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SMOKE CONTROL

John H. Klote

INTRODUCTION

In building fire situations, smoke often flows to locations remote from the fire, threatening life and damaging property. Stairwells and elevators frequently become smoke-logged, thereby blocking and/or and inhibiting evacuation. Today smoke is recognized as the major killer in fire situations.[1]

In the late 1960s, the idea of using pressurization to prevent smoke infiltration of stairwells started to attract attention. This was followed by the idea of the "pressure sandwich," i.e., venting or exhausting the fire floor and pressurizing the surrounding floors. Frequently, the building's ventilation system is used for this purpose. The term "smoke control" was coined as a name for such systems that use pressurization produced by mechanical fans to limit smoke movement in fire situations.

Research in the field of smoke control has been conducted in Australia, Canada, England, France, Japan, the United States, and West Germany. This research has consisted of field tests, full-scale fire tests, and computer simulations. Many buildings have been built with smoke control systems and numerous others have been retrofitted for smoke control.

In this chapter the term smoke is defined in accordance with the American Society for Testing and Materials (ASTM)[2] and the National Fire Protection Association (NFPA)[3] definitions which state that smoke consists of the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis of combustion.

SMOKE MOVEMENT

A smoke control system must be designed so that it is not overpowered by the driving forces that cause smoke movement. For this reason, an understanding of the fundamental concepts of smoke movement and of smoke control is a prerequisite to intelligent smoke control design. The major driving forces causing smoke movement are stack effect, buoyancy, expansion, wind, and the heating, ventilating, and air conditioning (HVAC) system. Generally, in a fire situation, smoke movement will be caused by a combination of these driving forces. The following subsections are a discussion of each driving force as it would act independent of the presence of any other driving force.

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Stack Effect

When it is cold outside, there is often an upward movement of air within building shafts such as stairwells, elevator shafts, dumbwaiter shafts, mechanical shafts, or mail chutes. This phenomenon is referred to as normal stack effect. The air in the building has a buoyant force because it is warmer and less dense than the outside air. This buoyant force causes air to rise within the shafts of buildings. The significance of normal stack effect is greater for low outside temperatures and for tall shafts. However, normal stack effect can exist in a one-story building.

When the outside air is warmer than the building air, a downward airflow frequently exists in shafts. This downward airflow is called reverse stack effect. At standard atmospheric pressure, the pressure difference due to either normal or reverse stack effect is expressed as

$$\Delta P = K_s\left(\frac{1}{T_0} - \frac{1}{T_I}\right)h \qquad (1)$$

where:

ΔP = pressure difference, in. H_2O (Pa)

T_0 = absolute temperature of outside air, R (K)*

T_I = absolute temperature of air inside shaft, R (K)*

h = distance above neutral plane, ft (m)**

K_s = coefficient, 7.64 (3460).

For a building 200 ft (60 m) tall, with a neutral plane at the midheight, an outside temperature of 0°F (−18°C) and an inside temperature of 70°F (21°C), the maximum pressure difference due to stack effect would be 0.22 in. H_2O (55 Pa).

* Because the Fahrenheit and Celsius temperature scales are so commonly used by design engineers, these scales are used exclusively in the discussions in the text and in figures. However, the reader is cautioned to use absolute temperatures in calculations where such temperatures are stipulated.

** The neutral plane is the horizontal plane where the hydrostatic pressure inside equals that outside.

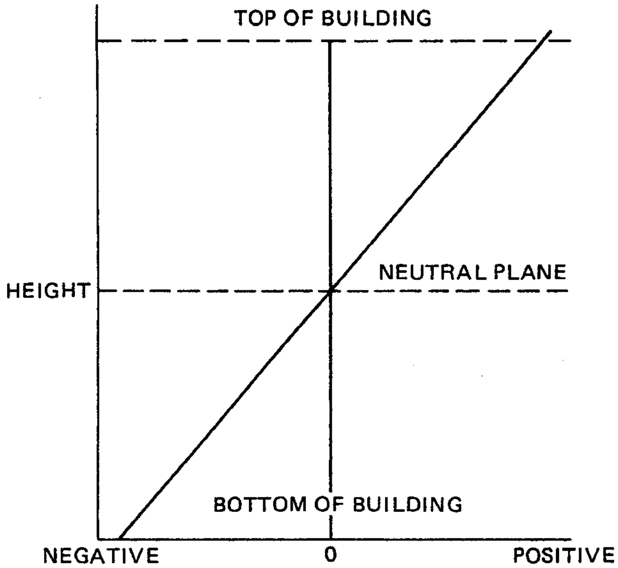

Fig. 4-12.1. Pressure difference between an inside shaft and the outside due to normal stack effect.

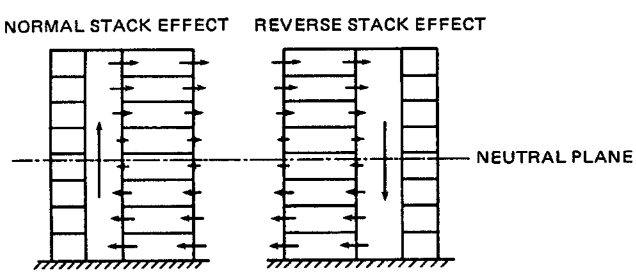

Fig. 4-12.2. Air movement due to normal (left) and reverse stack effect (right). Note: arrows indicate direction of air movement.

This means that at the top of the building, a shaft would have a pressure of 0.22 in. H_2O (55 Pa) greater than the outside pressure. At the bottom of the shaft, the shaft would have a pressure of 0.22 in. H_2O (55 Pa) less than the outside pressure. Figure 4-12.1 is a diagram of the pressure difference between a building shaft and the outside. In the diagram, a positive pressure difference indicates that the shaft pressure is higher than the outside pressure, and a negative pressure difference indicates the opposite.

Stack effect is usually thought of as existing between the inside of a building and the outside atmosphere. The air movement in buildings caused by both normal and reverse stack effect is illustrated in Figure 4-12.2. In this case, the pressure difference expressed in Equation 1 would actually refer to the pressure difference between the shaft and the outside of the building.

Figure 4-12.3 can be used to determine the pressure difference due to stack effect. For normal stack effect, the term $\Delta P/h$ is positive, and the pressure difference is positive above the neutral plane and negative below it. For reverse stack effect, the term $\Delta P/h$ is negative, and the pressure difference is negative above the neutral plane and positive below it.

In unusually airtight buildings with exterior stairwells, reverse stack effect has been observed even with low outside air temperatures.[4] In this situation, the exterior stairwell temperature was considerably lower than the building temperature. The stairwell was the cold column of air and other shafts within the building were the warm columns of air.

When considering stack effect, if the air leakage paths between a building and the outside are fairly uniform with height, the neutral plane will be located near the midheight of the building. However, when the leakage paths are not uniform, the location of the neutral plane can vary considerably, as in the case of vented shafts. McGuire and Tamura[5] provide methods for calculating the location of the neutral plane for some vented conditions.

Smoke movement from a building fire can be dominated by stack effect. In a building with normal stack effect, the existing air currents (as shown in Figure 4-12.2) can move smoke considerable distances from the fire origin. If the fire is below the neutral plane, smoke moves with the building air into and up the shafts. This upward smoke flow is enhanced by any buoyancy forces on the smoke existing due to its temperature. Once above the neutral plane, the smoke flows out of the shafts into the upper floors of the building. If the leakage between floors is negligible, the floors below the neutral plane, except the fire floor, will be relatively smoke free until the quantity of smoke produced is greater than can be handled by stack effect flows.

Smoke from a fire located above the neutral plane is carried by the building airflow to the outside through openings in the exterior of the building. If the leakage between floors is negligible, all floors other than the fire floor will remain relatively smoke-free, again, until the quantity of smoke produced is greater than can be handled by stack

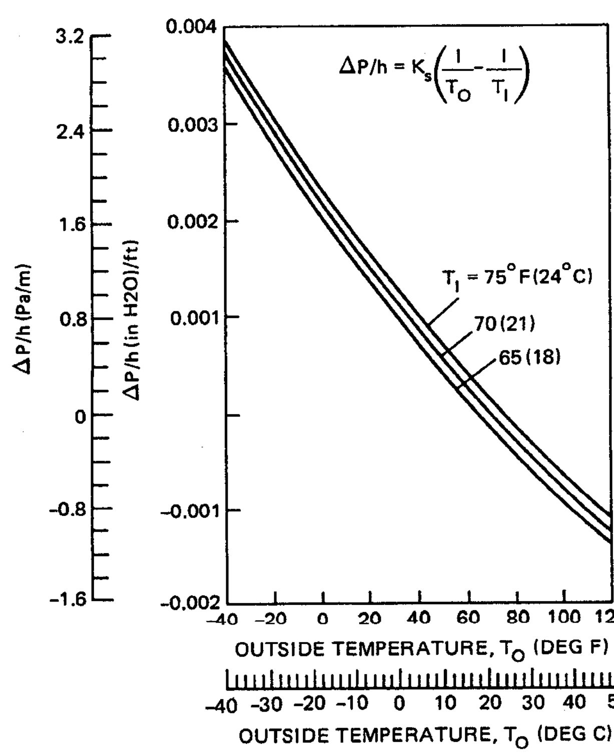

Fig. 4-12.3. Pressure difference due to stack effect.

effect flows. When the leakage between floors is considerable, there is an upward smoke movement to the floor above the fire floor.

The air currents caused by reverse stack effect are also shown in Figure 4-12.2. These forces tend to affect the movement of relatively cool smoke in the reverse of normal stack effect. In the case of hot smoke, buoyancy forces can be so great that smoke can flow upward even during reverse stack effect conditions.

Buoyancy

High-temperature smoke from a fire has a buoyancy force due to its reduced density. The pressure difference between a fire compartment and its surroundings can be expressed by an equation of the same form as Equation 1.

$$\Delta P = K_s\left(\frac{1}{T_0} - \frac{1}{T_F}\right)h \qquad (2)$$

where:

ΔP = pressure difference, in. H_2O (Pa)
T_0 = absolute temperature of the surroundings, R (K)
T_F = absolute temperature of the fire compartment, R (K)
h = distance above the neutral plane, ft (m)
K_s = coefficient, 7.64 (3460).

The pressure difference due to buoyancy can be obtained from Figure 4-12.4 for the surroundings at 68°F (20°C). The neutral plane is the plane of equal hydrostatic pressure between the fire compartment and its surroundings. For a fire with a fire compartment temperature of 1470°F (800°C), the pressure difference 5 ft (1.52 m) above the neutral plane is 0.052 in. H_2O (13 Pa). Fang[6] has studied pressures caused by room fires during a series of full-scale fire tests. During these tests, the maximum pressure difference reached was 0.064 in. H_2O (16 Pa) across the burn room wall at the ceiling.

Much larger pressure differences are possible for tall fire compartments where the distance, h, from the neutral plane can be larger. If the fire compartment temperature is 1290°F (700°C), the pressure difference 35 ft (10.7 m) above the neutral plane is 0.35 in. H_2O (88 Pa). This amounts to an extremely large fire, and the pressures produced by it are beyond the state-of-the-art of smoke control. However, the example is included here to illustrate the extent to which Equation 2 can be applied.

In a building with leakage paths in the ceiling of the fire room, this buoyancy-induced pressure causes smoke movement to the floor above the fire floor. In addition, this pressure causes smoke to move through any leakage paths in the walls or around the doors of the fire compartment. As smoke travels away from the fire, its temperature drops due to heat transfer and dilution. Therefore, the effect of buoyancy generally decreases with distance from the fire.

Expansion

In addition to buoyancy, the energy released by a fire can cause smoke movement due to expansion. In a fire compartment with only one opening to the building, building air will flow into the fire compartment and hot smoke will flow out of the fire compartment. Neglecting the added mass of the fuel (which is small compared to the airflow), the ratio of volumetric flows can simply be expressed as a ratio of absolute temperatures.

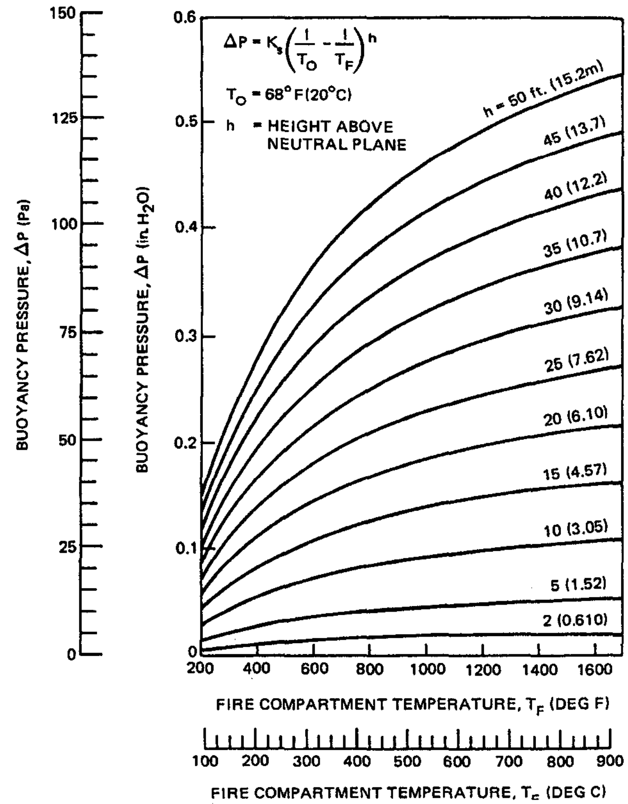

Fig. 4-12.4. Pressure difference due to buoyancy.

$$\frac{Q_{out}}{Q_{in}} = \frac{T_{out}}{T_{in}}$$

where:

Q_{out} = volumetric flow rate of smoke out of the fire compartment, cfm (m^3/s)
Q_{in} = volumetric flow rate of air into the fire compartment, cfm (m^3/s)
T_{out} = absolute temperature of smoke leaving fire compartment, R (K)
T_{in} = absolute temperature of air into fire compartment, R (K).

For a smoke temperature of 1290°F (700°C) the ratio of volumetric flows would be 3.32. The reader is reminded to use absolute temperatures for calculation. In such a case, if the air flowing into the fire compartment is 3180 cfm (1.5 m^3/s), then the smoke flowing out of the fire compartment would be 10,600 cfm (4.98 m^3/s). In this case, the gas has expanded to more than three times its original volume.

For a fire compartment with open doors or windows, the pressure difference across these openings due to expansion is negligible. For a tightly sealed fire compartment, however, the pressure differences due to expansion may be important.

Wind

In many instances, wind can have a pronounced effect on smoke movement within a building. The pressure, P_w, that the wind exerts on a surface can be expressed as

$$P_w = \frac{1}{2}C_w\rho_o V^2 \qquad (3)$$

where:

C_w = dimensionless pressure coefficient
ρ_O = outside air density
V = wind velocity.

For an air density of 0.075 lb/ft^3 (1.20 kg/m^3) this relation becomes

$$P_w = C_w K_w V^2 \quad (3a)$$

where:

P_w = wind pressure, in. H_2O (Pa)
V = wind velocity, mph (m/s)
K_w = coefficient, 4.82×10^{-4} (0.600).

The pressure coefficients, C_w, are in the range of -0.8 to 0.8, with positive values for windward walls and negative values for leeward walls. The pressure coefficient depends on building geometry and varies locally over the wall surface. In general, wind velocity increases with height in the boundary layer nearest the surface of the earth. Detailed information concering wind velocity variations and pressure coefficients is available from a number of sources.[7–10] Specific information about wind data, with respect to air infiltration in buildings, has been generated by Shaw and Tamura.[11]

A 35 mph (15.6 m/s) wind produces a pressure on a structure of 0.47 in. H_2O (117 Pa) with a pressure coefficient of 0.8. The effect of wind on air movement within tightly constructed buildings with all doors and windows closed is slight. However, the effects of wind can become important for loosely constructed buildings or for buildings with open doors or windows. Usually, the resulting airflows are complicated and, for practical purposes, computer analysis is required.

Frequently in fire situations, a window breaks in the fire compartment. If the window is on the leeward side of the building, the negative pressure caused by the wind vents the smoke from the fire compartment. This can greatly reduce smoke movement throughout the building. However, if the broken window is on the windward side, the wind forces the smoke throughout the fire floor and even to other floors. This both endangers the lives of building occupants and hampers fire fighting. Pressures induced by the wind in this type of situation can be relatively large and can easily dominate air movement throughout the building.

HVAC Systems

Before the development of the concept of smoke control, HVAC systems were shut down when fires were discovered.

The HVAC system frequently transports smoke during building fires. In the early stages of a fire, the HVAC system can serve as an aid to fire detection. When a fire starts in an unoccupied portion of a building, the HVAC system can transport the smoke to a space where people can smell the smoke and be alerted to the fire. However, as the fire progresses, the HVAC system will transport smoke to every area that it serves, thus endangering life in all those spaces. The HVAC system also supplies air to the fire space, which aids combustion. These are the reasons HVAC systems traditionally have been shut down when fires have been discovered. Although shutting down the HVAC system prevents it from supplying air to the fire, this does not prevent smoke movement through the supply and return air ducts, air shafts, and other building openings due to stack effect, buoyancy, or wind.

SMOKE MANAGEMENT

The term "smoke management," as used in this chapter, includes all methods that can be used independently or in combination to modify smoke movement for the benefit of occupants and fire fighters and for the reduction of property damage. The use of barriers, smoke vents, and smoke shafts are traditional methods of smoke management.

The effectiveness of a barrier in limiting smoke movement depends on the leakage paths in the barrier and on the pressure difference across the barrier. Holes where pipes penetrate walls or floors, cracks where walls meet floors, and cracks around doors are a few possible leakage paths. The pressure difference across these barriers depends on stack effect, buoyancy, wind, and the HVAC system.

The effectiveness of smoke vents and smoke shafts depends on their proximity to the fire, the buoyancy of the smoke, and the presence of other driving forces. In addition, when smoke is cooled due to sprinklers the effectiveness of smoke vents and smoke shafts is greatly reduced.

Elevator shafts in buildings have been used as smoke shafts. Unfortunately, this prevents their use for fire evacuation and these shafts frequently distribute smoke to floors far from the fire. Specially designed smoke shafts, which have essentially no leakage on floors other than the fire floor, can be used to prevent the smoke shaft from distributing smoke to nonfire floors.

PRINCIPLES OF SMOKE CONTROL

Smoke control uses the barriers (walls, floors, doors, etc.) used in traditional smoke management in conjunction with airflows and pressure differences generated by mechanical fans.

Figure 4-12.5 illustrates a pressure difference across a barrier acting to control smoke movement. Within the barrier is a door, and the high-pressure side of the door can be either a refuge area or an escape route. The low-pressure side is exposed to smoke from a fire. Airflow through the cracks around the door and through other construction cracks prevents smoke infiltration to the high-pressure side.

When the door in the barrier is opened, air flows through the open door. When the air velocity is low, smoke can flow against the airflow into the refuge area or escape

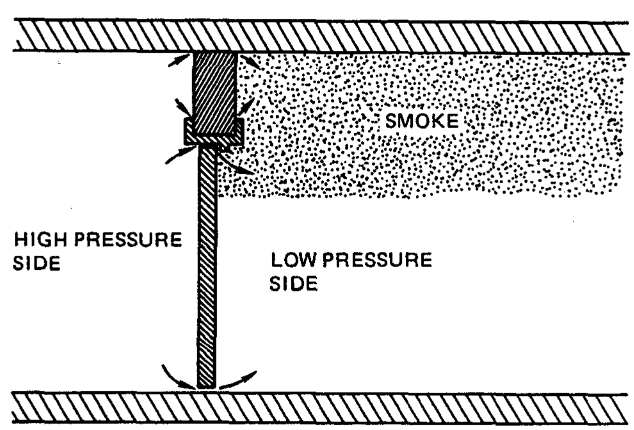

Fig. 4-12.5. Pressure difference across a barrier of a smoke control system preventing smoke infiltration to the high-pressure side of the barrier.

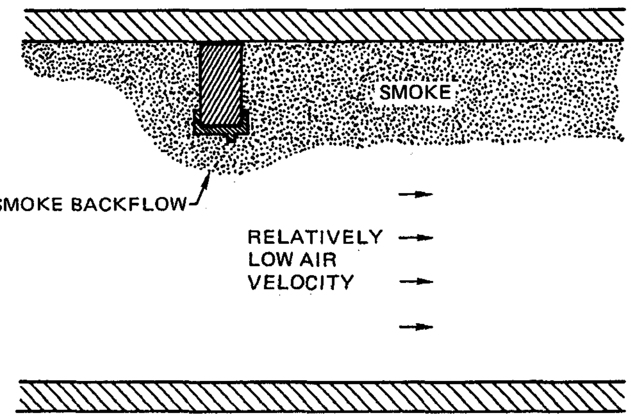

Fig. 4-12.6. Smoke backflow against low air velocity through an open doorway.

route, as shown in Figure 4-12.6. This smoke backflow can be prevented if the air velocity is sufficiently large, as shown in Figure 4-12.7. The magnitude of the velocity necessary to prevent backflow depends on the energy release rate of the fire, as discussed in the section of this chapter regarding airflow.

The two basic principles of smoke control can be stated as follows:

1. Airflow by itself can control smoke movement if the average air velocity is of sufficient magnitude.
2. Air pressure differences across barriers can act to control smoke movement.

The use of air pressure differences across barriers to control smoke is frequently referred to as pressurization. Pressurization results in airflows in the small gaps around closed doors and in construction cracks, thereby preventing smoke backflows through these openings. Therefore, in a strict physical sense, the second principle is a special case of the first principle. However, considering the two principles separately is advantageous for smoke control design. For a barrier with one or more large openings, air velocity is the appropriate physical quantity for both design considerations and for acceptance testing. However, when there are only cracks, such as around closed doors, determination of the velocity is difficult and including it in the design is impractical. In this case, the appropriate physical quantity is pressure difference. Separate consideration of the two principles has the added advantage of emphasizing the different considerations necessary for open and closed doors.

Because smoke control relies on air velocities and pressure differences produced by fans, it has the following three advantages in comparison to the traditional methods of smoke management:

1. Smoke control is less dependent on tight barriers. Allowance can be made in the design for reasonable leakage through barriers.
2. Stack effect, buoyancy, and wind are less likely to overcome smoke control than passive smoke management. In the absence of smoke control, these driving forces cause smoke movement to the extent that leakage paths allow. However, pressure differences and airflows of a smoke control system act to oppose these driving forces.
3. Smoke control can be designed to prevent smoke flow through an open doorway in a barrier by the use of airflow. Doors in barriers are opened during evacuation and are sometimes accidentally left open or propped open throughout fires. In the absence of smoke control, smoke flow through these doors is common.

Smoke control systems should be designed so that a path exists for smoke movement to the outside; such a path acts to relieve pressure of gas expansion due to the fire heat.

The smoke control designer should be cautioned that dilution of smoke in the fire space is not a means of achieving smoke control, i.e., smoke movement cannot be controlled by simply supplying and exhausting large quantities of air from the space or zone in which the fire is located. This supplying and exhausting of air is sometimes referred to as purging the smoke. Because of the large quantities of smoke produced in a fire, purging cannot assure breathable air in the fire space. In addition, purging in itself cannot control smoke movement, because it does not provide the needed airflows at open doors and the pressure differences across barriers. However, for spaces separated from the fire space by smoke barriers, purging can significantly limit the level of smoke.

Airflow

Theoretically, airflow can be used to stop smoke movement through any space. However, the two places where air velocity is most commonly used to control smoke movement are open doorways and corridors. Thomas[12] has developed an empirical relation for the critical velocity to prevent smoke from flowing upstream in a corridor.

$$V_k = K\left(\frac{gE}{W\rho cT}\right)^{1/3} \tag{4}$$

where:

V_k = critical air velocity to prevent smoke backflow
E = energy release rate into corridor
W = corridor width
ρ = density of upstream air
c = specific heat of downstream gases
T = absolute temperature of downstream mixture of air and smoke
K = constant of the order of 1
g = gravitational constant.

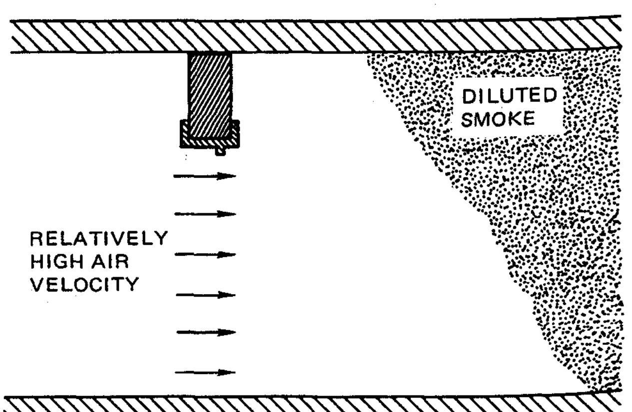

Fig. 4-12.7. No smoke backflow with high air velocity through an open doorway.

The downstream properties are considered to be taken at a point sufficiently far downstream of the fire for the properties to be uniform across the cross-section. The critical air velocity can be evaluated at ρ = 0.081 lb/ft^3 (1.3 kg/m^3), c = 0.24 Btu/lb°F (1.005 kJ/kg°C), T = 81°F (27°C), and K = 1.

$$V_k = K_v \left(\frac{E}{W}\right)^{1/3} \quad (4a)$$

where:

V_k = critical air velocity to prevent smoke backflow, fpm (m/s)
E = energy release rate into corridor, Btu/hr (W)
W = corridor width, ft (m)
K_v = coefficient, 5.68 (0.0292).

This relation can be used when the fire is located in the corridor or when the smoke enters the corridor through an open door, air transfer grille, or other opening. The critical velocities calculated from the above relation are approximate because only an approximate value of K was used. However, critical velocities calculated from this relation are indicative of the type of air velocities required to prevent smoke backflow from fires of different sizes.

Equation 4 can be evaluated from Figure 4-12.8. For example, for an energy release rate of 0.512 × 10^6 Btu/hr (150 kW) into a corridor 4.00 ft (1.22 m) wide, the above relation yields a critical velocity of 286 fpm (1.45 m/s). However, for a larger energy release rate of 7.2 × 10^6 Btu/hr (2.1 MW), the relation yields a critical velocity of 690 fpm (3.50 m/s) for a corridor of the same width.

In general, a requirement for a high air velocity results in a smoke control system that is expensive and difficult to design. The use of airflow is most important in preventing smoke backflow through an open doorway that serves as a boundary of a smoke control system. Thomas[12] indicated that Equation 4 can be used to obtain a rough estimate of the airflow needed to prevent smoke backflow through a door. Many designers feel that it is prohibitively expensive to design systems to maintain air velocities in doorways greater than 300 fpm (1.5 m/s). A discussion of the elements of an appropriate design air velocity in a smoke control system is provided later, in this chapter.

Equation 4 is not appropriate for sprinklered fires that have small temperature differences between the upstream air and downstream gases. Shaw and Whyte[13] provide an analysis with experimental verification of a method to determine the velocity needed through an open doorway to prevent backflow of contaminated air. This analysis is specifically for small temperature differences and includes the effects of natural convection. If this method is used for a sprinklered fire where the temperature difference is only 3.6°F (2°C), then an average velocity of 50 fpm (0.25 m/s) would be the minimum velocity needed through a doorway to prevent smoke backflow. This temperature difference is small, and it is possible that larger values may be appropriate in many situations. Further research is needed in this area.

Even though airflow can be used to control smoke movement, it is not the primary control method because of the large quantities of air required for such systems to be effective. The primary means to control smoke movement is by air pressure differences across partitions, doors, and other building components.

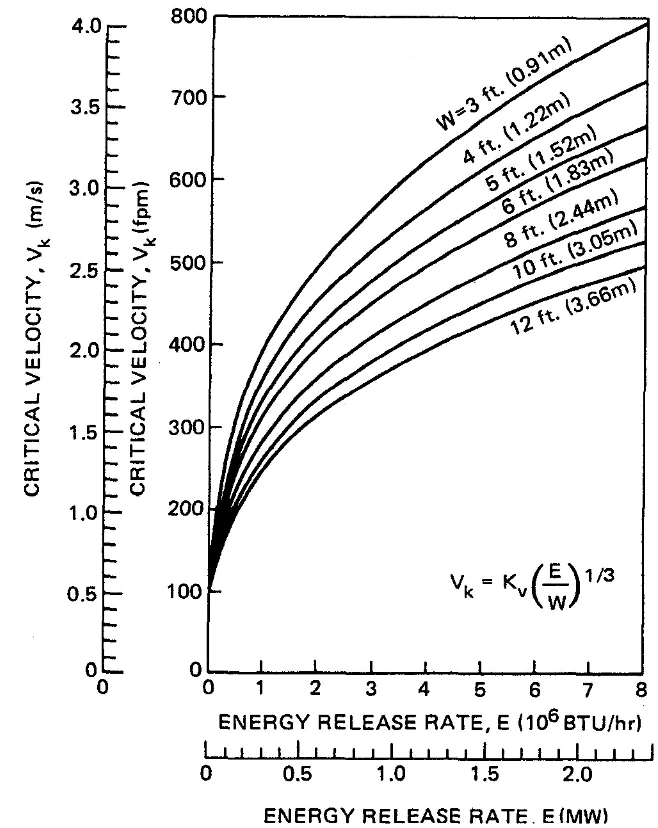

Fig. 4-12.8. Critical velocity to prevent smoke backflow.

Pressurization

The airflow rate through a construction crack, door gap, or other flow path is proportional to the pressure difference across that path raised to the power n. For a flow path of fixed geometry, n is theoretically in the range of 0.5 to 1. However, for all flow paths except extremely narrow cracks, using n = 0.5 is reasonable and the flow can be expressed as

$$Q = CA\sqrt{\frac{2\Delta P}{\rho}} \quad (5)$$

where:

Q = volumetric airflow rate
C = flow coefficient
A = flow area (also called leakage area)
ΔP = pressure difference across the flow path
ρ = density of air entering the flow path.

The flow coefficient depends on the geometry of the flow path as well as on turbulence and friction. In the present context, the flow coefficient is generally in the range of 0.6 to 0.7. For ρ = 0.075 lb/ft^3 (1.2 kg/m^3) and C = 0.65, the flow equation above can be expressed as

$$Q = K_f A\sqrt{\Delta P} \quad (5a)$$

where:

Q = volumetric flow rate, cfm (m^3/s)
A = flow area, ft^2 (m^2)
ΔP = pressure difference across flow path, in. H_2O (Pa)
K_f = coefficient, 2610 (0.839).

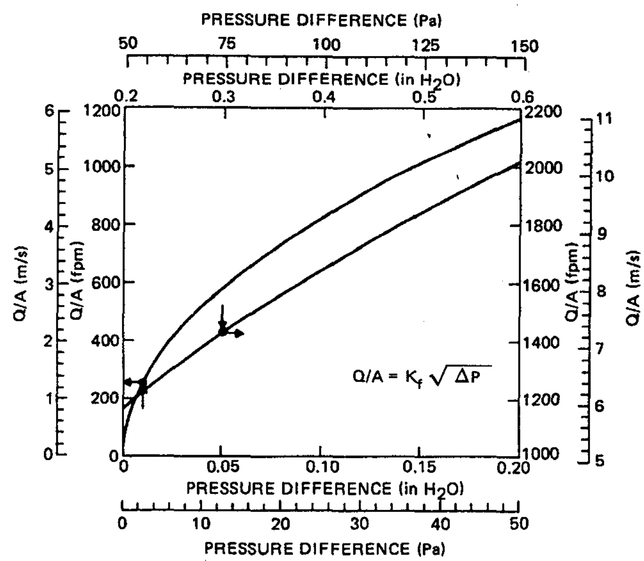

Fig. 4-12.9. ***Airflow due to pressure difference.***

Airflow rate can also be determined from Figure 4-12.9. The flow area is frequently the same as the cross-sectional area of the flow path. A closed door with a crack area of 0.11 ft^2 (0.01 m^2) and a pressure difference of 0.01 in. H_2O (2.5 Pa) would have an air leakage rate of approximately 29 cfm (0.013 m^3/s). If the pressure difference across the door were increased to 0.30 in. H_2O (75 Pa), then the flow would be 157 cfm (0.073 m^3/s).

In field tests of smoke control systems, pressure differences across partitions or closed doors have frequently fluctuated by as much as 0.02 in. H_2O (5 Pa). These fluctuations have generally been attributed to wind, although they could have been due to the HVAC system or some other source. Pressure fluctuations and the resulting smoke movement are a current topic of research. To control smoke movement, the pressure differences produced by a smoke control system must be sufficiently large that they are not overcome by pressure fluctuations, stack effect, smoke buoyancy, and the forces of the wind. However, the pressure difference produced by a smoke control system should not be so large that door opening problems result.

PURGING

In general, the systems discussed in this chapter are based on the two basic principles of smoke control. However, it is not always possible to maintain sufficiently large airflows through open doors to prevent smoke from infiltrating a space that is intended to be protected. Ideally, such occurrences of open doors will only happen for short periods of time during evacuation. Smoke that has entered such a space can be purged, i.e., diluted by supplying outside air to the space.

Consider the case where a compartment is isolated from a fire by smoke barriers and self-closing doors, so that no smoke enters the compartment when the doors are closed. However, when one or more of the doors is open, there is insufficient airflow to prevent smoke backflow into the compartment from the fire space. To facilitate analysis, it is assumed that smoke is of uniform concentration throughout the compartment. When all the doors are closed, the concentration of contaminant in the compartment can be expressed as

$$\frac{C}{C_0} = e^{-at} \qquad (6)$$

where:

C_0 = initial concentration of contaminant
C = concentration of contaminant at time, t
a = purging rate in number of air changes per minute
t = time after doors closed, in minutes
e = constant, approximately 2.718.

The concentrations C_0 and C must both be in the same units, and they can be any units appropriate for the particular contaminant being considered. McGuire, Tamura, and Wilson[14] evaluated the maximum levels of smoke obscuration from a number of tests and a number of proposed criteria for tolerable levels of smoke obscuration. Based on this evaluation, they state that the maximum levels of smoke obscuration are greater by a factor of 100 than those relating to the limit of tolerance. Thus, they indicate that an area can be "reasonably safe" with respect to smoke obscuration if its atmosphere will not be contaminated to an extent greater than 1 percent by the atmosphere prevailing in the immediate fire area. It is obvious that such dilution would also reduce the concentrations of toxic smoke components. Toxicity is a more complicated problem, and no parallel statement has been made regarding the dilution needed to obtain a safe atmosphere with respect to toxic gases.

Equation 6 can be solved for the purging rate as

$$a = \frac{1}{t} \log_e \left(\frac{C_0}{C}\right) \qquad (7)$$

For example, if doors are open, the contaminant in a compartment is 20 percent of the burn room concentration, and at six minutes after the door is closed, the contaminant concentration is 1 percent of the burn room; then Equation 7 indicates that the compartment must be purged at a rate of one air change every two minutes.

In reality, it is impossible to assure that the concentration of the contaminant is uniform throughout the compartment. Because of buoyancy, it is likely that higher concentrations of contaminant would tend to be near the ceiling. Therefore, an exhaust inlet located near the ceiling and a supply outlet located near the floor would probably purge the smoke even faster than the previous calculations indicate. Caution should be exercised in the location of the supply and exhaust points to prevent the supply air from blowing into the exhaust inlet and thus short-circuiting the purging operation.

DOOR OPENING FORCES

The door opening forces resulting from the pressure differences produced by a smoke control system must be considered. Unreasonably high door opening forces can result in occupants having difficulty in, or being unable to open doors to refuge areas or escape routes.

The force required to open a door is the sum of the forces (1) to overcome the pressure difference across the door and (2) to overcome the door closer. This can be expressed as

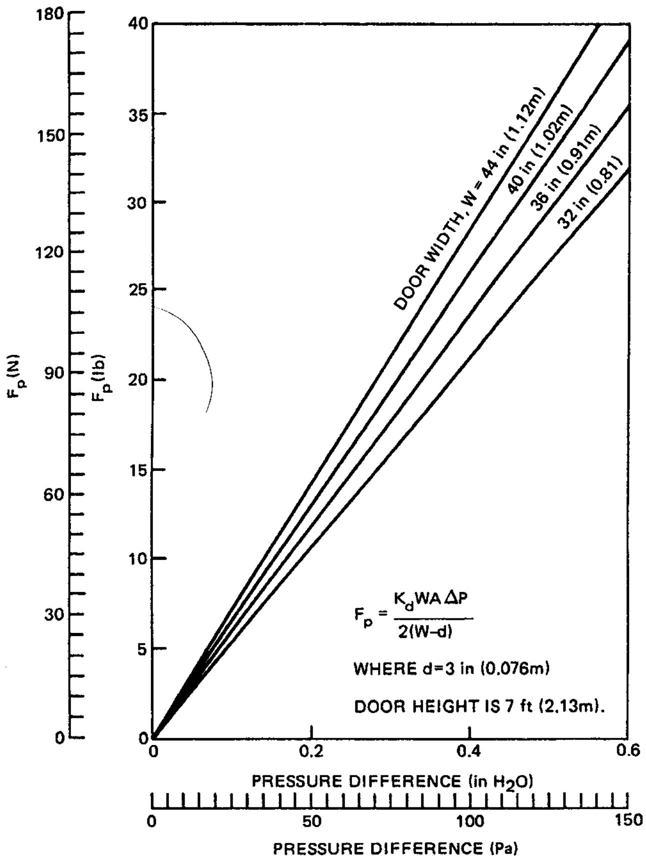

Fig. 4-12.10. Door opening force due to a pressure difference.

$$F = F_{dc} + \frac{K_d WA\Delta P}{2(W-d)} \tag{8}$$

where:

F = the total door opening force, lb (N)
F_{dc} = the force to overcome the door closer, lb (N)
W = door width, ft (m)
A = door area, ft^2 (m^2)
ΔP = pressure difference across the door, in. H_2O (Pa)
d = distance from the doorknob to the edge of the knob side of the door, ft (m)
K_d = coefficient, 5.20 (1.00).

This relation assumes that the door opening force is applied at the knob. Door opening forces due to pressure difference can be determined from Figure 4-12.10. The force to overcome the door closer is usually greater than 3 lb (13 N) and in some cases, can be as large as 20 lb (90 N). For a door that is 7 ft (2.13 m) high and 36 in. (0.91 m) wide, subject to a pressure difference of 0.30 in. H_2O (75 Pa), the total door opening force is 30 lb (133 N), if the force to overcome the door closer is 12 lb (53 N).

FLOW AREAS

Airflow paths must be identified and evaluated in the design of smoke control systems. Some leakage paths are obvious, such as cracks around closed doors, open doors, elevator doors, windows, and air transfer grilles. Construction cracks in building walls are less obvious but no less important.

The flow area of most large openings, such as open windows, can be calculated easily. However, flow areas of cracks are more difficult to evaluate. The area of these leakage paths depends on workmanship, i.e., how well a door is fitted or how well weatherstripping is installed. A door that is 36 in. by 7 ft (0.9 × 2.1 m) with an average crack width of ⅛ in. (3.2 mm) has a leakage area of 0.21 ft^2 (0.020 m^2). However, if this door is installed with a ¾ in. (19 mm) undercut, the leakage area is 0.32 ft^2 (0.30 m^2). This is a significant difference. The leakage area of elevator doors has been measured in the range of 0.55 to 0.70 ft^2 (0.051 to 0.065 m^2) per door.

For open stairwell doorways, Cresci[15] found that complex flow patterns exist and that the resulting flow through open doorways was considerably below the flow calculated by using the geometric area of the doorway as the flow area in Equation 5a. Based on this research, it is recommended that the flow area of an open stairwell doorway be half that of the geometric area (door height multiplied by width) of the doorway. An alternate approach for open stairwell doorways is to use the geometric area as the flow area and use a reduced flow coefficient. Because it does not allow the direct use of Equation 5a, this alternate approach is not used here.

Typical leakage areas for walls and floors of commercial buildings are tabulated as area ratios in Table 4-12.1. These data are based on a relatively small number of tests performed by the National Research Council of Canada.[16–19] The area ratios are evaluated at typical airflows at 0.30 in. H_2O (75 Pa) for walls, and 0.10 in. H_2O (25 Pa) for floors. It is believed that actual leakage areas are primarily dependent on workmanship rather than construction materials, and in some cases, the flow areas in particular buildings may vary from the the values listed. Considerable data concerning leakage through building components is also provided in the *ASHRAE Handbook.*[20]

The determination of the flow area of a vent is not always straightforward, because the vent surface is usually covered by a louver and screen. Thus the flow area is less

TABLE 4-12.1 ***Typical Leakage Areas for Walls and Floors of Commercial Buildings***

Construction Element	Wall Tightness	Area Ratio A/A_W
Exterior Building Walls (includes construction cracks, cracks around windows and doors)	Tight	0.70×10^{-4}
	Average	0.21×10^{-3}
	Loose	0.42×10^{-3}
	Very Loose	0.13×10^{-2}
Stairwell Walls (includes construction cracks but not cracks around windows or doors)	Tight	0.14×10^{-4}
	Average	0.11×10^{-3}
	Loose	0.35×10^{-3}
Elevator Shaft Walls (includes construction cracks but not cracks around doors)	Tight	0.18×10^{-3}
	Average	0.84×10^{-3}
	Loose	0.18×10^{-2}
		A/A_F
Floors (includes construction cracks and areas around penetrations)	Tight	0.66×10^{-5}
	Average	0.52×10^{-4}
	Loose	0.17×10^{-3}

A = leakage area; A_W = wall area; A_F = floor area.

than the vent area (vent height multiplied by width). Because the slats in louvers are frequently slanted, calculation of the flow area is further complicated. Manufacturers' data should be sought for specific information.

EFFECTIVE FLOW AREAS

The concept of effective flow areas is quite useful for analysis of smoke control systems. The various paths of smoke movement in the system can be parallel with one another, in series, or a combination of parallel and series paths. The effective flow area of a given system of flow paths is the area of a single opening that results in the same flow as the given system when subjected to the same pressure difference over the total system of flow paths. This concept is similar to an effective resistance of a system of electrical resistances.

The effective area, A_e, for the three parallel leakage areas of Figure 4-12.11 is

$$A_e = A_1 + A_2 + A_3 \qquad (9)$$

If A_1 is 1.08 ft^2 (0.10 m^2) and A_2 and A_3 are 0.54 ft^2 (0.05 m^2) each, then the effective flow area, A_e, is 2.16 ft^2 (0.20 m^2).

Equation 9 can be extended to any number of flow paths in parallel; i.e., it can be stated that the effective area is the sum of the individual leakage paths.

$$A_e = \sum_{i=1}^{n} A_i \qquad (10)$$

where n is the number of flow areas, A_i, in parallel.

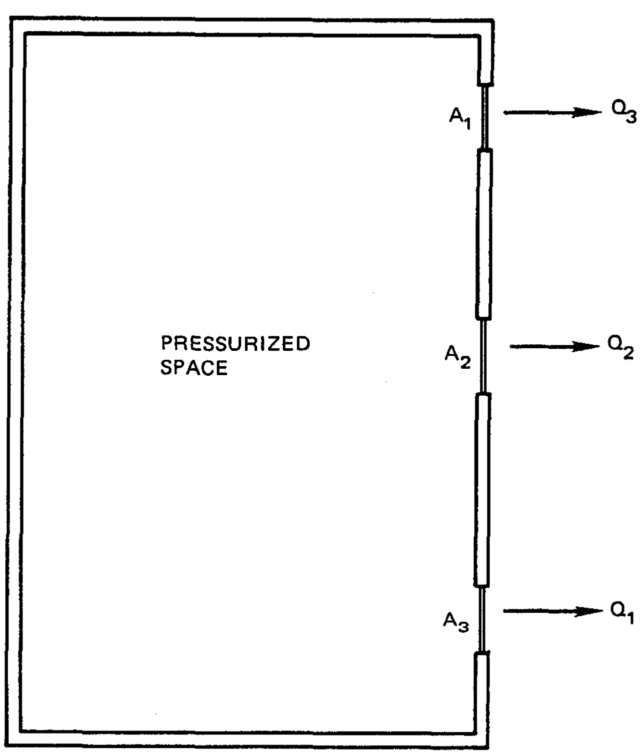

Fig. 4-12.11. Leakage paths in parallel.

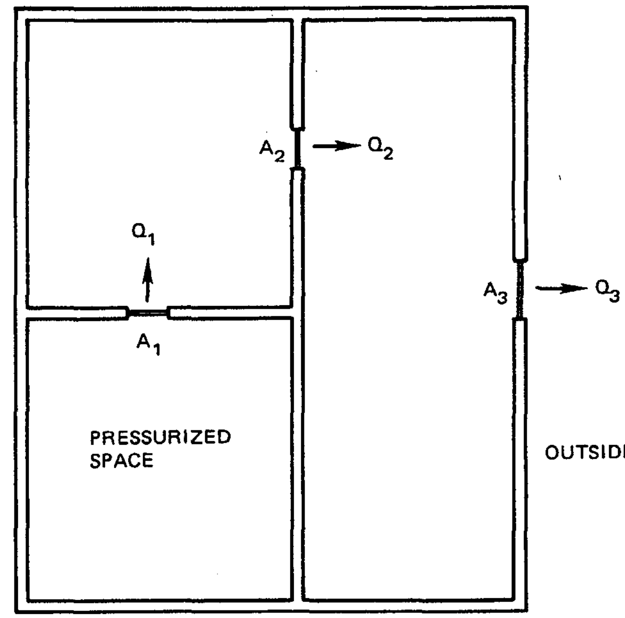

Fig. 4-12.12. Leakage paths in series.

Three leakage areas in series from a pressurized space are illustrated in Figure 4-12.12. The effective flow area of these paths is

$$A_e = \left(\frac{1}{A_1^2} + \frac{1}{A_2^2} + \frac{1}{A_3^2}\right)^{-1/2} \qquad (11)$$

The general rule for any number of leakage areas is

$$A_e = \left(\sum_{i=1}^{n} \frac{1}{A_i^2}\right)^{-1/2} \qquad (12)$$

where n is the number of leakage areas, A_i, in series. In smoke control analysis, there are frequently only two paths in series. For this case, the effective leakage area is

$$A_e = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2}} \qquad (13)$$

EXAMPLE 1:

Calculate the effective leakage area of two equal flow paths of 0.2 ft^2 in series. Let $A = A_1 = A_2 = 0.02$ m^2.

$$A_e = \frac{A^2}{\sqrt{2A^2}} = \frac{A}{\sqrt{2}} = 0.15 \text{ ft}^2 \quad (0.014 \text{ m}^2)$$

EXAMPLE 2:

Calculate the effective area of two flow paths in series, where $A_1 = 0.22$ ft^2 (0.02 m^2) and $A_2 = 2.2$ ft^2 (0.2 m^2).

$$A_e = \frac{A_1 A_2}{\sqrt{A_1^2 + A_2^2}} = 0.219 \text{ ft}^2 \quad (0.0199 \text{ m}^2)$$

This example illustrates that when two areas are in series and one is much larger than the other, the effective area is approximately equal to the smaller area.

The method of developing an effective area for a system of both parallel and series paths is to systemically combine groups of parallel paths and series paths. The system illustrated in Figure 4-12.13 is analyzed as an example.

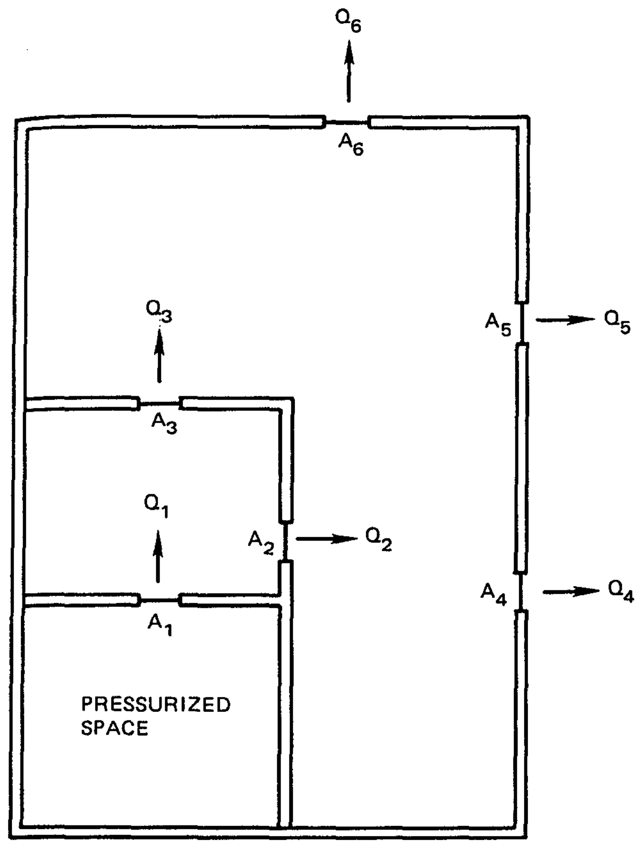

Fig. 4-12.13. Combination of leakage paths in parallel and series.

The figure shows that A_2 and A_3 are in parallel; therefore, their effective area is

$$A_{23_e} = A_2 + A_3$$

Areas A_4, A_5, and A_6 are also in parallel, so their effective area is

$$A_{456_e} = A_4 + A_5 + A_6$$

These two effective areas are in series with A_1. Therefore, the effective flow area of the system is given by

$$A_e = \left(\frac{1}{A_1^2} + \frac{1}{A_{23_e}^2} + \frac{1}{A_{456_e}^2}\right)^{-1/2}$$

EXAMPLE 3:

Calculate the effective area of the system in Figure 4-12.13, if the leakage areas are $A_1 = A_2 = A_3 = 0.22$ ft^2 (0.02 m^2) and $A_4 = A_5 = A_6 = 0.11$ ft^2 (0.01 m^2).

$$A_{23_e} = 0.44 \text{ ft}^2 \quad (0.04 \text{ m}^2)$$
$$A_{456_e} = 0.33 \text{ ft}^2 \quad (0.03 \text{ m}^2)$$
$$A_e = 0.16 \text{ ft}^2 \quad (0.015 \text{ m}^2)$$

SYMMETRY

The concept of symmetry is useful in simplifying problems and thereby easing solutions. Figure 4-12.14 illustrates the floor plan of a multistory building that can be divided in one-half by a plane of symmetry. Flow areas on one side of the plane of symmetry are equal to corresponding flow areas on the other side. For a building to be so treated, every floor of the building must be such that it can be divided in the same manner by the plane of symmetry. If wind effects are not considered in the analysis or if the wind direction is parallel to the plane of symmetry, then the airflow in only one-half of the building need be analyzed. It is not necessary that the building be geometrically symmetric, as shown in Figure 4-12.14; it must be symmetric only with respect to flow.

DESIGN PARAMETERS: A GENERAL DISCUSSION

Ideally, building and fire codes should contain design parameters leading to the design of functional and economical smoke control systems. Unfortunately, because smoke control is a new field, consensus has not yet been reached as to a definition of reasonable design parameters. Clearly, the designer has an obligation to adhere to any smoke control design criteria existing in appropriate codes or standards, but such criteria should be scrutinized to determine whether or not they will result in an effective system. If necessary, the designer should seek a waiver of the local codes, to ensure an effective smoke control system.

Five areas for which design parameters must be established are: (1) leakage areas, (2) weather data, (3) pressure differences, (4) airflow, and (5) number of open doors in the smoke control system.

Leakage areas have already been discussed in this chapter. An additional consideration affecting pressure differences and airflow is whether or not a window in the fire

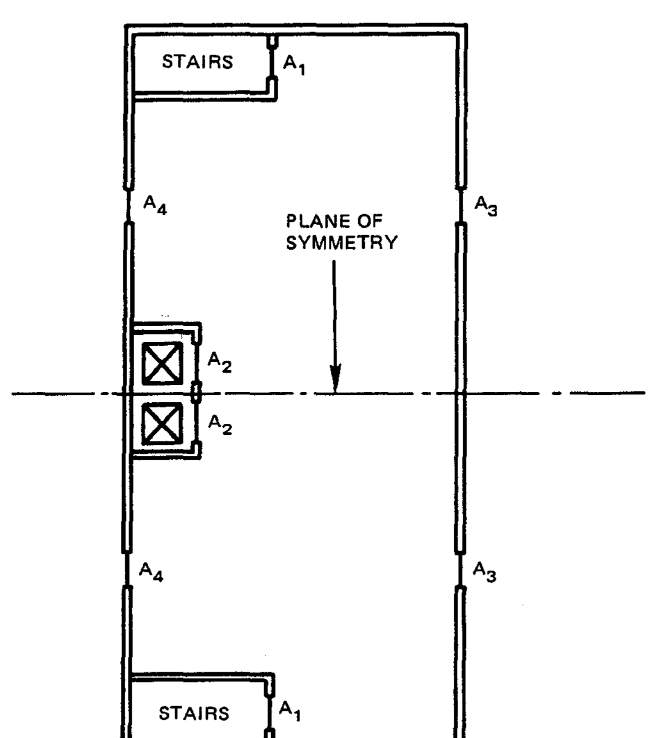

Fig. 4-12.14. Building floor plan illustrating symmetry concept.

compartment is broken. This factor is included in the following discussion of these parameters. In the absence of code requirements for specific parameters, the following discussion may be helpful to the designer.

Weather Data

The state-of-the-art of smoke control is such that little consideration has been given to the selection of weather data specifically for the design of smoke control systems. However, design temperatures for heating and cooling during winter and summer are recommended in the *ASHRAE Handbook*.[20] For example, 99 and 97.5 percent winter design temperatures have been provided. These values represent the temperatures that are equaled or exceeded in these portions of the heating season.*

A designer may wish to consider using these design temperatures for the design of smoke control systems. It should be remembered that in a normal winter, there would be approximately 22 hours at or below the 99 percent design value and approximately 54 hours at or below the 97.5 percent design value. Furthermore, extreme temperatures can be considerably lower than the winter design temperatures. For example, the ASHRAE 99 percent design temperature for Tallahassee, Florida is 27°F (−3°C), but the lowest temperature observed there by the National Climatic Center[21] was −2°F (−19°C) on February 13, 1899.

Temperatures are generally below the design values for short periods of time, and because of the thermal lag of building materials, these short intervals of low temperature usually do not result in problems with respect to heating systems. However, the same cannot necessarily be said of a smoke control system. There is no time lag for a smoke control system, i.e., a smoke control system is subjected to all the forces of stack effect that exist at the moment the system is being operated. If the outside temperature is below the winter design temperature for which a smoke control system was designed, then problems from stack effect may result. A similar situation can result with respect to summer design temperatures and reverse stack effect.

Wind data is needed for a wind analysis of a smoke control system. At present, no formal method of performing such an analysis exists, and the approach most generally taken is to design the smoke control system so as to minimize any effects of wind. The development of temperature and wind data for design of smoke control systems is an area for future effort.

Pressure Differences

It is appropriate to consider both the maximum and minimum allowable pressure differences across the boundaries of smoke control zones. The maximum allowable pressure difference should be a value that does not result in excessive door opening forces, but it is difficult to determine what constitutes excessive door opening forces. Clearly, a person's physical condition is a major factor in determining a reasonable door opening force for that person. NFPA *101®*, *Life Safety Code®*,[22] states that the force required to open any door in a means of egress shall not exceed 30 lb (133 N). In the section of this chapter on purging, a method of determining the door opening force is provided.

* The heating season usually consists of three winter months. A more exact definition of these temperatures is available in Chapter 24 of the *ASHRAE Handbook—1985 Fundamentals*.[20]

The criterion used in this chapter for selecting a minimum allowable pressure difference across a boundary of a smoke control system is that no smoke leakage should occur during building evaluation.** In this case, the smoke control system must produce sufficient pressure differences so that it is not overcome by the forces of wind, stack effect, or buoyancy of hot smoke. The pressure differences due to wind and stack effect can become very large in the event of a broken window in the fire compartment. Evaluation of these pressure differences depends on evacuation time, rate of fire growth, building configuration, and the presence of a fire suppression system. In the absence of a formal method of analysis, such evaluation must of necessity be based on experience and engineering judgment.

A method for determining the pressure difference across a smoke barrier resulting from the buoyancy of hot gases is provided in the section of this chapter regarding buoyancy. For a particular application, it may be considered necessary to design a smoke control system to withstand an intense fire next to a door at the boundary of a smoke control zone. Earlier in this chapter it was stated that in a series of full-scale fire tests, the maximum pressure difference reached was 0.064 in. H_2O (16 Pa) across the burn room wall at the ceiling. To prevent smoke infiltration, the smoke control system should be designed to maintain a pressure slightly higher than that generated in fire conditions. A minimum pressure difference in the range of 0.08 to 0.10 in. H_2O (20 to 25 Pa) is suggested.

If a smoke control boundary is exposed to hot smoke from a remote fire, a lower pressure difference due to buoyancy will result. For a smoke temperature of 750°F (400°C), the pressure difference caused by the smoke 5.0 ft (1.53 m) above the neutral plane would be 0.04 in. H_2O (10 Pa). In this situation, it is suggested that the smoke control system be designed to maintain a minimum pressure in the range of 0.06 to 0.08 in. H_2O (15 to 20 Pa).

Water spray from fire sprinklers cools smoke from a building fire and reduces the pressure differences due to buoyancy. In such a case it is probably wise to allow for pressure fluctuations. Accordingly, a minimum pressure difference in the range of 0.02 to 0.04 in. H_2O (5 to 10 Pa) is suggested.

Windows in the fire compartment can break due to exposure to high temperature gases. In such cases, the pressure due to the wind on the building exterior can be determined from Equation 3. If this window is the only opening to the outside on the fire floor and the window faces into the wind, the boundary of the smoke control system could be subjected to higher pressures. One possible solution is to vent the fire floor on all sides to relieve such pressures. For a building that is much longer than it is wide, it may be necessary to vent only on the two longer sides.

In addition to wind effects, stack effect can be increased in the event of a broken fire compartment window. With a fire on a lower floor during cold weather, stack effect will increase pressures of the fire floor above surrounding spaces. Even though little research has been done on the subject, the chances of a window breaking in the fire compartment are reduced by the operation of fire sprinklers.

** Other criteria might involve maintaining a number of smoke-free egress routes or preventing smoke infiltration to a refuge area. Discussion of all possible alternatives is beyond the scope of this chapter.

Airflow

When the doors in the boundaries of smoke control systems are open, smoke can flow into refuge areas or escape routes unless there is sufficient airflow through the open door to prevent smoke backflow, as discussed in the previous section. One criterion for selecting a design velocity through an open door is that no smoke backflow should occur during building evacuation.* Selection of this velocity depends on evacuation time, rate of fire growth, building configuration, and the presence of a fire suppression system. In the absence of a formal method of analysis, such an evaluation must be based on experience and engineering judgment.

At present, there is still much to be learned about the critical velocity needed to stop smoke backflow through an open door. In the absence of a specific relationship for doorways, the method of analysis presented for corridors in the earlier section regarding airflow can be used to yield approximate results. The width of the doorway may be used in place of the width of the corridor. This technique is based on the assumption that smoke properties are uniform across the cross-section. As previously illustrated, for a particular application, it may be considered necessary to design for an intensive fire, such as one with an energy release rate of 8×10^6 Btu/hr (2.4 MW). A critical velocity of approximately 800 fpm (4 m/s) would be required to stop smoke.

In another application, it may be estimated that the building would be subjected to a much less intense fire with an energy release rate of 427,000 Btu/hr (125 kW). To protect against smoke backflow during evacuation, the critical velocity would be 300 fpm (1.5 m/s).

In a sprinklered building, it might be considered that the smoke away from the immediate fire area would be cooled to near ambient temperature by the spray from the sprinklers. In such a case a design velocity in the range of 50 to 250 fpm (0.25 to 1.25 m/s) may be used. Research is needed to fully evaluate the effect of sprinklers on smoke control design parameters.

Number of Open Doors

The need for air velocity through open doors in the perimeter of a smoke control system has been discussed in this chapter. Another design consideration is the number of doors that could be opened simultaneously when the smoke control system is operational. A design that allows for all doors to be opened simultaneously may ensure that the system will always work, but it will probably add to the cost of the system.

Deciding on the number of doors that will be opened simultaneously depends largely on the building occupancy. For example, in a densely populated building, it is very likely that all the doors will be opened simultaneously during evacuation. However, if a staged evacuation plan or refuge area concept is incorporated in the building fire emergency plan, or if the building is sparsely occupied, only a few of the doors may be opened simultaneously during a fire.

PRESSURIZED STAIRWELLS

Many pressurized stairwells have been designed and built with the goal of providing a smoke-free escape route in the event of a building fire. A secondary objective is to provide a smoke-free staging area for fire fighters. On the fire floor, a pressurized stairwell must maintain a positive pressure difference across a closed stairwell door so that smoke infiltration is prevented.

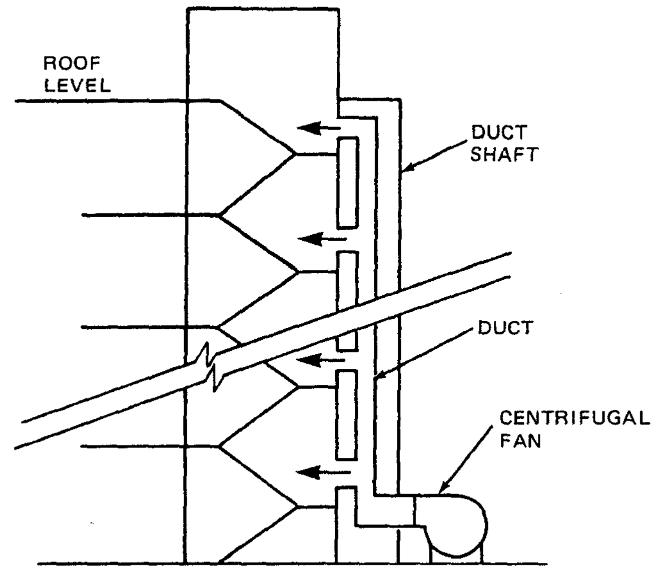

Fig. 4-12.15. Stairwell pressurization by multiple injection with the fan located at ground level.

During building fire situations, some stairwell doors are opened intermittently during evacuation and fire fighting, and some doors may even be blocked open. Ideally, when the stairwell door is opened on the fire floor, there should be sufficient airflow through the door to prevent smoke backflow. Designing such a system is difficult because of the large number of permutations of open stairwell doors and weather conditions that affect the airflow through open doors.

Stairwell pressurization systems are divided into two categories—single and multiple injection systems. A single injection system is one that has pressurized air supplied to the stairwell at one location; the most common injection point is at the top of the stairwell. Associated with this system is the potential for smoke feedback into the pressurized stairwell, i.e., of smoke entering the stairwell through the pressurization fan intake. Therefore, the capability of automatic shutdown in such an event should be considered.

For tall stairwells, single injection systems can fail when a few doors are open near the air supply injection point. All of the pressurized air can be lost through the few open doors, and the system can then fail to maintain positive pressures across doors farther from the injection point. Such a failure mode is especially likely with bottom injection systems when a ground level stairwell door is open.

For tall stairwells, supply air can be supplied at a number of locations over the height of the stairwell. Figures 4-12.15 and 4-12.16 are two examples of many possible multiple injection systems which can be used to overcome the limitations of single injection systems. In these figures the supply duct is shown in a separate shaft, but systems have been built that have eliminated the expense of a separate duct shaft by locating the supply duct in the stairwell

* Other criteria might include the allowance of limited smoke leakage into areas to be protected. Under such criteria, the toxicity of the smoke is a factor that must be considered.