular arrays of cylindrical tubes (tube banks) and fiber bundles,

particularly for fully developed transverse and axial flow.[5] Recently, numerical predictions have extended the range of such analyses to take into account the effects of fully developed inclined flow and of developing transverse flow.[6] In the low flow range of interest here, the pressure-drop coefficient varies inversely with the Reynolds number and flow rate is proportional to pressure difference.

For randomly packed filaments, an equilateral triangular array may represent a reasonable approximation of the geometrical orientation of the fibers. Assuming a tightly packed equilateral triangular array with a pitch to fiber-diameter ratio (P/D) of 1.10, the relationship $C_p Re = 500$, where C_p is the pressure coefficient and Re is the Reynolds number, may be appropriate for inclined or vertical tubes (75° to 90°) at low Reynolds numbers (of the order of 1 based on filament diameter).

As an illustration, estimates of air leakage were attempted for a door assembly provided with a filament brush seal (or sweep) along the door edges where flow would occur. A typical brush was assumed to consist of flexible polymeric filaments with the following characteristics:

Individual filament diameter	0.15 mm (0.006 in.)
Spacing between filaments	0.015 mm (0.0006 in.)
Brush depth (normal to flow)	2.5 mm (0.1 in.)
Gap thickness (width without brush)	12.5 mm (0.5 in.)
Aggregate number of filaments	91800 per meter
Number of filaments (normal to flow)	15

The computed leakage flow for a typical door having a perimeter of 5.18 m is of a reasonable order of magnitude (0.015 m^3/s at Δp = 75 Pa). However, considerably greater leakages at door corners would be expected where individual segments of vertical and horizontal brush seals meet. A comparison of flow rates for the different geometries of selected narrow gaps, a comb-type labyrinth, and a filament brush seal is given in Table 1.

Design for Smoke Control

The ASHRAE manual for design of smoke control systems for buildings[7] provides limited information on flow through closed door assemblies that are designed specifically to restrict air and smoke passage. If the information in this paper were employed in the design of a pressurized smoke control system, changes in air supply quantities may be anticipated. For example, the handbook estimates a flow rate of 0.073 m^3/s through a gap of area equal to 0.01 m^2 for Δp = 75 Pa. For a flow perimeter of 5.18 m, the equivalent straight-through gap thickness would be 1.93 mm, and from Figure 1, the leakage flow rate is found to

Table 1. Calculated airflow through door gaps. Sides and top perimeter 5.18 m; Δp = 75 Pa.

Gap Configuration	Thickness Basic Gap (mm)	Restricted Section (mm)	Calculated Flow (m^3/s)
Straight-through	3		0.123
	1		0.026
Single bend	3		0.110
Double bend	3		0.098
Baffle at Leading Edge	3	3	0.109
Labyrinth	3	0.5	0.047
	10	1	0.040
	10	0.5	0.016
	10	0.2	0.0047
Filament brush seal	12.5	0.015	0.015

be 0.072 m^3/s. This is the region in which Q is proportional to $\Delta p^{1/2}$. However, at the much lower pressure difference of Δp = 2.5 Pa, the value of flow rate as determined from Gross and Haberman[1] is 0.0075 m^3/s versus the ASHRAE manual value of 0.013 m^3/s. This is the region where the flow rate has been shown to be almost proportional to the pressure difference.

Conclusions

A generalized relationship between pressure difference and flow through narrow gaps has been shown in a previous paper[1] to provide a more accurate means of predicting airflow through closed door assemblies with special application to smoke control. This paper has demonstrated the capabilities of several methods of restricting flow along door edges such as sharp single and double bends and simple baffles. Approximate estimates have also been provided of flow through labyrinths and filament brush seals of known or assumed geometrical configurations.

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