Smoke Control

50

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Introduction

In building fires, smoke often flows to locations remote from the fire, threatening life and damaging property. Research has shown that smoke is the major killer in building fires (Harland and Woolley 1979; [37]).

NFPA 92 [29] defines a smoke control system as an engineered system that includes all methods that can be used singly or in combination to modify smoke movement. These methods are the physical mechanisms of smoke control which are discussed later in this chapter. Research in the field of smoke control has been conducted in Australia, Canada, England, France, Japan, the United States, and Germany. This research has consisted of field tests, full-scale fire tests, scale model fire tests, and computer simulations. Many buildings have been built with smoke control systems and numerous others have been retrofitted for smoke control.

The conventional approach to smoke control consists of using the physical mechanisms to prevent people from coming into contact with smoke to the extent possible. A newer approach consists of evaluating the effect of some smoke contact with the intent of providing a tenable environment for occupants. Smoke control systems based on this newer approach are referred to as *tenability systems*. This chapter focuses on the conventional approach, but tenability systems are discussed near the end of the chapter. For an exhaustive treatment of smoke control including weather design data, design fires, conventional systems, tenability systems, and method of analysis see the *Handbook of Smoke Control Engineering* [21].

In this chapter the term *smoke* is used in accordance with the NFPA 92 definition that states that smoke consists of the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis of combustion, together with the quantity of air that is entrained or otherwise mixed into the mass. It is important for smoke control purposes that the definition of smoke includes the air that is mixed with the particulates and other gases because smoke control often involves exhausting smoke which is mostly air. Including air as a part of smoke is also important for tenability systems.

Physical Mechanisms of Smoke Control

The physical mechanisms of smoke control are (1) compartmentation, (2) dilution, (3) pressurization, (4) airflow, and (5) buoyancy. For centuries, compartmentation has been recognized as a way of controlling the spread of fire and smoke. When a person closes the door to a burning room, smoke flow from the room decreases considerably. Also, the amount of air available to the fire drops off. Today this passive

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smoke protection is recognized in many building and fire codes even without a design analysis. Engineered smoke control systems that use only passive smoke barriers are a form of tenability systems that are discussed later in this chapter.

Dilution can occur naturally as when smoke flows away from a fire and mixes with air as it flows or be forced by fan powered flows. Naturally occurring dilution can be analyzed by the methods discussed in the section on tenability systems.

Fan powered dilution can be used to remove smoke from the fire space after a fire has been extinguished, and it can be used to remove smoke from a space connected to the fire space after the connection has been has been closed. Fan powered dilution consists of supplying air to the fire space and either exhausting air (or smoke) from the space or providing a path for a path for air (or smoke) to flow from the space. This kind of fan powered dilution can be analyzed by the methods discussed in the section on tenability systems.

The use of dilution to produce or maintain tenable conditions in the fire space is not recommended because such a system is beyond the current state of the technology. The air supplied to the fire space can increase the burning rate of the fire resulting in increased smoke production. The increased smoke production in the fire space has the potential to result in untenable conditions in the fire space. Because of this failure mode the use of dilution in the fire space is generally not recommended.

Many smoke control systems use mechanical fans to control smoke by pressurization. Pressure difference across a barrier can control smoke movement. The idea is that a pressure difference is produced across a barrier such that the smoke on the low pressure side of the barrier is prevented from migrating to the high pressure side, and this is shown in Fig. 50.1a for a relatively small amount of smoke. However, pressurization can control smoke from a

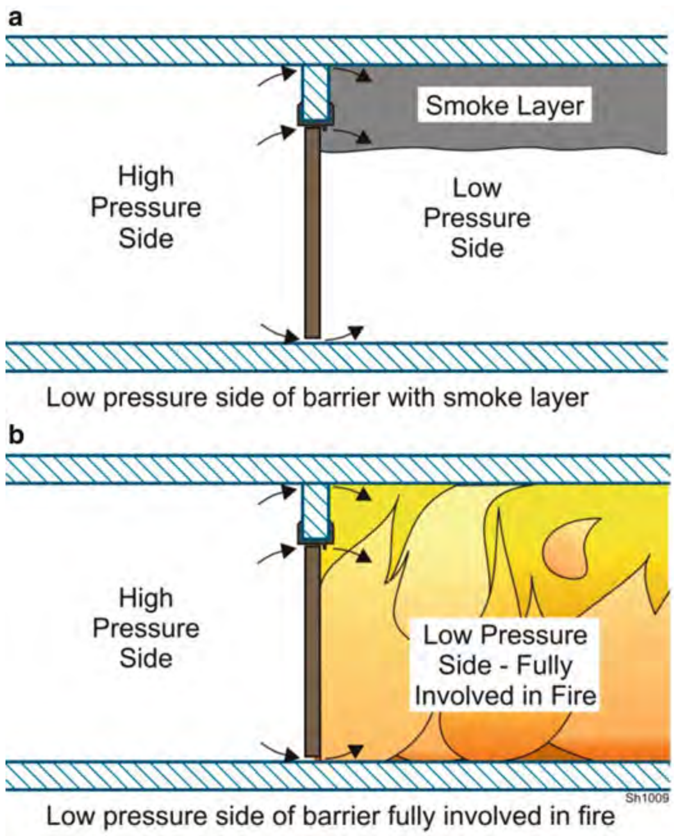

Fig. 50.1 Pressure difference across a barrier can control smoke flow

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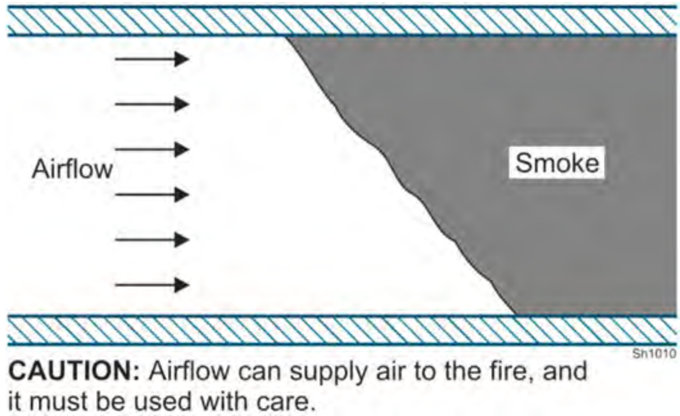

Fig. 50.2 Airflow can control the flow of smoke

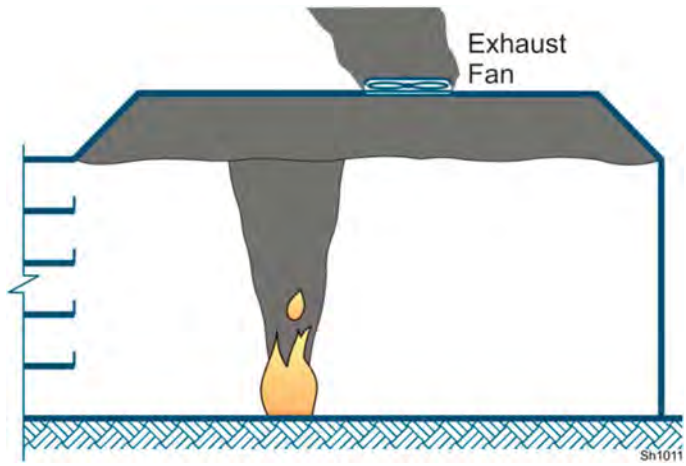

Fig. 50.3 Buoyancy can be used for smoke control as in an atrium smoke exhaust system

large fully developed fire as shown in Fig. 50.1b. In a room with a fully developed fire, everything that can burn is burning. Pressurization smoke control systems are discussed later in this chapter.

Airflow has been used extensively to control smoke flow during fires in subway, railroad and highway tunnels (Fig. 50.2). Airflow can also be used to control smoke between atria and spaces connected to atria. A number of empirical equations have been developed to calculate the air velocity needed for specific applications. Because the large amounts of air are needed for this method can supply additional oxygen to the fire, the use of airflow to control smoke needs to be done with caution.

Atria smoke exhaust systems rely on the buoyancy for a smoke plume to form above the fire and move the smoke away from occupants (Fig. 50.3). This form of smoke control is called atrium smoke management, and it is the subject of Chap. 51.

Pressurization Smoke Control Systems

Commonly used pressurization smoke control systems are (1) stairwell pressurization, (2) elevator pressurization, and (3) zoned smoke control. The concept of stairwell pressurization is to supply air to the stairwell with the intent of maintaining tenable conditions in stairwell. The idea of elevator pressurization is to supply air to the elevator shaft with the intent of preventing smoke flow through elevator shaft to locations

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Table 50.1 Activation signals for pressurization smoke control systems

System	Smoke Detector	Heat Detector	Sprinkler Water Flow	Manual Pull Station
Stairwell pressurization	Yes	Yes	Yes	Yes[a]
Elevator pressurization	Yes	Yes	Yes	Yes[a]
Zoned smoke control	Yes	Yes	Yes	No

[a]Manual pull stations are not recommended for activation of stairwell or elevator pressurization systems that rely of fire floor exhaust

remote from the fire floor. The idea of zoned smoke control is to rely on pressurization or passive smoke control with the intent of preventing or minimizing smoke movement beyond the zone where the fire is located.

The primary purpose of pressurization smoke control systems is to maintain a tenable environment in the means of egress. Other purposes of these systems are to control smoke movement between fire area and adjacent spaces, provide conditions to help fire service, reduce property damage, and aid in post-fire smoke removal.

Table 50.1 lists sources of signals that can be used to activate pressurization smoke control systems. Zoned smoke control should not be activated from manual fire alarm pull stations. For proper operation of zoned smoke control needs, the location of the fire needs to be identified. A person who has seen a fire may start to leave the building and some distance away from the fire zone realize that he or she should pull the manual pull station. If zoned smoke control were activated by this manual pull station, the wrong zone would be identified as where the fire was located. Some stairwell pressurization systems and elevator pressurization systems rely on fire floor exhaust, and activation of these systems by manual pull stations can result in the wrong floor being exhausted. For this reason, manual pull stations are not recommended for activation of stairwell or elevator pressurization systems that rely of fire floor exhaust.

Network Modeling

Network models are a class of software that can simulate the flow of air or water through a complex system of paths which is called the network. Network modeling for smoke control application dates back to the 1960s, but these early models were subject to numerical difficulties and data input was extremely cumbersome and time consuming.

Network computer models such as CONTAM [36] have become widely used for analysis of pressurization smoke control systems due to their robust numerical routines and sophisticated data input. While CONTAM was developed for indoor air quality applications, care was taken to assure that it could be used for smoke control applications. Because CONTAM is a product of the US National Institute of Standards and Technology (NIST), it can be downloaded from the NIST website at no cost. In this chapter, when CONTAM is discussed, it should be noted that it may be possible that other network models could be used.

These models represent a building by a network of spaces or nodes, each at a specific pressure and temperature. The stairwells and other shafts can be modeled by a vertical series of spaces, one for each floor. Air flows through leakage paths from regions of high pressure to regions of low pressure. These leakage paths are doors and windows that may be opened or closed. Leakage can also occur through partitions, floors, and exterior walls and roofs. The airflow through a leakage path is a function of the pressure difference across the leakage path.

In network models, air from outside the building can be introduced by a pressurization system into any level of a shaft or into other building spaces. This allows simulation of stairwell pressurization, elevator shaft pressurization, stairwell vestibule pressurization, and pressurization of any other building space. In addition, any building space can be exhausted. This allows analysis of zoned smoke control systems where the fire zone is exhausted and other zones are

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pressurized. The pressures and flows throughout the building are obtained by solving the conservation equations for the network. This analysis can include the driving forces of wind, the pressurization system, and inside-to-outside temperature difference.

The primary purpose of network simulations is to determine if a particular smoke control system in a particular building is capable of being balanced such that it will perform as intended. Network models are capable of simulating the pressures and flows throughout very large and complex building networks with high accuracy.

There are many flow paths in buildings including gaps around closed doors, open doors, construction cracks in walls and floors. These flow paths can be approximated for a design analysis, and the results of a network model simulation are approximations. However, these approximate results can be useful in identifying problems with specific smoke control systems. If such problems are identified, the smoke control system can be modified appropriately. A secondary purpose of these simulations is to provide information to help size the system components such as supply fans, exhaust fans, and vents.

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 is a prerequisite to intelligent smoke control design. The driving forces of air and smoke movement in building are (1) stack effect, (2) buoyancy of combustion gases, (3) expansion of combustion gases, (4) wind, (5) forced ventilation, and (6) elevator piston effect. Forced ventilation consisting of supply air is used for pressurization smoke control. Also, forced ventilation is used in heating, ventilating and air-conditioning (HVAC) systems. Generally, in a fire, smoke movement will be caused by a combination of these driving forces. The following sections discuss of each driving force as it would act in the absence of any other driving force.

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 a *normal stack effect* as shown in Fig. 50.4. 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, and the pressure difference due to normal stack effect is shown in Fig. 50.5. The significance of normal stack effect is greater for low outside temperatures and for tall shafts.

When the outside air is warmer than the building air, downward airflow frequently happens in shafts. This downward airflow is called *reverse stack effect* (Fig. 50.5), and the pressure difference due to reverse stack effect is shown in Fig. 50.5b. At standard atmospheric pressure, the pressure difference due to either normal or reverse stack effect is

$$\Delta p_{SO} = 7.63\left(\frac{1}{T_O + 460} - \frac{1}{T_S + 460}\right)z$$

$$\Delta p_{SO} = 3460\left(\frac{1}{T_O + 273} - \frac{1}{T_S + 273}\right)z \quad \text{for SI} \tag{50.1}$$

where

Δp_{SO} = pressure difference from a shaft to the outside, in. H_2O (Pa),

T_O = temperature outside, °F (°C),

T_S = temperature in the shaft, °F (°C),

z = distance above the neutral plane, ft (m).

The neutral plane is a horizontal plane where the pressure in the shaft is the same as that outdoors. For a shaft 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 normal stack effect would be 0.22 in. H_2O (55 Pa). This means that at the top

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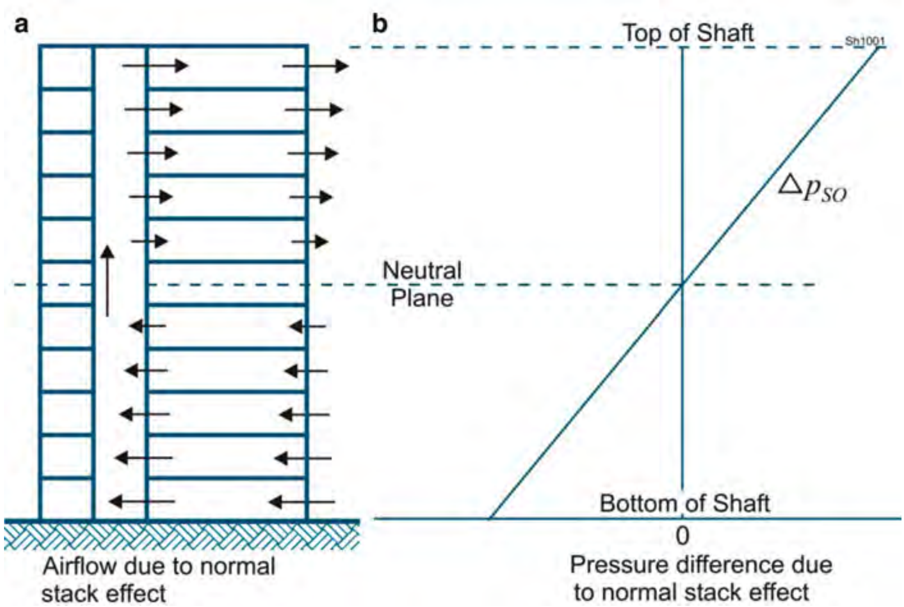

Fig. 50.4 Airflow and pressure differences of normal stack effect

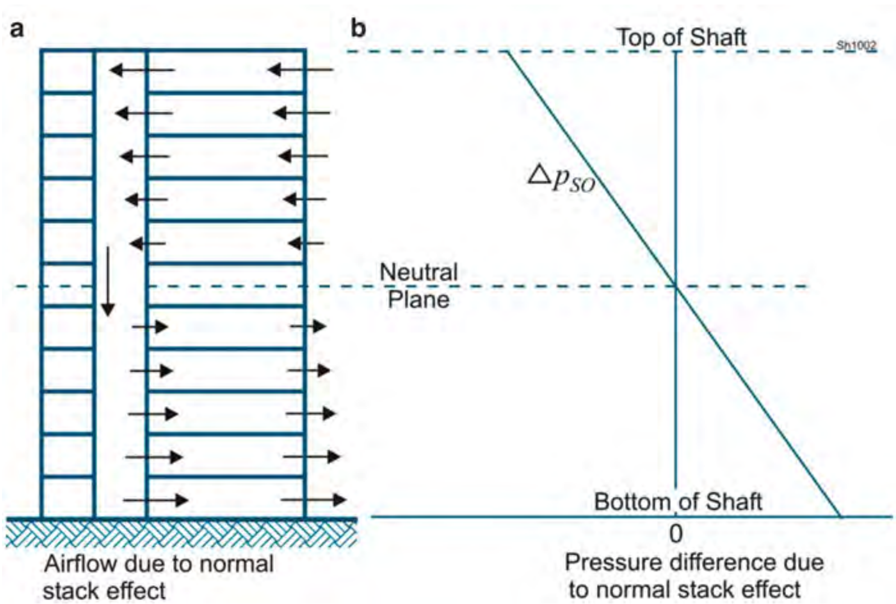

Fig. 50.5 Airflow and pressure differences of reverse stack effect

of the shaft, the shaft would have a pressure of about 0.22 in. H_2O (55 Pa) greater than that outside. At the bottom of the shaft, the shaft would have a pressure of about 0.22 in. H_2O (55 Pa) less than the outside pressure.

Stack effect can have a significant impact on smoke flow during building fires. When it is cold outdoors, the upward airflow in shafts can be enhanced by the buoyancy of the smoke. Figure 50.6 shows smoke flows in a building

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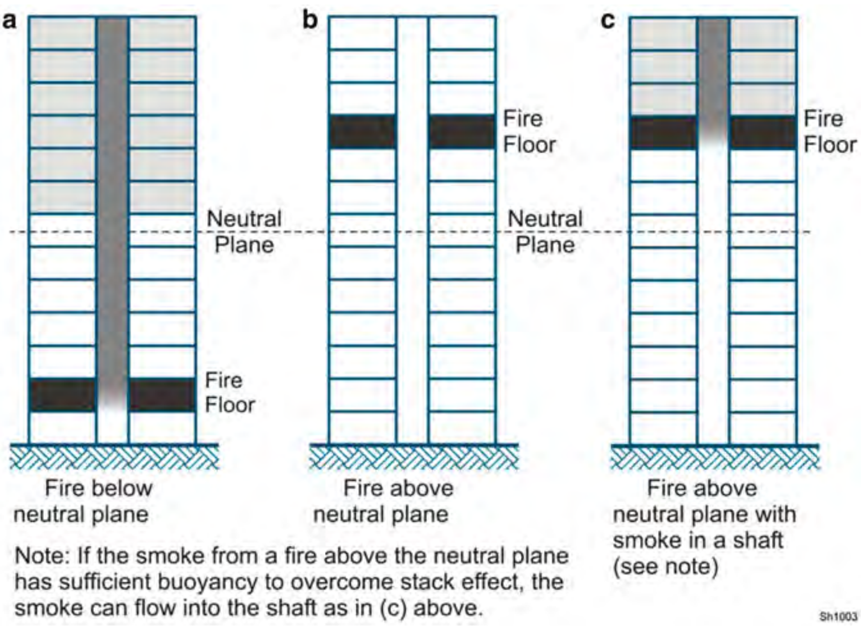

Fig. 50.6 Smoke movement in a high rise building due to normal stack effect

subjected to normal stack effect. For a fire below the neutral plane, smoke tends to enter and flow up shafts, and above the neutral plane this smoke flows from the shaft to building spaces (Fig. 50.6a). Smoke from a fire above the neutral plane can flow through cracks and gaps in the floor to the floor above the fire, but the forces of stack effect work to prevent smoke from entering shafts as shown in Fig. 50.6b. If the smoke from a fire above the neutral plane has sufficient buoyancy to overcome stack effect and flow into a shaft, it will flow up the shaft and infiltrate floors above the fire floor as can be seen in Fig. 50.6c.

For a building with shafts of various heights and different shaft temperatures, the flows can become very complicated. These flows would not look like those of either Fig. 50.4 or Fig. 50.5. Each shaft could have its own neutral plane with respect to the outside, and sometimes a shaft may have more than one neutral plane. Equation (50.1) is not applicable for such complicated buildings, but the flows and pressures in such buildings can be analyzed by CONTAM.

Myth: It is a myth that the pressure difference due to stack effect is nearly proportional to the temperature difference between the building and the outside

Fact: This pressure difference is nearly proportional to the temperature difference between a *shaft* and the outside

Another Meaning of Stack Effect

The term stack effect is often used in a different way from that discussed above. Sometimes engineers will say that a pressurized stairwell (or elevator) needs to be designed to account for the impact of stack effect. If the stairwell (or elevator) is properly pressurized, there is no neutral plane, and the flows do not look like those in Figs. 50.4 or 50.5. Strictly speaking there is no stack effect in the pressurized stairwell (or elevator). What is meant when an engineer says “that a pressurized stairwell (or elevator shaft) needs to be designed to account for the impact of stack effect” is that it needs to be

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designed to account for the temperature differences that cause stack effect.

Myth: It is a myth that stack effect is the major factor impacting stairwell and elevator pressurization

Fact: Today the impact of stack effect is a minor factor for most pressurized stairwells and elevators. The pressurization air for many stairwells and elevators is untreated outside air that is not heated or cooled. The temperature of these shafts is often nearly the same as the outside temperature, and the impact of stack effect is significantly reduced as compared to shafts pressurized with air treated to the building temperature

Buoyancy of Combustion Gases

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 (50.1) with the variables updated as shown in Equation (50.2).

$$\Delta p_{FS} = 7.63\left(\frac{1}{T_O + 460} - \frac{1}{T_F + 460}\right)z$$
$$\Delta p_{FS} = 3460\left(\frac{1}{T_O + 273} - \frac{1}{T_F + 273}\right)z \quad \text{for SI} \tag{50.2}$$

where

Δp_{FS} = pressure difference from a fire space to the surroundings, in. H_2O (Pa),

T_O = temperature surroundings, °F (°C),

T_F = temperature in the fire space, °F (°C),

z = distance above the neutral plane, ft (m).

For a fire, the neutral plane is the horizontal plane of where the pressure in the fire space is the same as that of the surroundings. For a fire with a fire compartment temperature of 1470 °F (800 °C) and surroundings at 68 °F (20 °C), the pressure difference 5 ft (1.52 m) above the neutral plane can be calculated from Equation (50.2) to be 0.052 in. H2O (13 Pa). Fang [7] 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. H2O (16 Pa) across the burn room wall at the ceiling.

Expansion of Combustion Gases

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 flows into the fire compartment and hot smoke flows 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

$$\frac{V_{out}}{V_{in}} = \frac{T_{out} + 460}{T_{in} + 460}$$
$$\frac{V_{out}}{V_{in}} = \frac{T_{out} + 273}{T_{in} + 273} \quad \text{for SI} \tag{50.3}$$

where

V_{out} = volumetric flow of smoke out of the fire compartment, cfm (m^3/s),

V_{in} = volumetric flow of air into the fire compartment, cfm (m^3/s),

T_{out} = temperature of smoke leaving the fire compartment, °F (°C),

T_{in} = temperature of air entering the fire compartment, °F (°C).

For fire gas temperature of 2200 °F (1260 °C), the gas will expand to about five times its original volume. For a fire room with open doors or windows, the pressure difference across these openings due to expansion is negligible because of the large flow areas involved. However, for a fire space without open doors or windows, the pressure differences due to expansion may be important, provided there is sufficient oxygen to support combustion for a significant time.

Wind

In many instances, wind can have a pronounced impact on smoke movement within a building. The pressure that wind exerts on a wall is

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$$p_w = 0.00645\, C_w \rho_o U_H^2$$
$$p_w = \frac{1}{2} C_w \rho_o U_H^2 \quad \text{for SI} \tag{50.4}$$

where
p_w = wind pressure, in H_2O (Pa),
C_w = pressure coefficient, dimensionless,
ρ_o = outside air density, lb/ft^3 (kg/m^3),
U_H = velocity at wall height H, mph (m/s).

The pressure coefficients, C_w, depends on wind direction, building geometry and local obstructions to the wind. The pressure coefficients are in range of −0.8 to 0.8, with positive values for windward walls and negative values for leeward walls.

Wind is often measured at airports, and the standard height for measuring velocity and direction is 33 ft (10 m). The Chap. 2 of the *Handbook of Smoke Control Engineering* lists design wind speeds for many locations in the US, Canada, and other countries. The local design wind can be calculated as follows

$$U_H = U_{met} \left(\frac{\delta_{met}}{H_{met}} \right)^{a_{met}} \left(\frac{H}{\delta} \right)^{a} \tag{50.5}$$

where
U_H = wind velocity at wall w/height H, mph (m/s),
U_{met} = measured velocity, mph (m/s),
H_{met} = height of wind measurement, ft (m),
δ_{met} = boundary layer height in the vicinity of the wind anemometer, ft (m),
a_{met} = wind exponent in the vicinity of the wind anemometer, dimensionless,
H = height of wall, ft (m),
δ = boundary layer height at wall, ft (m),
a = wind exponent at wall.

A number of approaches have been developed for categorizing terrain boundary layer and the wind exponent. For additional information about wind see Chap. 3 of the *Handbook of Smoke Control Engineering*, Shaw and Tamura [33], Kandola [12–14], Aynsley [3], and Klote [16]. Some civil engineering texts have useful information about wind [6, 24, 25, 35].

Forced Ventilation

The current code requirements for heating, ventilating and air conditioning (HVAC) systems started with a 1939 report by the National Board of Fire Underwriters [28]. The NBFU examined NFPA fire data from January 1936 to April 1938. Of 25 fires recorded, 19 involved combustion of parts of the air moving system. In five cases of no fire in the HVAC system, smoke was distributed by the system. Modern HVAC systems are built of materials intended to withstand fires. Also modern HVAC systems either shut down in the event of a fire or go into a smoke control mode of operation. This mode of operation is called zoned smoke control, and it is discussed later.

Elevator Piston Effect

The transient pressures and flows produced when an elevator car moves in a shaft are called *piston effect*. Figure 50.7 shows the airflows resulting from an upward-moving elevator car. Such piston effect can pull smoke into a normally pressurized elevator lobby or elevator shaft. In a

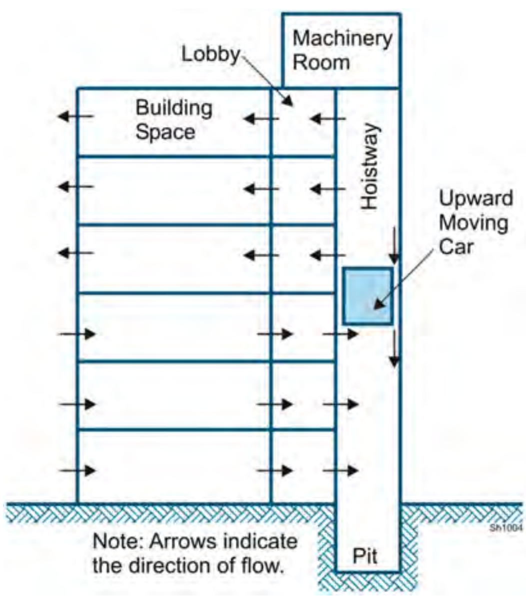

Fig. 50.7 Airflow due to an upward moving elevator car

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joint US and Canadian project, an analysis of piston effect was developed and validated [15, 20, 23].

The upper limit of piston effect for an elevator with enclosed lobbies is

$$\Delta p_{u,ir} = \frac{1.66 \times 10^{-6}\rho}{2}\left(\frac{A_s A_e U}{A_a A_{ir} C_c}\right)^2$$
$$\Delta p_{u,ir} = \frac{\rho}{2}\left(\frac{A_s A_e U}{A_a A_{ir} C_c}\right)^2 \quad \text{for SI} \qquad (50.6)$$

where

$\Delta p_{u,si}$ = upper limit pressure difference from the shaft to the building, in H_2O (Pa),
ρ = air density in hoistway, lb/ft^3 (kg/m^3),
A_s = cross-sectional area of shaft, ft^2 (m^2),
A_{ir} = leakage area between building and lobby, ft^2 (m^2),
A_a = free area around the elevator car, ft^2 (m^2),
A_e = effective area, ft^2 (m^2),
U = elevator car velocity, fpm (m/s),
C_c = flow coefficient for flow around car, dimensionless.

The flow coefficient, C_c, was determined experimentally at about 0.94 for a multiple car hoistway and 0.83 for a single car hoistway. The free area around the elevator car is the cross-sectional area of the shaft less the cross-sectional area of the car. For an elevator with enclosed lobbies, the effective area is

$$A_e = \left(\frac{1}{A_{sr}^2} + \frac{1}{A_{ir}^2} + \frac{1}{A_{io}^2}\right)^{-1/2} \qquad (50.7)$$

where

A_{sr} = leakage area between shaft and lobby, ft^2 (m^2),
A_{io} = leakage area between the building and the outside, ft^2 (m^2).

Figure 50.8 shows the upper limit of piston effect from the lobby to the building for car velocities from 100 to 1000 fpm (1 to 5 m/s). All elevator velocities are in this range with the exception of those of extremely tall buildings. The pressure differences shown in Fig. 50.8 happen for a brief time as the elevator car passes a floor.

Effective Flow Areas

Effective flow areas were essential in the early days of smoke control design to simplify flow networks. With computer network models such as CONTAM, there is much less need for network simplification. However, the effective flow area concept is still used for the following: (1) with the equation approach for analysis of pressurized stairwells, (2) with analysis of elevator piston effect, (3) to reduce data input to

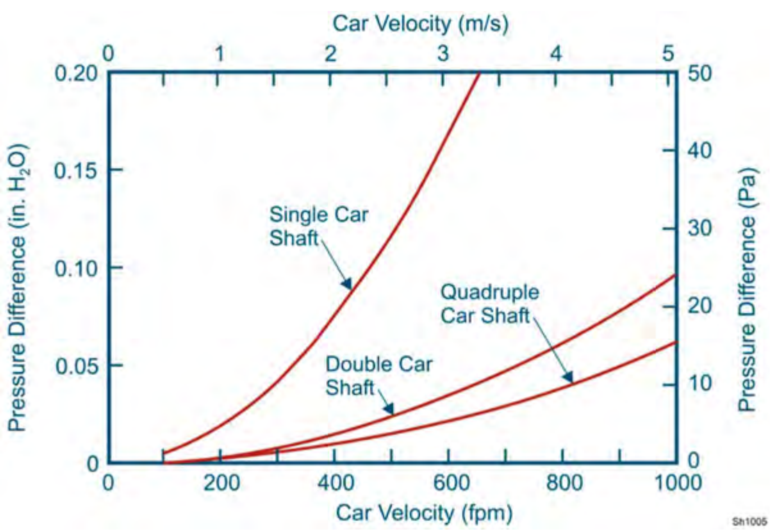

Fig. 50.8 Calculated upper limit of piston effect across elevator lobby doors

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network models, and (4) to solve some problems without calculations.

The various paths of air movement in the system can be parallel with one another (Fig. 50.9a), in series with one another (Fig. 50.9b), or a combination of parallel and series paths (Fig. 50.9c). 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.

For the three parallel flow paths in Fig. 50.9a, the effective area is

$$A_e = A_1 + A + A_3 \qquad (50.8)$$

and for any number of flow paths in parallel the effective area is

$$A_e = \sum_{i=1}^{n} A_i \qquad (50.8a)$$

For the three series flow paths in Fig. 50.9b, the effective area is

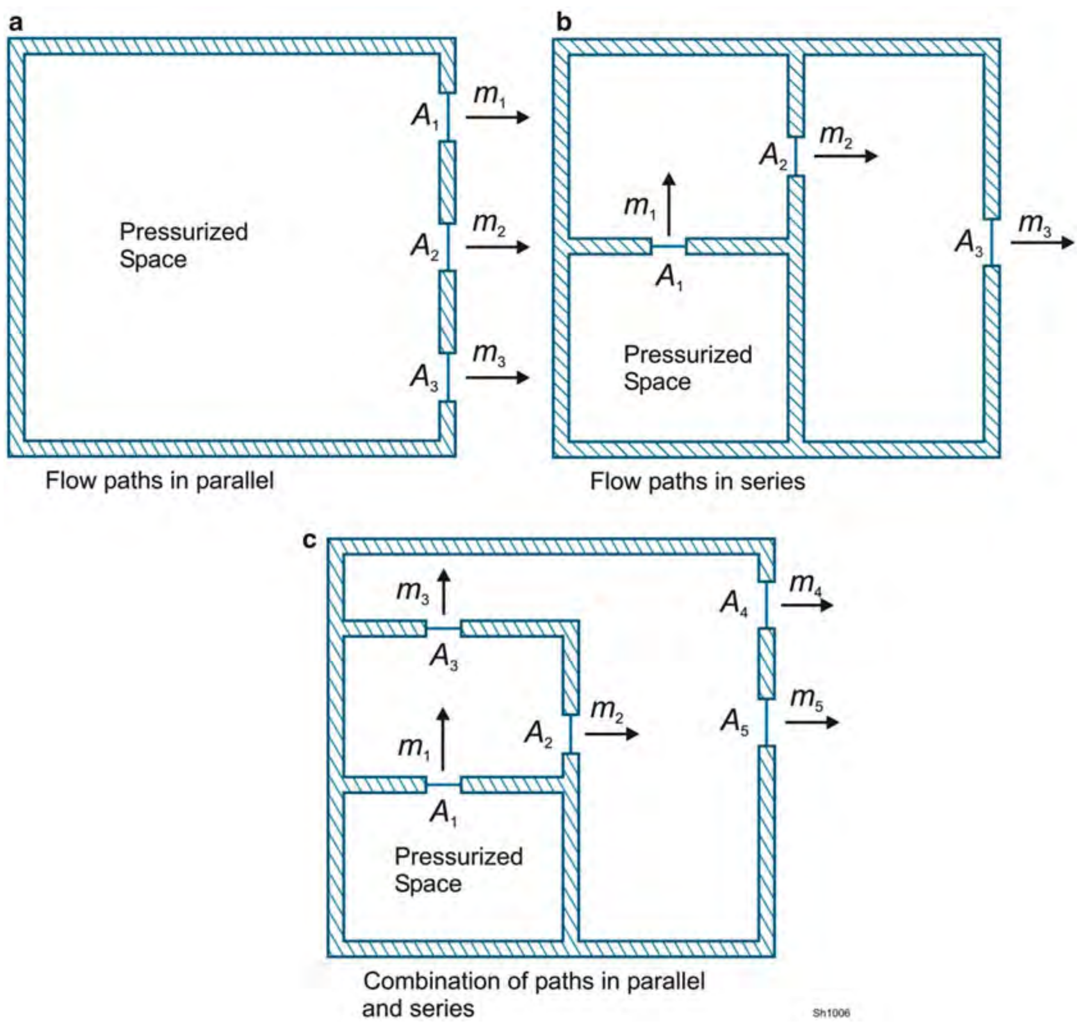

Fig. 50.9 Flow paths in parallel, in series, and a combination of both

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$$A_e = \left(\frac{1}{A_1^2} + \frac{1}{A_2^2} + \frac{1}{A_3^2} \right)^{-1/2} \quad (50.9)$$

and for any number of paths in series the effective area is

$$A_e = \left(\sum_{i=1}^{n} \frac{1}{A_i^2} \right)^{-1/2} \quad (50.9a)$$

where
A_e = effective flow area, ft² (m²),
A_i = flow area of path i, ft² (m²).

The above equations for effective flow areas are based on having the same flow coefficients and temperatures for all the paths in the total system of flow paths. For a system with both parallel and series paths, and the method of developing an effective area for the system is to combine parallel paths first and then series paths. Example *1* illustrates calculation of effective flow areas.

Example 1. Effective Flow Areas

Part 1: In Fig. 50.9a, what is the effective flow area if A_1, A_2 and A_3 are 0.1 ft²?

Because these areas are in parallel, $A_e = A_1 + A_2 + A_3 = 1 + 1 + 1 = 3$ ft²

Part 2: In Fig. 50.9b, what is the effective flow area if A_1, is 0.1 ft² and A_2 and A_3 are both 1 ft²?

Because these areas are in series, $A_e = \left(\frac{1}{A_1^2} + \frac{1}{A_2^2} + \frac{1}{A_3^2} \right)^{-1/2} = \left(\frac{1}{0.1^2} + \frac{1}{1^2} + \frac{1}{1^2} \right)^{-1/2}$
$= (100 + 1 + 1)^{=1/2} = 0.099$ ft²

This shows that for a system of flow areas in series with on area much smaller than the others, the effective flow area is slightly less than the smallest area.

Part 3: In Fig. 50.9c, what is the effective flow area if A_1, is 0.1 ft² and all the other flow areas are 1 ft²?

$A_1 = 0.1$ ft² and $A_2 = A_3 = A_4 = A_5 = 1$ ft².

Because A_2 and A_3 are in parallel, the effective flow are of A_2 and A_3 is $A_{23e} = A_2 + A_3 = 1 + 1 = 2$ ft².

Because A_4 and A_5 are in parallel, the effective flow are of A_4 and A_5 is $A_{45e} = A_4 + A_5 = 1 + 1 = 2$ ft².

The effective flow area of the system of flow paths in Fig. 50.9c is $A_e = \left(\frac{1}{A_1^2} + \frac{1}{A_{23e}^2} + \frac{1}{A_{45e}^2} \right)^{-1/2} = \left(\frac{1}{0.1^2} + \frac{1}{2^2} + \frac{1}{2^2} \right)^{-1/2}$
$= \left(100 + \frac{1}{4} + \frac{1}{4}\right)^{=1/2} = 0.0998$ ft²

The reader can look at Fig. 50.9c and see that A_{23e} and A_{34e} are both much larger than A_1, so that for practical purposes, the effective flow area of the system is A_1.

Symmetry

As with effective areas, symmetry was essential in the early days of smoke control design to simplify flow networks, symmetry is also used with the equation approach for analysis of stairwell pressurization. Figure 50.10 illustrates the floor plan of a multistory building that can be

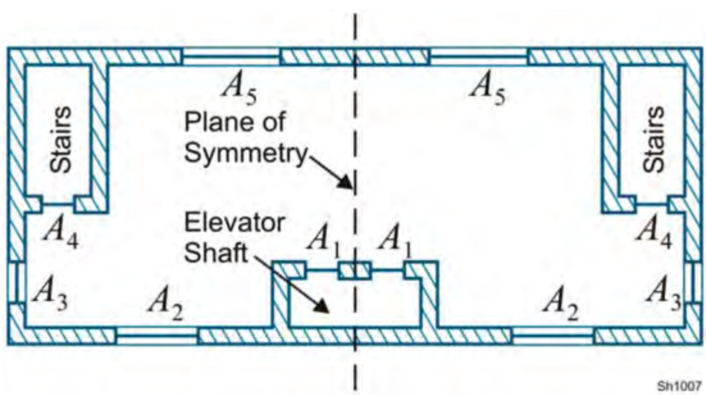

Fig. 50.10 Floor plan of building floor illustrating symmetry

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divided in 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 needs to be analyzed. It is not necessary that the building be geometrically symmetric, as shown in Fig. 50.10. A building that is not geometrically symmetric can be symmetric with respect to flow.

Flow and Pressure Difference

The primary equation used for analysis of pressurization smoke control systems is the orifice equation given in Equation (50.10).

$$m = 12.9\ CA\sqrt{2\rho\Delta p}$$
$$m = CA\sqrt{2\rho\Delta p} \quad \text{for SI} \tag{50.10}$$

For mass flow at 70 °F (21 °C) and standard atmospheric pressure, the orifice equation becomes

$$m_{sv} = 2610CA\sqrt{\Delta p}$$
$$m_{sv} = 0.839CA\sqrt{\Delta p} \quad \text{for SI} \tag{50.11}$$

where

m = mass flow through the path, lb/s (kg/s),
m_{sv} = mass flow through the path, scfm (standard m^3/s),
C = flow coefficient, dimensionless,
A = flow area (or leakage area), ft^2 (m^2),
Δp = pressure difference across path, in H_2O (Pa),
ρ = gas density in flow path, lb/ft^3 (kg/m^3).

One standard cubic foot per minute, scfm, equals 0.00125 lb per second, and one standard cubic meter per second (standard m^3/s) equals 1.2 kg per second at 70 °F (21 °C) and standard atmospheric pressure. Alternatively, the orifice equation can be expressed in terms of volumetric flow as shown in Equation (50.12).

$$V = 776\ CA\sqrt{\frac{2\Delta p}{\rho}}$$
$$V = CA\sqrt{\frac{2\Delta p}{\rho}} \quad \text{for SI} \tag{50.12}$$

where V is volumetric flow through the path in cubic feet per minute, cfm (m^3/s).

Equations (50.10), (50.11) and (50.12) are equivalent forms of the same equation, and the label "orifice equation" applies to all of them. The orifice equation gets its name because it is used to calculate the flow through an orifice. For these flow equations, the area term is the cross-sectional area, and the flow coefficient is called the discharge coefficient. A network flow program such as CONTAM uses this flow meter terminology. Flow areas and flow coefficients for building components are discussed later, and Idelchik [10] also is a source of flow data.

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 (such as how well a door is fitted or how well weatherstripping is installed). A door that is 36 in. by 7 ft (0.9 by 2.1 m) with an average crack width of 1/8 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 0.55–0.70 ft^2 (0.051–0.065 m^2) per door.

For many flow paths in buildings, a flow coefficient of 0.65 is used. The open doors of

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Table 50.2 Flow areas of walls and floors of commercial buildings

Construction element	Leakage	Area ratio: Leakage area per unit wall area in^2/ft^2	ft^2/ft^2	m^2/m^2
Exterior Building Walls (includes construction cracks, cracks around windows and doors)	Tight	7.2×10^{-3}	5.0×10^{-5}	5.0×10^{-5}
	Average	2.5×10^{-2}	1.7×10^{-4}	1.7×10^{-4}
	Loose	5.0×10^{-2}	3.5×10^{-4}	3.5×10^{-4}
	Very Loose	1.7×10^{-1}	1.2×10^{-3}	1.2×10^{-3}
Stairwell Walls (includes construction cracks but not cracks around windows or doors)	Tight	2.0×10^{-3}	1.4×10^{-5}	1.4×10^{-5}
	Average	1.6×10^{-2}	1.1×10^{-4}	1.1×10^{-4}
	Loose	5.0×10^{-2}	3.5×10^{-4}	3.5×10^{-4}
Elevator Shaft Walls (includes construction cracks but not cracks around doors)	Tight	2.6×10^{-2}	1.8×10^{-4}	1.8×10^{-4}
	Average	1.2×10^{-1}	8.4×10^{-4}	8.4×10^{-4}
	Loose	2.6×10^{-1}	1.8×10^{-3}	1.8×10^{-3}
		Leakage area per unit floor area		
Floors (includes construction cracks and gaps around penetrations)	Tight	9.5×10^{-4}	6.6×10^{-6}	6.6×10^{-6}
	Average	7.5×10^{-3}	5.2×10^{-5}	5.2×10^{-5}
	Loose[4]	2.4×10^{-2}	1.7×10^{-4}	1.7×10^{-4}

Note: The data in this table are for use with the orifice equation with a flow coefficient of $C = 0.65$. Floor leakage does not account for gaps that sometimes exist between the floor and curtain walls

pressurized stairwells commonly have stationary vortices which reduce the flow significantly [5, 19]. These vortices are thought to be caused by the asymmetric flow from the stairs, and stationary vortices can be expected at many open doors in other locations of smoke control systems. For open doors in stairwells, the geometric area of the opening should be used for the flow area along with a flow coefficient of 0.35.

Typical leakage areas for walls and floors of commercial buildings are tabulated as area ratios as shown in Table 50.2. These data are based from field tests performed by the National Research Council of Canada (Tamura and Wilson 1966; Tamura and Shaw 1976a, 1976b, 1978; [38–40]). Considerable data concerning leakage through building components are also provided in the *Handbook of Smoke Control Engineering*.

The determination of the flow area of a vent is not always straightforward especially when the vent surface is covered by a louver or screen. For vents with louvers, the flow area is referred to as the *free area*, and the free area is smaller than the geometric area (height multiplied by width) of the vent area. Because the slats in louvers are frequently slanted, calculation of the flow area is further complicated. When available, manufacturers' data regarding free are should be used. It is generally considered that the free area of a vent with a louver is about half the geometric area.

The density of air and smoke are expressed by the ideal gas law which is

$$\rho = \frac{144\,p}{R(T+460)}$$
$$\rho = \frac{p}{R(T+273)} \quad \text{for SI} \tag{50.13}$$

where

ρ = density, lb/ft^3 (kg/m^3),
p = pressure, lb/in^2 (Pa),
R = gas constant, 53.34 ft lbf/lbm/°R (287 J/kg K)
T = temperature, °F (°C).

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Friction Losses in Shafts

The pressure losses due to friction in ducts, stairwells and elevator shafts can be significant when flow rates are high. Tamura and Shaw (1976b) [40] and Achakji and Tamura [1] conducted tests of pressure loss in stairwells. Network computer models such as CONTAM employ algorithms that use this test data to calculate pressure losses due to friction in ducts, stairwells and other flow paths.

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 or being unable to open doors along the egress route such as into a stairwell.

The force to open a side hinged swinging door is shown in Fig. 50.11. The force required to open such a door when the smoke control system is operating can be determined using Equation (50.14).

$$F = F_{dc} + \frac{5.2 WA\Delta p}{2(W-d)}$$
$$F = F_{dc} + \frac{WA\Delta p}{2(W-d)} \quad \text{for SI} \tag{50.14}$$

where:
F = total door-opening force, lb (N),
F_{dc} = door closer force, lb (N),
W = door width, ft (m),
A = door area, ft^2 (m^2),
d = distance from doorknob to knob side of door, ft (m),
Δp = pressure difference, in. H_2O (Pa).

Equation (50.14) applies when the door opening force is applied at the knob. Example 2 illustrates calculation of the door opening force.

Example 2. Door Opening Force
What is the door opening force for a side hinged swinging door 3 ft wide by 7 ft high with a door closer that requires 9 lb of force and a pressure difference across it of 0.35 in. H_2O? The knob is 3 in. (0.25 ft) from the edge of the door.

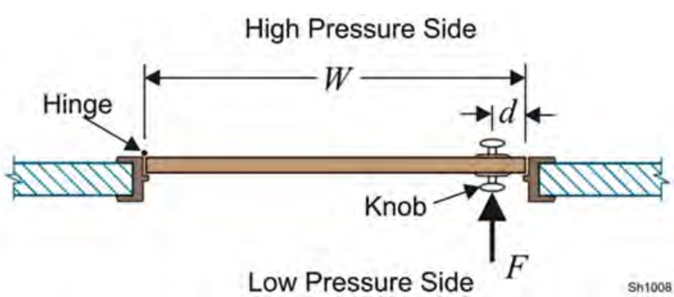
$W = 3$ ft; $F_{dc} = 9$ lb; $A = 3(7) = 21$ ft^2; $d = 0.25$ ft; $\Delta p = 0.35$ in. H_2O

The door-opening force is $F = F_{dc} + \frac{5.2WA\Delta p}{2(W-d)} = 9 + \frac{5.2(3)(21)(0.35)}{2(3-0.25)} = 30$ lb

Design Pressure Differences

Pressurization smoke control systems are designed to operate within a pressure difference range. This range is between the minimum design pressure difference and the maximum design pressure difference. A minimum design pressure difference intended to prevent smoke migration across a barrier of a smoke control system is generally stipulated by the applicable

Fig. 50.11 Door-opening force for side hinged door



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building and life safety regulations. A smoke control system should be designed to maintain this minimum design pressure difference under likely conditions of stack effect and wind.

The pressure difference across a barrier must not result in door-opening forces that exceed the maximum values stipulated by the applicable building and life safety regulations. For example, in NFPA 101, Life Safety Code [30], this maximum force is 30 lb (133 N). Calculation of door opening forces is discussed above. Acceptable pressurization consists of maintaining pressure differences across the barriers of a smoke control system that are between the minimum and maximum design values.

Stairwell Pressurization

Pressure differences across a stairwell tend to vary over the height of the stairwell. Figure 50.12 shows two pressure profiles for pressurized stairwells during cold winter months. One profile is for an idealized building, and the other is for a more realistic building with vertical leakage through floors and an elevator shaft. When it is cold outside, the pressure differences tend to be less at the bottom of the stairwell than at the top as can be seen in Fig. 50.12. When it is hot outside, the trend is the opposite. For both winter and summer conditions, the pressure profile for an idealized building is a straight line. An idealized building has no vertical leakage through the floors and shafts, and has leakage that is the same from floor to floor.

The pressure profiles of stairs in actual buildings depends on many factors including: (1) the leakage values of the various openings (flow paths) through building elements such as walls and floors, (2) the building floor plans, (3) the size of the elevator shaft or shafts and the number of elevator doors, (4) the presence or absence of elevator vents, and (5) the leakage through other shafts. There are many possible shapes for such pressure profiles in actual buildings.

For a building with vertical leakage, the flows through the floors and shafts act to even out to some extent the highest and lowest pressure differences across the stairwell. The profile for a building with vertical leakage is bounded by the extremes of the pressure profile of the idealized building. This means that other things being equal, the smallest pressure difference of the idealized analysis will be less than that of the actual building, and that the largest pressure difference of the idealized analysis will be more than that of the actual building. This is the reason that the algebraic equation method discussed below is conservative.

An algebraic equation method for analysis of pressurized stairwells is presented in Chap. 10 to the *Handbook of Smoke Control Engineering*. This algebraic equation method is based on

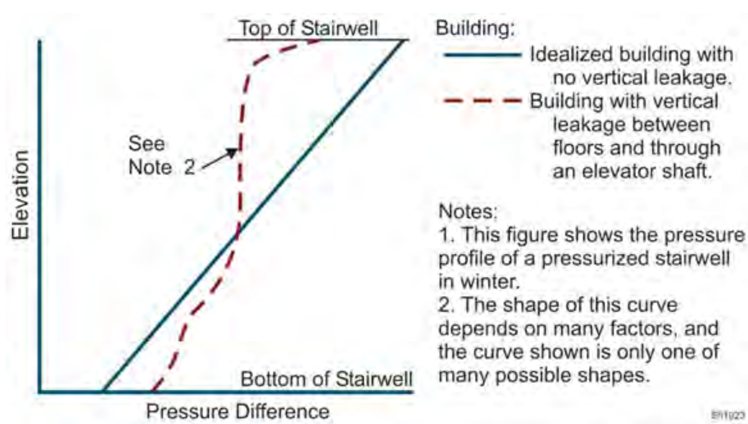

Fig. 50.12 Pressure profile of a pressurized stairwell in winter

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(1) the idealized building, (2) flows calculated by the orifice equation, (3) effective flow areas, and (4) symmetry. The algebraic equation method does not account for pressure losses in the stairwell due to friction, but these losses tend to be small for stairwells when all the stair doors are closed.

Network computer models such as CONTAM are capable of analyzing pressurized stairwells much more realistically than the algebraic equation method. CONTAM can simulate the impact of a realistic building flow network based on the performance of pressurized stairwells. As already mentioned, computer network models can also simulate pressure losses in the stairwell due to friction.

Height Limit

For some tall stairwells, acceptable pressurization may not be possible because of the impact of the indoor to outdoor temperature differences. This is more likely with systems with treated supply air than those with untreated supply air.

The height limit is the height above which acceptable pressurization is not possible for an idealized building. For standard atmospheric pressure at sea level, the height limit can be determined by Equation (50.15).

$$H_m = 0.131 \frac{F_R(\Delta p_{max} - \Delta p_{min})}{\left|\frac{1}{T_O + 460} - \frac{1}{T_S + 460}\right|}$$

$$H_m = 2.89 \times 10^{-4} \frac{F_R(\Delta p_{max} - \Delta p_{min})}{\left|\frac{1}{T_O + 273} - \frac{1}{T_S + 273}\right|} \quad \text{for SI} \tag{50.15}$$

where

H_m = height limit, ft (m),

F_R = flow area factor (dimensionless),

Δp_{max} = maximum design pressure difference, in. H_2O (Pa),

Δp_{min} = minimum design pressure difference, in. H_2O (Pa).

The flow area factor is

$$F_R = 1 + \frac{A_{SB}^2(T_B + 460)}{A_{BO}^2(T_S + 460)}$$

$$F_R = 1 + \frac{A_{SB}^2(T_B + 273)}{A_{BO}^2(T_S + 273)} \quad \text{for SI} \tag{50.16}$$

where

A_{SB} = flow area between the stairwell and the building, ft^2 (m^2),

A_{BO} = flow area per stairwell between the building and the outside, ft^2 (m^2),

T_S = temperature in stairwell, °F (°C),

T_B = temperature in building, °F (°C).

The area, A_{SB}, is the total flow area between the stairwell and the building, which would typically include the gaps around all the closed doors and the leakage paths in the walls. For a stairwell with an unpressurized vestibule, A_{SB}, is the sum of the effective flow areas for all floors from the stairwell to the building.

The area, A_{BO}, is on a per stairwell basis because of symmetry considerations. For a building with an open floor plan, A_{BO} consists of the total leakage area of the exterior walls divided by the number of stairwells. For more complex floor plans, an effective flow area concept discussed above needs to be used to calculate A_{BO}.

Stairwell Temperature

Today, the supply air for most stairwells in North America is not treated so that pressurized stairwells are hot in the summer and cold in the winter. In many applications, the use of untreated supply air can be justified for the following reasons: (1) fire drills are usually held in the spring or fall when the outside temperature usually is mild, and (2) during a fire emergency being exposed to nearly outdoor temperatures seems reasonable considering occupants are often traveling to the safety of the outdoors.

When pressurization air is untreated in cold climates, there is a concern about the water freezing in sprinkler and standpipe risers in stairwells. To prevent such freezing, listed heat tracing systems can be used on the risers.. Alternately,

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pressurization air can be treated to a minimum temperature in the range of 45–50 °F (7–10 °C) to prevent such freezing of water in the riser. ~~Using heat trace systems and untreated pressurization air has the advantage of minimizing the impact of stack effect, but using air treated to a minimum temperature has the advantage of minimizing the potential of freezing water on the stairwell floor during firefighting.~~

When pressurization air is untreated, the stairwell temperature can be expressed as

$$T_S = T_O + \eta(T_B - T_O) \quad (50.17)$$

where

T_S = temperature in the stairwell, °F (°C),
T_O = temperature outdoors, °F (°C),
T_B = temperature in the building, °F (°C),
η = heat transfer factor (dimensionless).

There has been little research on the heat transfer factor. It is believed that the heat transfer factor is in the range of 0.05–0.15. In the absence of better data for a specific application, a heat transfer factor of 0.15 is suggested as being conservative regarding the impact of stack effect.

For untreated supply air, it takes a few minutes for the temperature in the stairwell to stabilize near that of the outdoors. During this stabilization, excessive pressure differences could be produced. To prevent this, supply air can gradually be increased so that when the stairwell temperature is near that of the building there is insufficient flow to cause excessive pressurization. If needed, the temperature stabilization can be evaluated by a heat transfer analysis.

Simple and Complicated Buildings

For simple stairwell pressurization systems in simple buildings, some designers may know from experience that the pressurized stairwell will work as intended, and the fans can be sized by simple calculations. A simple stairwell pressurization system is one that: (1) has air supplied at a constant (or nearly so) volumetric flow rate, (2) is intended to maintain acceptable pressurization with all the doors closed, and (3) has no features to prevent loss of pressure when stair doors are opened. As discussed later, a compensated stairwell system has features intended to prevent pressure loss when stair doors are opened, but such systems can be rather complex with regard to their design, installation and operation.

Figure 50.13a is an example of a simple building. The algebraic equation method can be used to size the supply fans for a simple building. Some engineers have developed their own rules of thumb that are appropriate for certain kinds of stairwell pressurization systems in some buildings. Rules of thumb are generally in the range of 300–550 cfm (0.14–0.26 m^3/s) per floor. Engineers determining a rule of thumb for stairwell pressurization should take into account the building specifications and the anticipated quality of construction. Of course, experienced engineers develop rules of thumb including an allowance to avoid the expense of replacing fans, motors and electrical wiring in the event that the stairwell would be somewhat more leaky than anticipated. Example *3* illustrates calculations for a simple stairwell system in a simple building.

Example 3. Simple Stairwell Pressurization in a Simple Building

The stairwells in a 20 story open plan office are to be pressurized, and the stairwells are the only pressurization smoke control systems in the building. The building has two stairwells that serve all floors. This building can be considered simple because the stairwells are all the same height and the floors are very similar from floor to floor. The winter design temperature is T_O = 10 °F, and the building temperature is T_B = 70 °F. The minimum and maximum design pressure differences are Δp_{min} = 0.10 in. H_2O and Δp_{max} = 0.35 in. H_2O. The floor-to-floor height is 10 ft, and building height is 200 ft. For a typical

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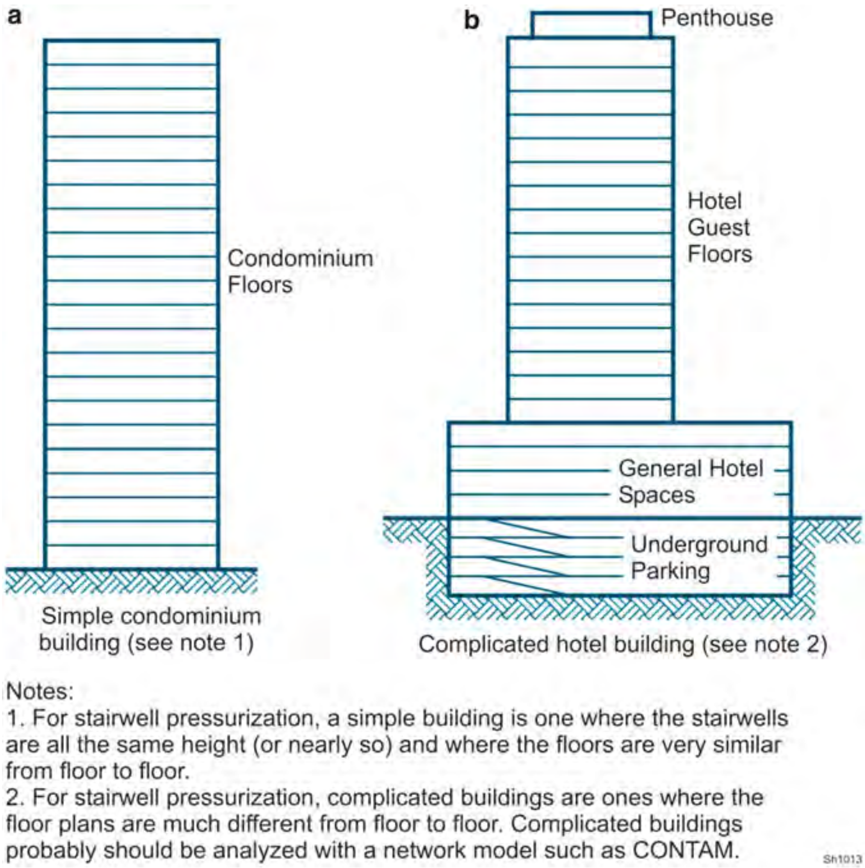

Fig. 50.13 Simple and complicated buildings with respect to stairwell pressurization

(continued)

floor, the flow area between the stairwell and the building is $A_{SB} = 0.34\ \text{ft}^2$, and the flow area per stairwell between the building and the outside is $A_{BO} = 0.30\ \text{ft}^2$.

Part 1: The stairwells are pressurized with untreated outside air, can this stairwell be pressurized?

Using a heat transfer factor of $\eta = 0.15$, the stairwell temperature is $T_S = T_O + \eta(T_B - T_O) = 10 + 0.15(70 - 10) = 19\ °\text{F}$.

The flow area factor is $F_R = 1 + \frac{A_{SB}^2(T_B+460)}{A_{BO}^2(T_S+460)} = 1 + \frac{0.34^2(70+460)}{0.30^2(19+460)} = 2.42$.

The height limit is $H_m = 0.131 \frac{F_R(\Delta p_{\max} - \Delta p_{\min})}{\left|\frac{1}{T_O+460} - \frac{1}{T_S+460}\right|} = 0.131 \frac{2.42(0.35 - 0.10)}{\left|\frac{1}{10+460} - \frac{1}{19+460}\right|} = 1980\ \text{ft}.$

Because the stairwells are in a simple building and the height limit is greater than the building height, the stairwells can be pressurized.

Part 2: The stairwells are pressurized with treated air at 70 °F, can this stairwell be pressurized?

The flow area factor is $F_R = 1 + \frac{A_{SB}^2(T_B+460)}{A_{BO}^2(T_S+460)} = 1 + \frac{0.34^2(70+460)}{0.30^2(70+460)} = 2.28$.

The height limit is $H_m = 0.131 \frac{F_R(\Delta p_{\max} - \Delta p_{\min})}{\left|\frac{1}{T_O+460} - \frac{1}{T_S+460}\right|} = 0.131 \frac{2.28(0.35 - 0.10)}{\left|\frac{1}{10+460} - \frac{1}{70+460}\right|} = 310\ \text{ft}.$

This height limit is much less than that of Part 1. As with part 1, the stairwells can be pressurized, because the stairwells are in a simple building and the height limit is greater than the building height.

Part 3: Each stairwell is to be pressurized with one fan. Choose the capacity of the fan.

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(continued)

Based on experience with similar construction and buildings, the design engineer chooses 420 cfm per floor for this application. Because the stairwell is 20 stories, the fan capacity is 8400 cfm. Each stairwell needs an 8400 cfm fan.

For buildings that are relatively complicated, computer-based network analysis of the pressurized stairwells is often needed to determine if the stairwell systems are capable of being balanced to perform as intended. For stairwells pressurized with untreated air, building complexity often has more impact than stack effect. Even buildings that are not especially tall are considered complicated when the floors plans vary significantly from floor to floor.

The building indicated in Fig. 50.13b consists of underground parking levels, general hotel floors, guest room floors and a penthouse. It can be difficult to maintain acceptable pressurization of stairwells that extend from the parking levels to the penthouse, because the plans of these floors are so different. Complicated buildings should probably be analyzed with a network analysis model such as CONTAM. Wind effects add complexity to building when there are many openings to the outdoors (operable windows, balconies with doors that open, etc.). For complicated buildings with many openings to the outdoors, analysis of the pressurized stairwell systems with a computer network model is needed.

Single and Multiple Injection

A single injection system has pressurization air supplied at one location. Air can be supplied at the top of the stairwell, the bottom, or at a location in between. Figure 50.14a and b illustrate top and bottom injection systems. When roof-mounted propeller fans are used for stairwell pressurization, propeller fans should have tops that shield the fan from wind effects. Wall-mounted propeller fans should not be used because they can be adversely impacted by the wind unless a wind analysis indicates otherwise.

With a bottom injection system such as illustrated in Fig. 50.14b, some of the supply air can short circuit the system by flowing directly out of the opened exterior bottom doorway reducing system effectiveness. The bottom doorway is expected to be open as occupants egress the building through the stairwell. Simulation of such detailed fluid flow is typically beyond the capability of network models such as CONTAM, but it can be simulated with more sophisticated computations fluid dynamics, CFD, computer models. It is recommended that bottom injection systems be analyzed using CFD to determine the extent to which supply air flows out of an open exterior door. Alternatively, the air can be introduced into the stairwell at least one floor above or below the exterior doors.

For tall stairwells, single injection systems can fail when a few doors near the air injection point are open simultaneously. Much of the pressurization air can be lost through these open doors, and the system will then fail to maintain positive pressures across doors further from the injection point compromising the effectiveness of the overall stairwell pressurization system. To reduce the potential for such failure, multiple injection systems can be used. Multiple injection systems can consist of one fan supplying air through a duct located in a shaft as shown in Fig. 50.14c. Other arrangements of multiple injection systems eliminate the need for a shaft by using more than one fan as shown in Fig. 50.14d.

There has been no research on this subject, but the consensus is that single injection systems for stairwell heights more than 100 ft (30.5 m) need a design analysis using computer network models. For multiple injection systems supplying air through a duct in a shaft, injection points are usually one to three floors apart. Multiple injection systems that have a separate fan at each

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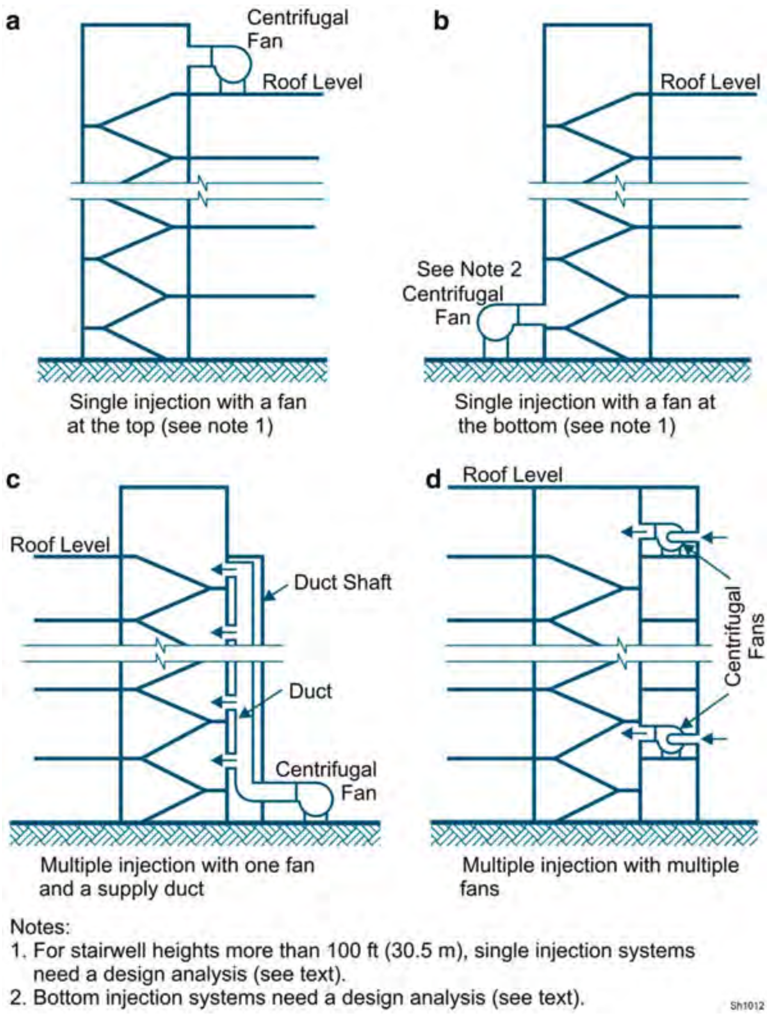

Fig. 50.14 Some single and multiple injection stairwell pressurization systems

injection point can have injection points much further apart. For systems with two injection points, one at the top and another near the bottom, a computer network model analysis is recommended for stairwell heights more than 200 ft (61 m).

Vestibules

Pressurized stairwells with vestibules are occasionally used. The vestibules can be: (1) unpressurized, (2) pressurized, (3) ventilated, or (4) a combination of pressurized and ventilated. Vestibules provide an additional barrier around a stairwell, and vestibules have the potential to reduce the probability of an open-door connection existing between the stairwell and the building.

An evacuation analysis can be performed to determine the extent to which both vestibule doors and stairway doors are likely to be opened simultaneously. For densely populated buildings, it is expected that on many floors both vestibule doors and stairway doors would be opened simultaneously. Therefore, vestibules may provide little benefit of an extra barrier for densely populated buildings.

The algebraic equation method of analysis can be used to analyze a pressurized stairwell with an

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unpressurized vestibule. The pressure differences and flows of stairwell systems with any kind of vestibules can be analyzed by computer network model. It is possible to evaluate the benefits of ventilated vestibules using tenability analysis.

System with Fire Floor Exhaust

System employing fire floor exhaust can achieve acceptable pressurization of tall stairwells in very complex buildings. A relatively small amount of air is supplied to the stairs, and the fire floor is exhausted such that acceptable pressurization is maintained on the fire floor where it is needed. It is common to also exhaust one or two floors above and below the fire floor. Fire floor exhaust is a form of zoned smoke control, and stairwell pressurization with such zoned smoke control is discussed later.

Stairwells and Open Doors

When any stair door is opened in a simple stairwell pressurization system, the pressure difference drops significantly. When all doors are closed suddenly in such a simple system, the pressure difference increases significantly. A compensated stairwell pressurization system is one that adjusts for changing conditions either by modulating supply airflow or by relieving excess pressure. The intent of a compensated system is to maintain acceptable pressurization when doors are opening and closing.

In the United States, most building and life safety regulations do not require pressurized stairwells to be compensated, and such stairwells are designed to maintain pressurization only when all the stair doors are closed. Traditionally, some engineers believed that pressurized stairwells need to be compensated, but an incidental finding of a study by Klote [18] casts doubt on this opinion. For two simulations in this study with a closed stair door on the fire floor and some other stair doors open, the stairwell remained tenable. The reason the stairwell remained tenable was that the smoke that leaked into the stairwell was diluted by the large amount of air supplied to the stairwell. In light of this finding, ASHRAE is sponsoring a research project to study the need for compensated stair systems.

Many kinds of compensated stairwell pressurization systems have been used, but the most common are (1) the open exterior door system and (2) the variable air volume (VAV) system. The open exterior door system has "constant-supply" airflow, and an exterior stairwell door that opens automatically upon system activation. This system is sometimes called the Canadian system because it originated in Canada, and it has been used extensively there. The supply air rate is not actually constant, but it varies to some extent with the pressure across the fan. For centrifugal fans this variation in flow is generally small. However, the term "constant-supply" is used to differentiate this system from the systems where the supply air rate is designed to intentionally change.

By keeping the exterior stairwell door open during system operation, the Canadian system eliminates the major source of pressure fluctuations. This system is simple and relatively inexpensive, but there are many locations where opening exterior doors automatically raises issues of building security. For complex buildings, it is recommended that this system be evaluated using a computer network model to assure that it operates as intended.

With the VAV system, the flow rate of supply air to the stairwell is adjusted to account for opening and closing of doors. Tamura (1990) conducted research on VAV systems at the National Research Council of Canada. It was found that the pressure drops when doors are opened, and it took about 3–7 min for the pressure to recover to the initial value. When all the stair open doors in a VAV system are closed, there is a pressure spike. In Tamura's research, the spike had a peak of 0.728 in. H_2O (181 Pa). This spike only lasted about 30 or 40 s, but the peak was much more than any reasonable maximum design pressure difference. Such peaks are a concern. A person encountering such a peak, would probably not be able to open the stair door,

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but they could open it a minute or so later provided they knew enough to try. It is possible that a person encountering such a peak would think the stair door was locked, and he or she might not try to open it again.

Wind can have a serious impact on VAV stair pressurization systems. During design analysis of some of these systems, some engineers have encountered very high pressure differences during some wind conditions. For example, when an exterior door is opened during the design wind speed, a compensated stair system may supply so much air that the pressure difference across some stair doors may exceed the maximum design value. It is possible to exceed this design value by as much as 100 %. During such an occurrence, it would be impossible or extremely difficult for occupants to enter the stairwell. For this reason, it is recommended that design analysis of VAV compensated stairwell pressurization systems include computer network model simulations under wind conditions.

Elevator Shaft Pressurization

The elevator pressurization systems discussed in this section are intended to prevent smoke from flowing from the fire floor through an elevator shaft and threatening life on floors away from the fire floor. This section does not address smoke control for elevator evacuation, but elevator evacuation is discussed in Chap. 12 of the *Handbook of Smoke Control Engineering*. Usually pressurized elevator shafts are in buildings that have pressurized stairwells, and the focus of this section is on both of these pressurization systems operating together. In the rare situation where pressurized elevator shafts are the only pressurization smoke control system in a building, the information in this section may also be useful.

The information discussed earlier about piston effect can be used to evaluate the impact of piston effect on the performance of pressurized elevator systems. The piston effect produces a pressure spike when a car passes a particular floor, and this happens for only a few seconds during the run of an elevator car. For elevators in multiple car shafts with car velocities less than 1000 fpm (5 m/s), piston effect should not adversely impact the performance of elevator pressurization. For elevators in single car shafts with car velocities less than 500 fpm (2.5 m/s), piston effect should not adversely impact the performance of elevator pressurization.

Design of pressurized elevator shafts is much more complicated than design of pressurized stairwells, but there are a number of approaches that can deal with this complexity. The reasons for this complexity are: (1) often the building envelope is not capable of effectively handling the large airflow resulting from both elevator and stairwell pressurization, and (2) open exterior doors on the ground floor can cause high pressure differences across the elevator shaft at the ground floor.

Usually a number of exterior doors on the ground floor are open during a building fire. During a fire, the fire service opens a number of exterior doors or keeps these doors open while fighting the fire. Occupants also open exterior doors during evacuation. The shaft pressurization system needs to operate as intended with these exterior doors open.

Generally a computer network model analysis is needed to determine if pressurized elevators and pressurized stairwells in a particular building are capable of being balanced to perform as intended. While it may be theoretically possible to use only a rule of thumb to design these systems, a computer network model analysis is strongly recommended.

The elevator pressurization systems discussed here are: (1) the basic system, (2) the exterior vent (EV) system, (3) the floor exhaust (FE) system, and (4) the ground floor lobby (GFL) system. As mentioned above, these systems are for use in buildings with pressurized stairwells. The results of 36 computer network model simulations using CONTAM were used to study the performance of an elevator shaft pressurization system for a 14-story building illustrated in Fig. 50.15. Further details of this analysis are presented in Chap. 11 of the *Handbook of Smoke Control Engineering*. The following discussion about elevator pressurization

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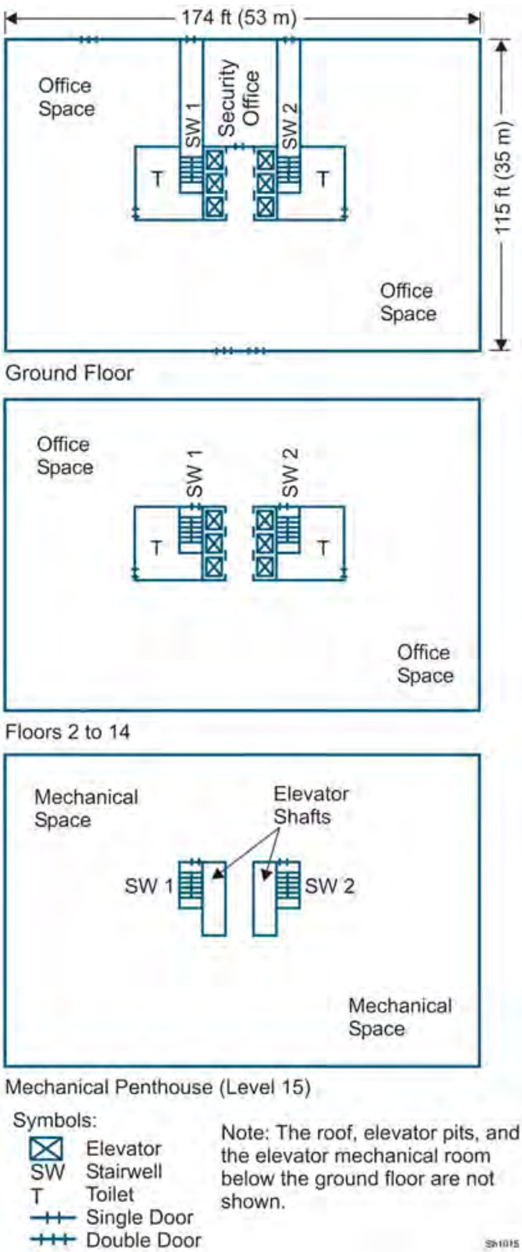

Fig. 50.15 Floor plans of the example 14 story open plan office building for elevator pressurization study

systems is based on these 36 simulations. For these simulations, the pressure difference criteria listed in Table 50.3 were used, and these criteria are consistent with pressure differences requirements in the *International Building Code* (ICC 2012). The leakage values and flow

Table 50.3 Pressure differences criteria for elevator pressurization simulations[a]

System	Minimum in. H_2O	Minimum Pa	Maximum in. H_2O	Maximum Pa
Pressurized elevators	0.10	25	0.25	62
Pressurized stairwells	0.10	25	0.35	87

[a]The above criteria are for the elevator simulations discussed Chap. 11 of the *Handbook of Smoke Control Engineering*, and some projects may have different criteria depending on code requirements and requirements of specific applications

Table 50.4 Flow areas and flow coefficients of doors used for elevator pressurization simulations[a]

Flow path	Path name[b]	Flow coefficient	Flow area ft^2	Flow area m^2
Single door (closed)	DOOR-SC	0.65	0.25	0.023
Single door (opened)	DOOR-SO	0.35	21	2.0
Double door (closed)	DOOR-DC	0.65	0.48	0.045
Double door (opened)	DOOR-DO	0.35	42	3.9
Elevator door (closed)	DOOR-EC	0.65	0.65	0.06
Elevator door (opened)	DOOR-EO	0.65	6	0.56

[a]The values in this table were chosen for the elevator simulations discussed Chap. 11 of the *Handbook of Smoke Control Engineering*. The flow areas and flow coefficients appropriate for a design analysis of a specific building may be different

[b]The path name is an identifier used in the CONTAM simulations

coefficients used for these simulations are listed in Tables 50.4 and 50.5. For the CONTAM simulations of the 14-story building, supply air was injected only at the top of the elevator shafts, but about half the supply air was injected at the top of the stairs and the rest at the second floor.

Basic System

In the basic system, each stairwell and elevator shaft has one or more dedicated fans that supply pressurization air. For reasons mentioned above,

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Table 50.5 Flow areas and flow coefficients of leakages used for elevator pressurization simulations

Flow path	Leakage classification	Path name	Flow coefficient	Flow area ft^2 per ft^2 of wall	Flow area m^2 per m^2 of wall
Exterior walls	Tight	WALL-EXT	0.65	0.50×10^{-4}	0.50×10^{-4}
	Average			0.17×10^{-3}	0.17×10^{-3}
	Loose			0.35×10^{-3}	0.35×10^{-3}
	Very loose			0.12×10^{-2}	0.12×10^{-2}
Interior walls	Loose	WALL	0.65	0.35×10^{-3}	0.35×10^{-3}
Floor (or roof)	Tight	FLOOR	0.65	0.66×10^{-5}	0.66×10^{-5}
	Average			0.52×10^{-4}	0.52×10^{-4}
	Loose			0.17×10^{-3}	0.17×10^{-3}
				ft^2 per ft of wall	m^2 per m of wall
Curtain wall gap	Tight	FLOORW	0.65	0.002	0.00061
	Loose			0.02	0.0061

See notes on Table 50.4

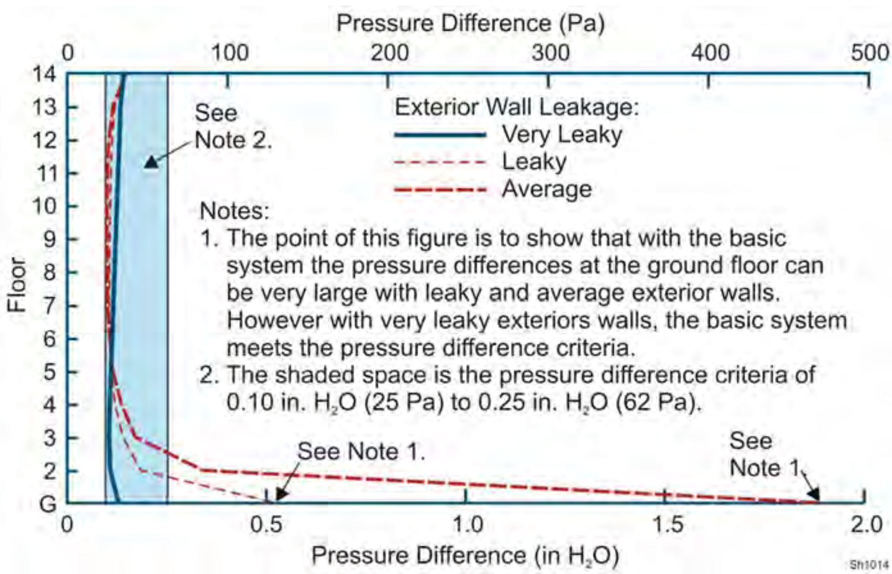

Fig. 50.16 Elevator pressure differences for basic elevator pressurization system

the basic system also includes stairwell pressurization, and the stair subsystems are not compensated systems. In most buildings the basic system does not result in successful pressurization, and the other systems discussed below consist of the basic system plus features to improve performance.

When the 14-story building contained very leaky exterior walls, the CONTAM simulations showed that the basic pressurization system would perform well, but this was not the case with less leaky exterior walls. It can be seen on Fig. 50.16 that for leaky exterior walls, the pressure difference across the elevator doors on the ground floor is about 0.5 in. H_2O (75 Pa). For exterior walls of average leakage the pressure difference across the elevator doors on floor 2 is about 0.35 in. H_2O (52 Pa), and at the ground floor it is about 1.9 in. H_2O (280 Pa). These values exceed the maximum criteria used for elevator doors, which is 0.25 in. H_2O (62 Pa) as indicated in Table 50.3. For average and leaky

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exterior walls, there is insufficient leakage in the building envelope to accommodate the large amount of pressurization air supplied to the shafts.

With very leaky exteriors walls, it can be seen on Fig. 50.16 that the basic system meets the pressure difference criteria identified in Table 50.3. Air was supplied to each elevator shaft at 27,700 cfm (13.1 m^3/s), and air was supplied to each stairwell at 6560 cfm (3.09 m^3/s). With very leaky exteriors walls, there is enough wall leakage area to accommodate this large amount of pressurization air. For the few buildings that have very leaky building envelopes, the basic system can be a simple way to pressurize elevators and stairwells. For less leaky buildings, the systems discussed present other options.

Exterior Vent (EV) System

The idea of the EV system is to use vents in the exterior walls to increase the leakiness of the building envelope such that successful pressurization can be achieved. The vents are usually closed, but they open when the pressurization system is activated. The vents should be located in a manner to minimize adverse wind effects, and the supply intakes need to be located away from the vents to minimize the potential for smoke migration into the supply air. These vents may need fire dampers depending on building and fire code requirements.

Figure 50.17a shows a typical floor of the example 14-story building with vents in the exterior walls. For the example building, the vents can be sized to assure the design criteria are met. The vents were sized such that the amount of pressurization used for the basic system produce acceptable pressurization with the EV system in the example building.

The example building has open office plan. For buildings with corridors, the simple EV approach of Fig. 50.17a is not appropriate. The flow resistance of corridor walls and other walls has a negative impact on system performance

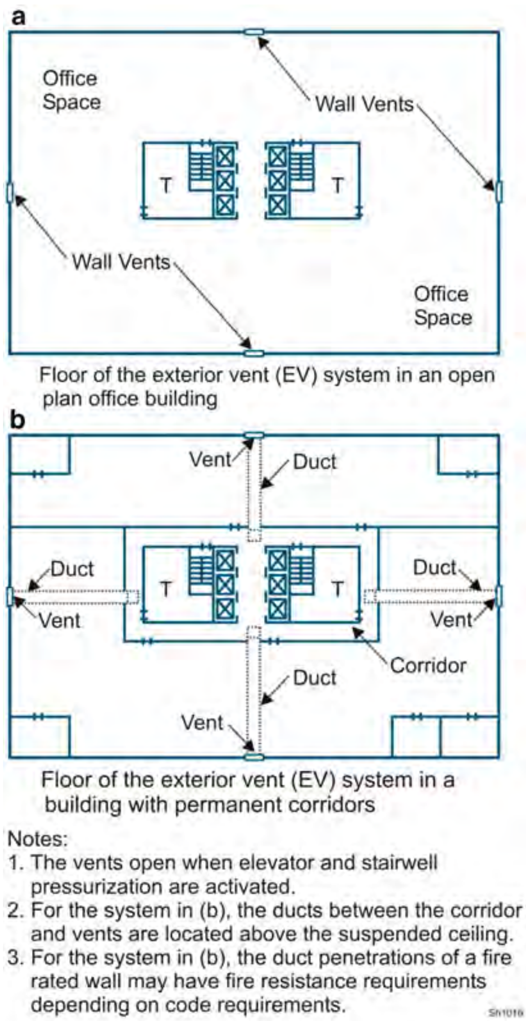

Fig. 50.17 Typical floor plans of buildings with the exterior vent (*EV*) system

when the vents are located in the exterior walls, but this can be overcome by use of ducted vents.

Figure 50.17b shows a ducted EV system that can be used for an office building with permanent corridors. The ducted EV system can be used for other occupancies such as hotels and condominiums. Any duct penetrations of a fire rated wall will need to be firestopped in accordance with applicable building and fire regulations. For a building where the floors can be either open plan or divided by tenant installed partitions, an EV system can be achieved by wall vents above a suspended ceiling and one or more

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air transfer grills in the ceiling of the elevator lobby.

With open exterior doors, it is not necessary to have exterior vents on the ground floor. Because the EV system may not be able to achieve acceptable pressurization with some or all the exterior doors closed, it may be necessary to have some of the exterior doors open automatically on system activation. The number of exterior doors that need to be opened automatically can be evaluated by the use of a computer network model.

In Figure 50.17a and b, the vents are in all four exterior walls with the intent of minimizing any adverse impact of the wind. It is suggested that the vent area be proportional to the area of the exterior walls. If fewer vents are used, it is suggested that wind effects be evaluated with the use of a computer network model.

Floor Exhaust (FE) System

The FE system deals with the building envelope issue by reducing the amount of supply air used. In the FE system, a relatively small amount of air is supplied to the elevator shafts and the stairwells, and the fire floor is exhausted such that acceptable pressurization is maintained on the fire floor where it is needed. It is common to also exhaust one or two floors above and below the fire floor.

The FE system is a kind of zoned smoke control. As discussed later, exhausting air from the fire floor and some floors above and below the fire floor has a beneficial impact on shaft pressurization. Often this system can achieve successful pressurization in tall and very complex buildings.

Typically the exhaust is through a shaft with a fan located in a mechanical floor or on the roof, and dampers between the shaft and the floors are closed on all floors when the system is not operating. On system activation, the dampers open on the floors to be exhausted. The outlet of the exhaust fan needs to be located away from the inlets the supply fans to minimize the potential for smoke feedback into supply air.

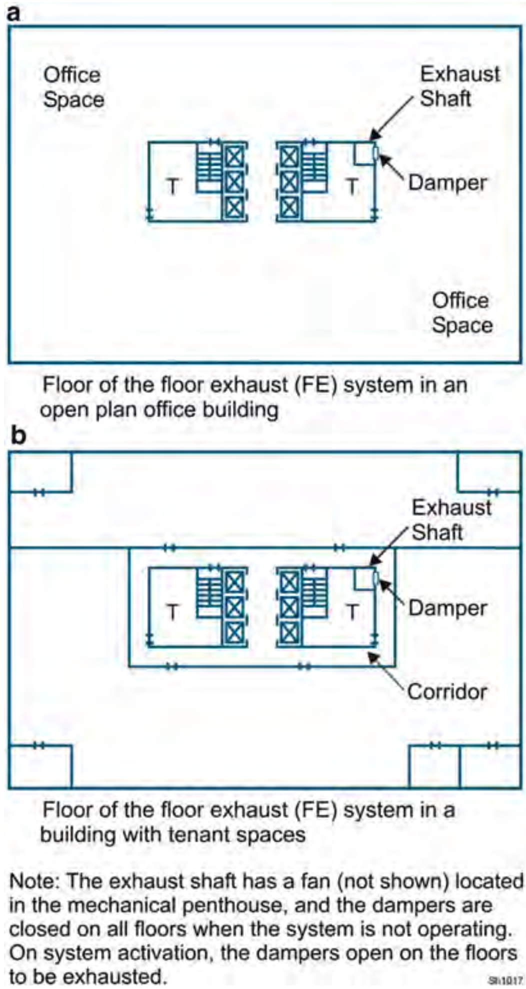

Fig. 50.18 Typical floor plans of buildings with the floor exhaust (*FE*) system

For the 14-story example building, the FE system is shown in Fig. 50.18a. For the simulations of the example building, each elevator shaft needed 15,100 cfm (7.14 m^3/s), and each stairwell needed 3800 cfm (1.79 m^3/s). The floor exhaust needed from the floors ranged from 4800 to 5400 cfm (2.28–2.55 m^3/s). For a building with many interior partitions, the exhaust can be from the corridor that the elevators and stairwells open onto, and this is shown in Fig. 50.18b.

As with the EV system, some of the exterior doors on the ground floor may need to open automatically upon system activation, and the

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number of such doors needed can be determined with the use of a computer network model.

Ground Floor Lobby (GFL) System

The GFL system has an enclosed elevator lobby on the ground floor to reduce the tendency of open exterior doors to cause high pressure differences across the elevator shaft at the ground floor. The GFL system often has a vent between the enclosed lobby and the building with the intent of preventing excessive pressure differences across the lobby doors. The lobby doors are the doors between the enclosed lobby and the building.

The pressure difference across the lobby door and the elevator door depend on the area of the vent. There is no established criterion for the maximum pressure difference across the lobby doors, but the pressure should not be so high as to prevent the doors from remaining closed. This value depends on the specific doors and hardware. For discussion here, a maximum pressure difference for the lobby doors was chosen as 0.35 in H_2O (87 Pa), but this value can be much different for specific applications. The vent should have a fire damper and a control damper in series. The control damper can be used to adjust the flow area of the vent so it can be balanced during commissioning. Figure 50.19 shows the ground floor of the example building with a GFL system.

As stated above, the intent of the elevator pressurization systems discussed in this chapter is to prevent smoke from flowing from the fire floor through an elevator shaft and threatening life on floors away from the fire floor. In the GFL system, the enclosed lobby on the ground floor protects the elevator from smoke from a fire on the ground floor. For this reason, the minimum elevator pressure difference criterion of Table 50.3 does not apply to the ground floor for a GFL system. The other criteria of Table 50.3 apply. Table 50.6 identifies the criteria that were used for the GFL system simulations. For the GFL system of the simulations discussed below, successful pressurization consists of meeting the criteria identified in Table 50.6.

For fires in high-rise buildings, frequently the fire service uses the elevators for rescue and for mobilization of firefighting equipment. When ground floor lobby doors are opened, the pressure difference may exceed the maximum pressure difference. If this can happen for a particular design, the fire service should be contacted to determine if this is acceptable to them.

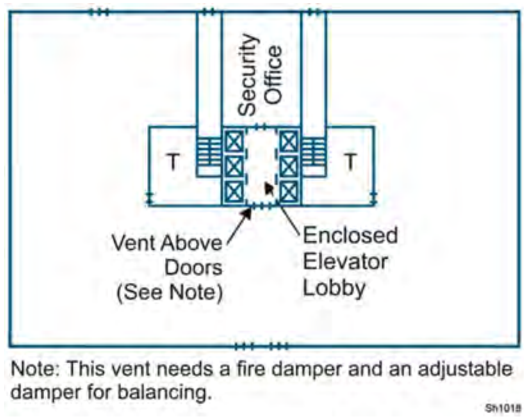

Fig. 50.19 Ground floor of a building with the ground floor lobby (*GFL*) system

Table 50.6 Pressure differences criteria for GFL elevator pressurization simulations[a]

Location	Criteria Number	Minimum in H_2O	Minimum Pa	Maximum in H_2O	Maximum Pa
Pressurized elevators on ground floor	1	NA	NA	0.25	62
Pressurized elevators on other floors	2	0.10	25	0.25	62
Pressurized stairwells on all floors	3	0.10	25	0.35	87
Ground floor elevator lobby door	4	NA	NA	0.35	87

[a]These pressure differences are with stairwell doors closed, the elevator doors closed, and the ground floor lobby door closed. The above criteria are for the GFL simulations discussed in this chapter, and some projects may have different criteria depending on code requirements and requirements of specific applications

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The floor-to-floor leakage can have a significant impact on the performance of a GFL system. This leakage consists of the leakage of the floor and that of the curtain wall gap (Table 50.5).

Zoned Smoke Control

The traditional approach for HVAC systems is to shut them down during building fires, but HVAC systems can be designed to operate in a smoke control mode during building fires. Zoned smoke control consists of exhausting the zone of the fire and possibly pressurizing the surrounding zones. For reasons discussed later in this chapter, pressurizing the surrounding zones is not recommended for zoned smoke control systems in tall buildings. For zoned smoke control systems that rely on smoke exhaust only, the zoned smoke control can complement the performance of stairwell pressurization in tall and complex buildings. In addition to using the HVAC system, dedicated equipment can be used for zoned smoke control.

In zoned smoke control, a building is divided into a number of zones each separated from the others by barriers. In the event of a fire, the zone with the fire is called the smoke zone, and the others are called the non-smoke zones. The zones that border on the smoke zone are called the surrounding zones. Passive smoke protection or pressurization smoke protection is used to limit the extent of smoke spread beyond the smoke zone. It is beyond the capability of smoke control to make conditions tenable in the smoke zone, and it is intended that occupants evacuate the smoke zone as soon as possible.

Smoke arrangements of smoke control zones are shown in Fig. 50.20. In this Figure the smoke zone is indicated by a minus sign, and the surrounding zones are indicated by a plus sign. Often the smoke zone is one floor of the building (Fig. 50.20a). A common approach is to make the smoke zone be the fire floor plus the floor directly above and below the fire floor as shown in Fig. 50.20b. In a relatively low sprawling building made of a number of wings, the smoke zone can be part of a floor as in Fig. 50.20c. A surrounding zone can be one floor as in Fig. 50.20a and b, and it can be part of a floor as in Fig. 50.20c. A surrounding zone can also be a number of floors as shown in Fig. 50.20d.

The traditional approach to zoned smoke control is to exhaust the smoke zone and to pressurize the surrounding zones, but many other approaches have been used. The methods that can be used to treat the smoke zone are: (1) fan powered exhaust, (2), passive smoke control using smoke barriers (3) exterior wall vents, or (4) smoke shafts. Fan powered smoke exhaust is the most common method, and passive smoke control using smoke barriers may be satisfactory when fan powered exhaust is not practical. Exterior wall vents and smoke shafts are not commonly used, but they are discussed in Chap. 13 of the *Handbook of Smoke Control Engineering*.

The methods that can be used for the zones surrounding the smoke zone are: (1) fan powered pressurization or (2) passive smoke control using smoke barriers. Fan powered pressurization of the surrounding zones has a negative impact on stairwell pressurization as discussed below. For the rest of this section, fan powered pressurization will be called pressurization, and fan powered exhaust will be called exhaust.

When the floors of a building are divided into many rooms with normally closed doors, these floors do not lend themselves to the traditional concept of zoned smoke control. This can also be said of wings of a building that are divided into many rooms with normally closed doors. For such applications, a form of zoned smoke control can be used that relies on a combination of corridor exhaust and passive smoke control using smoke barriers. Figure 50.21 shows a floor of a condominium building that can be considered a form of a smoke zone. The floor has corridor exhaust, and the other spaces rely on passive smoke protection of the corridor walls and ceiling floor assembly of the other spaces. This passive protection tends to minimize smoke flow through the ceiling floor assembly during a building fire.

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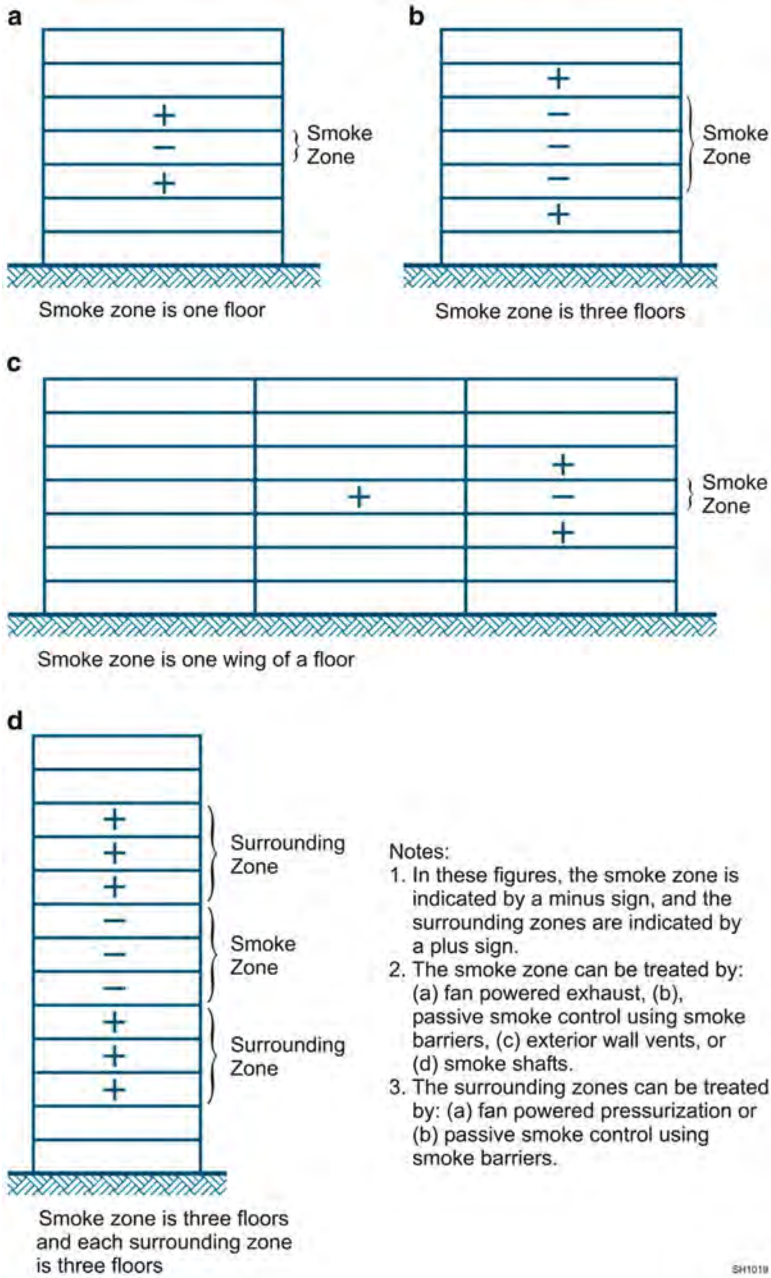
Fig. 50.20 Smoke arrangements of smoke control zones



Interaction with Pressurized Stairs

The interaction of zoned smoke control with pressurized stairwells can have a significant impact on the pressure differences across the stairwell doors. The following discussion is about smoke zones that are comprised of one floor and surrounding zones consisting of one floor above and one floor below. However, the same kind of interactions can happen with smoke zones and surrounding zones that are more than one floor.

Zoned smoke control using both exhaust and pressurization is shown in Fig. Fig. 50.22a, and pressure differences, Δp_{SB}, from the stairwell to the building are shown in Fig. 50.22b and Fig. 50.22c. Exhaust of the smoke zone increases

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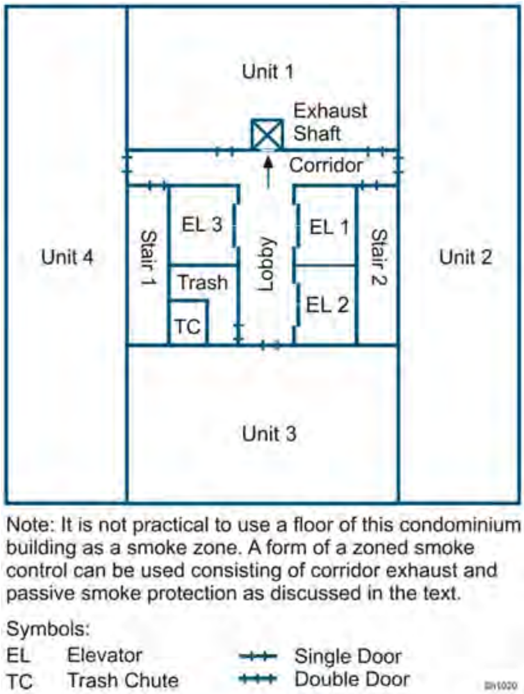

Fig. 50.21 Example of corridor exhaust and passive smoke control

the pressure difference across pressurized stairwell doors on the floor or floors of the smoke zone. Pressurization of the surrounding zones decreases the pressure difference across pressurized stairwell doors on these floors.

The pressure difference, Δp_{SB}, can be positive on all the floors as shown in Fig. 50.22b. This pressure difference can be negative on some floors as shown in Fig. 50.22c. Negative pressurization can happen on the floors that are pressurized, and this negative pressurization has the potential for the significant failure mode discussed below.

In Fig. 50.20a, smoke should be prevented from reaching the floor above the smoke zone, and negative stairwell pressurization should not compromise tenability of the stairwell. The effectiveness of this depends on proper identification of the fire floor. Properly maintained fire detection and alarm systems are very good at identifying the location of a fire, but issues can arise. In some fire scenarios, the first smoke detector to activate has been a floor or so above the fire floor. This can be attributed to any of the following: (1) smoke

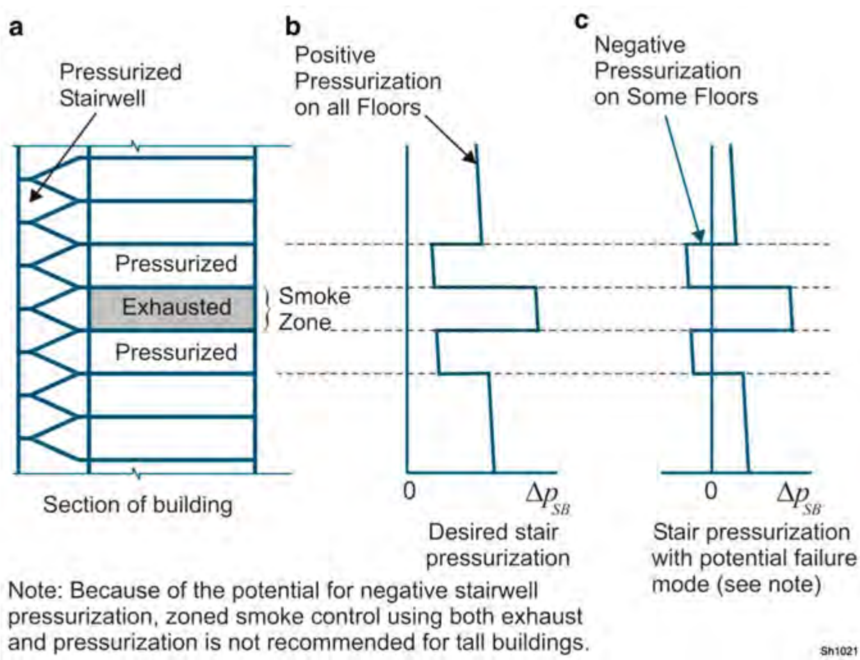

Fig. 50.22 Interaction between pressurized stairwells and zoned smoke control using both exhaust and pressurization

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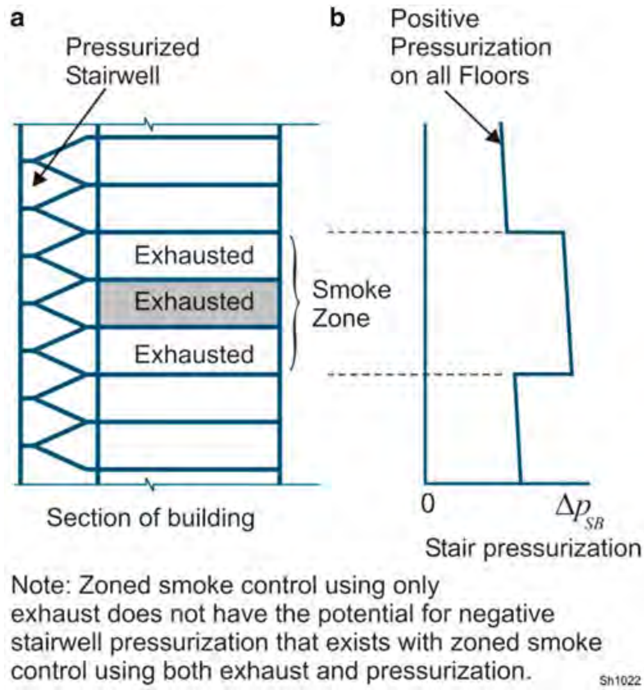

Fig. 50.23 Interaction between pressurized stairwells and zoned smoke control using only exhaust

flowing through a complex route to a floor above the fire, (2) smoke detectors not working properly on the fire floor, and (3) signals from smoke detectors being misidentified.

Regardless of the reason, when a fire floor is incorrectly identified, the smoke zone is incorrectly chosen. In this situation, the failure mode is that inadvertent pressurization of the fire floor can push smoke into the stairwells. An additional concern is that if this failure mode happens, it will probably happen to all the stairwells serving the fire floor. This failure mode is more of a concern for tall buildings because: (1) acceptable pressurization is more difficult in taller buildings than in shorter ones, and (2) stairwell smoke protection is more important in taller buildings than in shorter ones. Occupant density is another factor regarding the importance of stairwell smoke protection. In this context, a tall building might be thought of as one having a minimum of about 10 stories. Because of this failure mode, it is recommended that zoned smoke control using systems employing both exhaust and pressurization not be used for tall buildings where protection of the stairwells is especially important. Alternatively an analysis of this failure mode could be performed that includes factors such as evacuation time, emergency response time, and probability using the Firefighter's Smoke Control Station (FSCS) for corrective action.

The zoned smoke control shown in Fig. 50.23 does not have this failure mode. The zoned smoke control system of Fig. 50.23 consists of a three story smoke zone that is exhausted and the surrounding zones rely on passive smoke protection. The exhaust acts to increase Δp_{SB} for the three floors of the smoke zone (Fig. 50.23b). Because this system does not have pressurization of surrounding zones, Δp_{SB} is not reduced for surrounding zones, and this eliminates the failure mode discussed above.

In Fig. 50.23a the fire floor is shaded, and the smoke zone consists of the fire floor and the floors directly above and below. It is expected that there will be some smoke flow to the floor above the fire floor, and there may be some smoke flow to the floor below the fire floor. This smoke flow is restricted by the floor-ceiling assembly. A floor-ceiling assembly is a passive

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smoke barrier that has significant resistance to smoke flow. Even a floor-ceiling assembly not constructed as a passive smoke barrier has considerable resistance to smoke flow provided that the only openings through it are construction cracks and small cracks around pipe and conduit penetrations. This means that there will be some amount of time for occupants of the floors directly above and below the fire floor to evacuate those floors. Further, the small amount of smoke on these floors should act to convince occupants of the serious nature of the fire such that pre-movement time before evacuation will be significantly reduced.

Tenability Systems

As previously stated, the conventional smoke control systems discussed above are based on the approach of preventing occupants from coming into contact with smoke. These conventional systems have some level of smoke contact with the occupant at times when stair doors open for occupant entry or due to natural fluctuations in building pressures. Provided that the contaminates are sufficiently diluted, such smoke contact is usually considered to be of little concern. Tenability systems are designed with the intent of providing a tenable environment for occupants who are exposed to some concentration of smoke.

Analysis Components

Analysis of tenability systems requires consideration of the following components: (1) fire scenario, (2) smoke transport mechanisms, and (3) tenability thresholds.

Fire Scenario A fire scenario can be thought of as the outline of events and conditions that are critical to determining the outcome of alternate designs. In addition to the fire location and heat release rate (HRR), the fire scenario includes the status of the doors, the HVAC systems, and the smoke management system, and other systems. Species (O_2, N_2, CO, CO_2, etc.) generation can be included in the fire scenario. The scenario may also include specifics about the fuel, ignition of multiple fuel packages, and the effect of an fire suppression activities. The selection of the fire scenario can be based on a combination of professional judgment, fire dynamics, historical fire data, or code requirements. An analysis of a smoke control system is likely to include the consideration of a number of fire scenarios.

Smoke Transport Smoke can flow far from a fire and threaten life. The major driving forces that cause smoke movement are naturally occurring stack effect, buoyancy of combustion gases, expansion of combustion gases, wind effect, fan powered ventilation systems, and elevator piston effect.

Tenability Tenability calculations estimate the life hazard of a scenario. Tenability calculations address one or more of the following: exposure to toxic gases, exposure to heat, exposure to thermal radiation, and visibility through smoke. The exposures are time-integrated doses of toxic gases, heat, and thermal radiation. The conservative approach generally used for tenability systems is to make the tenability calculations as if an occupant were to remain at each location under consideration throughout the duration of the fire scenario.

Smoke Transport Calculations

Smoke transport analysis can be done with network models or computational fluid dynamic (CFD) models. Network models have already been discussed. The idea of a CFD model is to divide a space of interest into a large number of volumetric cells, and to solve the governing equations to calculate the flow, temperature, and concentrations of fire products at each cell.

The CFD models are appropriate for analysis of smoke flow in large spaces such as atria, malls, and arenas; and the network models are appropriate for analysis of smoke control systems that involve all or a large part of a large building. Fire dynamics simulator (FDS) is a CFD model that is in the public domain and was developed at the National Institute of Standards and Technology

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(NIST) specifically for fire applications [26, 27]. FDS is available from NIST at no cost. FDS can calculate temperatures, concentrations of gases, and visibility; this is a significant aid in the tenability analysis.

Computer network models, such as CONTAM which is available in the public domain, were previously discussed for conventional smoke control systems, but they can also be used for smoke transport calculations. CONTAM has been used to analyze a number of tenability systems ([8, 22], Ferreira 2002; [17, 18]). CONTAM can simulate the transport of contaminants, including the products of combustion. However, CONTAM cannot simulate heat transfer, so it cannot calculate the temperatures. The user needs to supply the temperatures of spaces to CONTAM, and zone fire models have been used to generate such temperature information. The zone fire model, CFAST, has been used for this purpose [11, 31, 32]. CFAST is available from NIST at no cost.

Tenability Calculations

There are a number of models that can be used to evaluate exposure to smoke. For most smoke control applications when smoke is diluted to meet visibility criteria, exposure to it is not life threatening. The fractional effective dose (FED) model is the simplest model for evaluating exposure to smoke, and it can be used to check that smoke is not life threatening.

The FED can be used to obtain an approximate of the effects of exposure to toxic gases.

$$\mathrm{FED} = \frac{\sum_{i=1}^{n} C_i \Delta t_i}{\mathrm{LC}t_{50}} \qquad (50.18)$$

where

FED = fractional effective dose, dimensionless,

$C_{,i}$ = mass concentration of material burned at the end of time interval i, lb/ft^3 (g/m^3),

Δt_i = time interval i, min (min),

$\mathrm{LC}t_{50}$ = lethal exposure dose from test data, lb ft^{-3} min (g m^{-3} min).

n = number of discrete concentration time pairs.

This equation is for uniform time intervals as calculated by computer models, and it evaluates the FED for the exposure time at the end of interval i (exposure time is $n\Delta t$). An FED greater than or equal to one indicates fatality. The concentration is in units mass of the material burned per unit volume. The lethal exposure dose, $\mathrm{LC}t_{50}$, is the product of the LC_{50} and the exposure time. The LC_{50} is the concentration of airborne combustion products that is lethal to 50 % of the subjects exposed for a specified time. The mass concentration of material burned, C_i, can be obtained from the smoke transport calculations.

For any time interval, the visibility can be calculated from

$$S_i = \frac{K}{2.303\delta_m C_i} \qquad (50.19)$$

where

S_i = visibility, ft (m),

K = proportionality constant,

δ_m = mass optical density, ft^2/lb (m^2/g),

C_i = mass concentration of fuel burned lb/ft^3 (g/m^3).

The proportionality constant, K, is 8 for illuminated signs and 3 for non-illuminated signs. For objects in reflected light (walls, hand rails, stairs, etc.), a value of $K = 3$ is normally used. Because C_i varies from location to location in fires, the visibility calculated from the above equation is considered to be the visibility at the point for which C_i is calculated. For example, if the calculated visibility was 20 ft (6.1 m), it would mean that a person could see 20 ft (6.1 m) through smoke where C_i was uniform.

Alternatively visibility can be calculated along a path through non-uniform smoke. There are many applications where non-uniform smoke happens such as smoke on a balcony in an atrium, smoke in a tunnel, and smoke in a hotel corridor. For example, Fig. 50.24 shows a person looking at an exit sign through non-uniform smoke. The smoke near the exit sign could exceed criteria for visibility at a point, but that does not mean that the person could not see the sign. Calculation of the visibility along the path between the person and the sign can evaluate if the sign can be seen.

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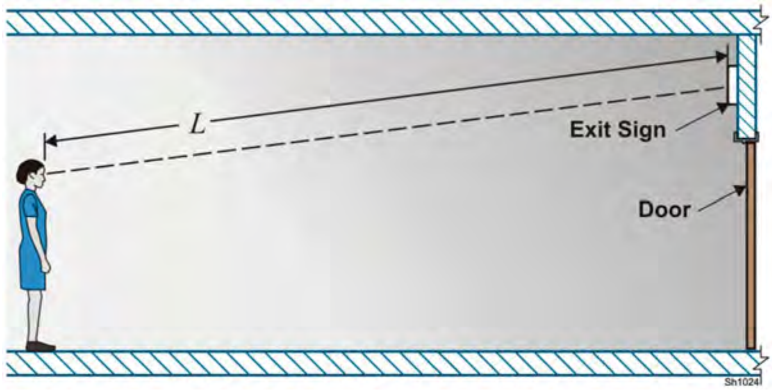

Fig. 50.24 Visibility through non-uniform smoke

Visibility along a path can also be calculated from percent obscuration as

$$S = -\frac{KL}{\log_e(1 - \lambda/100)} \quad (50.20)$$

where
S = visibility, ft (m),
K = proportionality constant,
L = length of path, ft (m),
λ = percent obscuration, dimensionless.

If the visibility is greater than or equal to the length of the path ($S > L$) an object can be seen over the path. When the path length is the same as the visibility ($L = S$), an object at the end of the path can barely be seen by a person with average eyesight. If the object were any farther away such a person could not see it. Percent obscuration, λ, can be calculated by FDS.

Generally, contact with dry air of temperatures greater than 250 °F (121 °C) can be expected to result in skin burns. Also, contact with dry air at a temperature less than approximately 250 °F (121 °C) leads to hyperthermia. For hyperthermia, heat exposure can be estimated from

$$F_{Ith} = \sum_{i=1}^{n} \frac{\Delta t}{\exp(5.67 - 0.0152 T_i)}$$

$$F_{Ith} = \sum_{i=1}^{n} \frac{\Delta t}{\exp(5.185 - 0.0373 T_i)} \quad \text{for SI} \quad (50.21)$$

where
F_{Ith} = total cumulative dose (dimensionless),
Δt = time interval, min (min),
T_i = temperature of air in interval i, °F (°C).

Incapacitation due to heat exposure would be expected for F_{Ith} greater than or equal to one. If contact with gases does not result in incapacitation due to heat exposure, thermal radiation from those gases would not result in incapacitation for the same exposure time. Generally, exposure to thermal radiation is not an issue for most smoke control applications.

Commissioning and Testing

Commissioning is the means to demonstrate to an owner and other project stakeholders that the installed smoke control system meets the smoke control system design for the project. Commissioning is the process for verifying and documenting that the performance of facilities, systems, and assemblies meets defined fire safety objectives and criteria. Commissioning refers to the process of examining, comparing, testing, and documenting the installation and performance of a smoke control system to ensure that it functions according to an approved design.

Special inspections are a means that an Authority Having Jurisdiction (AHJ) uses to determine that a smoke control system meets the applicable code requirements and regulations. The International Building Code (IBC) has requirements for a special inspection and describes the qualifications required for a special inspector (ICC 2012).

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Commissioning Process

The commissioning process begins at the start of the project and continues throughout the project. ASHRAE Guideline 5 provides methods for verifying and documenting that the performance of smoke control systems conforms with respect to the intent of the design [2]. For smoke control systems, an AHJ such as a building official or fire marshal typically enforces a combination of building codes, fire codes, and local standards. The intent of the smoke control system commissioning testing is to determine that the system meets the Owner's Project Requirements (OPR), including code requirements and inspections by the AHJ throughout the delivery of the project

In order to achieve successful commissioning of a system, a number of different people will typically be involved in the process. In addition to the building owner and AHJ, the system designer, general contractor, subcontractors, fire protection engineering consultants, and test and balance technicians can be involved. At the end of the testing, documentation is provided that the system is working properly according to the design.

Commissioning activities can occur at multiple stages during the construction process. Duct inspections, duct leakage testing, and barrier inspections are activities that typically occur early in the construction process when the ducts and barriers are readily visible. Component testing, including air flow measurement, can occur at a mid-point in construction where power is provided to individual devices, but central monitoring and control has not yet been provided. Sequence of operations and final performance testing typically occurs when construction is nearly complete, often just before the building is intended to obtain its permits and open to the public.

Commissioning Testing

Commonly, testing and balancing is required before formal acceptance testing to achieve the expected performance of all the components. Testing and balancing refers to the process where the as-built performance of smoke control systems is tested in the field and compared to the required design conditions. Adjustments to the installed system, such as refining the supply airflow rates, are made to ensure that the smoke control system is functioning as intended in the approved design documentation.

System performance testing is the phase where the code-specified performance parameters appropriate to the smoke control design are measured. For example, building codes require that a minimum pressure difference exist between a pressurized stairwell and other zones in the building, and that door opening force must not exceed a specified amount. In this case, performance testing would focus on measuring the pressure difference across stairwell doors and door opening forces. Some common parameters measured during smoke control system performance testing are: (1) exhaust/supply airflow quantities, (2) airflow velocities at atrium or other large open space perimeters, (3) door-opening forces, and (4) pressure differences between zones.

Smoke Bomb Tests Not Recommended: Chemical smoke from smoke bombs (also called smoke candles) is not recommended for any performance testing because it lacks the buoyancy of hot smoke from a real building fire. Smoke near a flaming fire has a temperature in the range of 1000–2000 °F (540–1100 °C). Heating chemical smoke to such temperatures to emulate smoke from a real fire is not recommended unless precautions are taken to protect life and property

Periodic Testing

After a smoke control system has been commissioned, testing must still be performed periodically so that the system is in the proper operating condition in the event of a fire. Periodic testing needs to be performed over the life of a

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building to determine that the installed smoke control systems are capable of operating as designed. Periodic testing includes: (1) manual testing involving ongoing inspection and maintenance and (2) automatic testing to determine that integral equipment is functional and operational. Automatic testing is often performed at a higher frequency than manual testing. Continued inspection and testing helps so that adjustments and repairs can be made to account for unforeseen changes to the building or failure of components.

Until recently, smoke control system reliability has been somewhat compromised because periodic testing was limited to manual testing. Inspections performed years after commissioning showed that some smoke control systems were inoperable, turned off, or made ineffective due to modifications to equipment or the building. It is expected that the reliability of smoke control systems will be significantly improved by the use of automatic weekly self-testing of system components, afforded by listed equipment carrying the appropriate product designations.

Nomenclature

A Flow area, ft^2 (m^2); or door area, ft^2 (m^2),
a Wind exponent at wall.
A_a Free area around the elevator car, ft^2 (m^2),
A_{BO} Flow area per stairwell between the building and the outside, ft^2 (m^2),
A_e Effective flow area, ft^2 (m^2),
A_i Flow area of path i, ft^2 (m^2).
A_{io} Leakage area between the building and the outside, ft^2 (m^2).
A_{ir} Leakage area between building and lobby, ft^2 (m^2),
a_{met} Wind exponent in the vicinity of the wind anemometer, dimensionless,
A_s Cross-sectional area of shaft, ft^2 (m^2),
A_{SB} Flow area between the stairwell and the building, ft^2 (m^2),
A_{sr} Leakage area between shaft and lobby, ft^2 (m^2),
C Flow coefficient, dimensionless,
$C_{,i}$ Mass concentration of material burned at the end of time interval i, lb/ft^3 (g/m^3),
C_c Flow coefficient for flow around car, dimensionless.
C_w Pressure coefficient, dimensionless,
d Distance from doorknob to knob side of door, ft (m),
F Total door-opening force, lb (N),
F_{dc} Door closer force, lb (N),
FED Fractional effective dose, dimensionless,
F_{Ith} Total cumulative dose (dimensionless),
F_R Flow area factor (dimensionless),
g Acceleration due to gravity, ft/s^2 (m/s^2),
H Height of wall, ft (m),
H_m Height limit, ft (m),
H_{met} Height of wind measurement, ft (m),
K Proportionality constant,
L Length of path, ft (m),
LCt_{50} Lethal exposure dose from test data, lb ft^{-3} min (g m^{-3} min).
m Mass flow through the path, lb/s (kg/s),
m_{sv} Mass flow through the path, scfm (standard m^3/s),
n Number of discrete concentration time pairs.
p Pressure, lb/in^2 (Pa),
p_{atm} Absolute atmospheric pressure, lb/ft^2 (Pa),
p_w Wind pressure, in H_2O (Pa),
R Gas constant, 53.34 ft lbf/lbm/°R (287 J/kg K)
S Visibility, ft (m),
T Temperature, °F (°C).
T_B Temperature in the building, °F (°C),
T_F Temperature in the fire space, °F (°C),
T_i Temperature of air in interval i, °F (°C).
T_{in} Temperature of air entering the fire compartment, °F (°C).

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T_O	Temperature outside, °F (°C); temperature surroundings, °F (°C),
T_{out}	Temperature of smoke leaving the fire compartment, °F (°C),
T_S	Temperature in the shaft, °F (°C),
U	Elevator car velocity, fpm (m/s),
U_H	Velocity at the upwind wall of height H, mph (m/s),
U_{met}	Measured velocity, mph (m/s),
V	Volumetric flow through the path, cfm (m^3/s).
V_{in}	Volumetric flow of air into the fire compartment, cfm (m^3/s),
V_{out}	Volumetric flow of smoke out of the fire compartment, cfm (m^3/s),
W	Door width, ft (m),
z	Distance above the neutral plane, ft (m).
δ	Boundary layer height at wall, ft (m),
ρ	Density, lb/ft^3 (kg/m^3),
η	Heat transfer factor (dimensionless).
λ	Percent obscuration, dimensionless.
δ_m	Mass optical density, ft^2/lb (m^2/g),
δ_{met}	Boundary layer height in the vicinity of the wind anemometer, ft (m),
ρ_o	Outside air density, lb/ft^3 (kg/m^3),
Δp	Pressure difference, in. H_2O (Pa).
Δp_{max}	Maximum design pressure difference, in. H_2O (Pa),
Δp_{min}	Minimum design pressure difference, in. H_2O (Pa).
Δp_{SF}	Pressure difference from a fire space to the surroundings, in. H_2O (Pa),
Δp_{SO}	Pressure difference from a shaft to the outside, in. H_2O (Pa),
$\Delta p_{u,si}$	Upper limit pressure difference from the shaft to the building, in H_2O (Pa),
Δt	Time interval, min (min),

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51 Smoke Control by Mechanical Exhaust or Natural Venting

James A. Milke

Introduction

Smoke management in large-volume spaces, such as atria and covered malls, poses separate and distinct challenges from well-compartmented spaces. In particular, smoke control strategies using pressure differences and physical barriers described by Klote in Chap. 50, and NFPA 92, *Standard for Smoke-Control Systems* [1], are infeasible. Without physical barriers, smoke propagation is unimpeded, spreading easily throughout the entire space. The tall ceiling heights in many large-volume spaces pose additional challenges because of the production of substantial quantities of smoke and delayed detection times. However, on the positive side, the combination of large-volume space and tall ceiling height permit the smoke to become diluted and cooled as it spreads vertically and horizontally, thereby reducing the level of hazard posed by the smoke. Even so, there is still a need to ensure that dangerous concentrations of smoke are prevented in large-volume spaces.

In addition to atria and covered malls, there are many other examples of large-volume spaces, including convention centers, airport terminals, sports arenas, and warehouses where smoke management is of concern. The engineering principles governing the design of smoke control systems for all of these various large-volume spaces are the same. However, differences in the smoke control system designs for the variety of large-volume spaces may be found. Differences in designs are a result of differences in fire scenarios and design goals, reflecting the range of building uses and operations and the nature of who or what may be exposed to the smoke. Given the similarities in engineering principles affecting smoke control system design, the term *atrium* will be used throughout this chapter to refer to all types of large-volume spaces.

The discussion presented in this chapter is divided into two sections. First, conditions within the atrium prior to actuation of a smoke control system are discussed. As part of this discussion, the smoke filling process is described along with the time required for actuation of a smoke control system. The second part of the chapter includes a description of conditions within the atrium after actuation of the smoke control system.

As a preface to any discussion on smoke control systems, a definition of smoke must be established (NFPA 92, *Standard for Smoke Control Systems* [1], Section 3.3.13):

> The airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass.

Although only the combustion products are visible and potentially toxic, what is visually observed as smoke is a mixture of the combustion products and the entrained air. Air is

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entrained along the entire height of the smoke plume below a smoke layer. Proportionally, the smoke is mostly entrained air. In the space between the base and tip of the flames, most of the entrained air is not consumed in the combustion process and only dilutes the combustion products. Entraining air into the smoke plume increases the mass flow in the plume to increase the quantity of smoke produced. However, the entrained air also dilutes the smoke to decrease the concentration of combustion gases and cool the smoke. In some cases, the smoke may be sufficiently diluted to mitigate the associated hazards.

Hazard Parameters

Smoke can adversely affect building occupants, fire brigade members, property (including the building structure and contents), and mission continuity. Typically, the threat to people or objects is posed when they come into contact with smoke for a sufficient period of time.

People who become exposed to smoke are generally harmed as a result of the exposure to toxic gases or elevated temperature. The toxic effects of smoke on people are described in Purser (see Chap. 63) and Klote et al. [2]. In addition, smoke may reduce visibility. A reduction of visibility may cause people to become disoriented and can in turn increase the amount of time they are exposed to the smoke [3]. A reduction of visibility may also increase the susceptibility of building occupants to trip over obstructions or even fall over balcony railings [4].

Building components can be affected by the elevated temperature due to smoke. Building components heated by smoke are considered in fire resistance analyses. In addition, building contents may be affected by exposure to the elevated temperatures, corrosive gases, or particulate matter. Contents exposed to heated smoke may be melted, distorted, or charred, depending on the temperature of the smoke and the degree of exposure. Contents that are submerged in smoke and come into contact with combustion gases and smoke particles may become stained or emit an odor of smoke. Exposure to smoke can damage electronic equipment, especially if restoration activities are not initiated promptly after the fire [5].

Following a fire, a building or portion thereof may be closed due to restoration, threatening mission continuity. This results in loss of revenue for the building owner, temporary unemployment of workers in the building, and loss of service of the facility to the community, among other outcomes.

Smoke Layer Interface Position

The smoke layer interface position is located a distance, z, above the top of the fuel, as indicated in Fig. 51.1. This parameter is used to assess the danger of people or objects being immersed in a smoke layer. Sole use of this parameter to assess hazard level is conservative by considering any concentration of smoke to be unacceptable. For people, even though the physiological effects due to being submerged in "light" smoke levels may be minor, the psychological effects and extended evacuation time may be appreciable. Being surrounded by smoke of any nature may decrease the speed of evacuation, perhaps until the smoke is no longer relatively benign. In terms of property protection issues, any smoke may be unacceptable because of smoke staining or smoke corrosivity.

Light Obscuration

As with the smoke layer depth parameter, light obscuration is not lethal by itself. Associated with an increase in light obscuration is a reduction in visibility, which is likely to yield a longer evacuation time and extend exposure to the toxins in smoke. In some documented fires, evacuation has been terminated due to a lack of sufficient visibility [6–8]. A fire fighter's injury in an atrium fire was attributed to a significant

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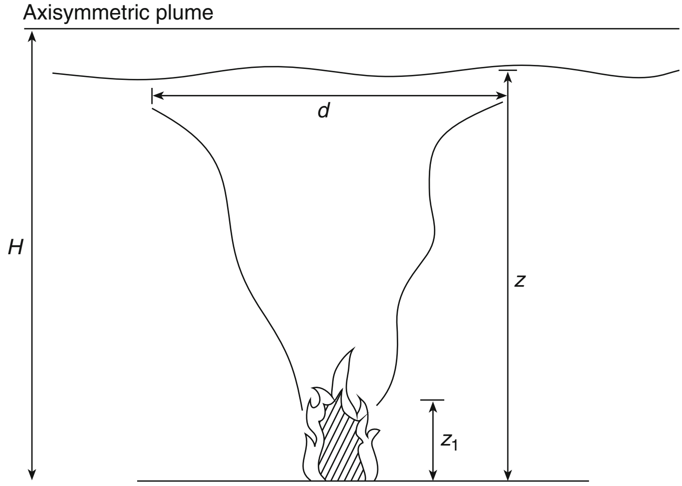
Fig. 51.1 Axisymmetric plume [1]



reduction in visibility due to light obscuration [4]. The fire fighter fell from an upper balcony because he could not see the edge.

Limiting values from 0.23 to 1.2 m^{-1} have been suggested for the extinction coefficient [6–8]. Alternatively, a critical limit may be based on a preferred minimum visibility distance to a particular target. For example, a limit of light obscuration can be suggested such that occupants can see an illuminated exit sign across a room or at the end of a corridor [3, 9].

Temperature and Gas Specie Concentration

The final two parameters, elevated temperature of the smoke layer and gas specie concentration (such as CO, CO_2, and HCN), can be directly related to the potential for harm (see Chap. 63). Critical limits for these two parameters can be suggested based on toxicity studies.

Smoke Management Approaches

The design of a smoke control system for an atrium is influenced by the following three characteristics of the atrium:

1. Geometric shape and dimensions
2. Relative location within the building
3. Separation from communicating spaces

Several approaches are available to achieve smoke management goals in an atrium (e.g., limit the fire size, provide physical barriers, and provide mechanical or natural ventilation). Selection of the best smoke management approach for a particular atrium should consider the use, size, and arrangement of the associated spaces.

Limiting the fire size can be accomplished by controlling the type, quantity, and arrangement of fuel. In addition, the fire size can be controlled through an automatic suppression system.

Physical barriers limit smoke spread to adjacent spaces. The ability of a physical barrier to limit smoke spread is dependent on the leakage of the barrier and pressure difference across the barrier. The barrier needs to withstand the exposure to smoke and an elevated temperature environment. In an atrium with a tall ceiling, the temperature of the smoke layer in the atrium may be only slightly above ambient temperatures in the space.

Mechanical or natural ventilation may be provided to remove smoke from the atrium. Removing smoke from the atrium can be intended to limit the accumulation of heat and smoke within the atrium or arrest the descent of the smoke layer. Mechanical ventilation can be provided to oppose smoke movement induced by the fire to restrict smoke spread to communicating

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spaces. Gravity vents may be provided to remove smoke, though their performance can be compromised by environmental factors.

Analytical Approach

Numerous tools are available to aid in the design and evaluate the adequacy of a smoke control system. The selection of a particular tool is dependent on the accuracy needed for the analysis and the applicability of the analytical tools given the characteristics of the large space and selected fire scenarios. The principal characteristics that affect applicability are

- Geometry of the large space: variation of horizontal cross-sectional area, sloped versus flat ceiling
- Transient aspects: unsteady versus steady heat release rate, constant versus transient operation of smoke control system
- Fire development: heat release rate as a function of time (for example, constant, power-law relationship with time, t^n)
- Environmental effects: stack effect, wind
- Interacting systems: other smoke control systems, HVAC, other exhaust systems (for example in laboratories)

The range of design tools available to assess the performance of smoke control system designs can be grouped into the following categories:

- Zone model (algebraic equation based)
- Zone model (computer based)
- Field model
- Physical scale model

The intent of an engineering analysis of smoke conditions in an atrium is to express the level of hazard in terms of physically based parameters, for example, smoke layer interface position, temperature, gas concentration (such as carbon monoxide), and light obscuration. The magnitude of each of these parameters can be predicted based on engineering principles. In addition to being predictable, critical threshold values are available for the hazard parameters in order to properly assess the severity of the threat (See Chap. 63). This chapter will concentrate on the life hazards posed by smoke. The hazards smoke poses to contents, property, and mission continuity are described elsewhere [2–4, 10].

Physical Scale Models

Physical scale models provide a representation of a space, though in a reduced scale. Physical scale models are especially useful in examining atria with irregular shapes or numerous projections. A review of applying physical scale models as a design aid for atrium smoke control systems was provided by Milke and Klote [11].

Quintiere provided a review of scaling relationships based on preserving the Froude number [12]. The Froude number, Fr, is defined as v/gl.

The scaling relations are

Temperature:

$$T_m = T_F \tag{51.1}$$

Geometric position:

$$x_m = x_F \left(\frac{l_m}{l_F}\right) \tag{51.2}$$

Pressure:

$$\Delta p_m = \Delta p_F \left(\frac{l_m}{l_F}\right) \tag{51.3}$$

Velocity:

$$v_m = v_F \left(\frac{l_m}{l_F}\right)^{1/2} \tag{51.4}$$

Time:

$$t_m = t_F \left(\frac{l_m}{l_F}\right)^{1/2} \tag{51.5}$$

Convectiveheat release:

$$\dot{Q}_{c,m} = \dot{Q}_{c,f} \left(\frac{l_m}{l_F}\right)^{5/2} \tag{51.6}$$

Volumetric flow rate:

$$V_{\text{fan},m} = V_{\text{fan},F} \left(\frac{l_m}{l_F}\right)^{5/2} \tag{51.7}$$

Experiments based on Froude modeling may be done with air at atmospheric pressure. Froude modeling does not preserve the Reynolds number. However, appropriate selection of the size of the physical scale model can ensure that fully

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developed flow is achieved to minimize the consequences of not preserving the Reynolds number. Because the smoke behavior in only certain areas of the scaled atrium may be of interest, fully developed flow only needs to be achieved in these particular areas. Often a physical scale model with a critical dimension of at least 0.3 m in any areas of interest will be sufficient to achieve fully developed, turbulent flow. As an example, in most shopping malls and atria, the critical dimension in question would be the floor-to-ceiling height of one of the balconies.

In addition, Froude modeling does not preserve the dimensionless parameters concerning heat transfer. Generally, this limitation has little effect because the temperature is the same for the physical scale model and the full-scale facility. Froude modeling does not apply to locations with high temperature and low Reynolds numbers (e.g., near the flame). However, Froude modeling provides useful information about smoke transport away from the fire.

Some surface effects can be preserved by scaling the thermal properties of the construction materials for the model. The thermal properties can be scaled by
Thermal properties:

$$(k\rho c_p)_{w,m} = (k\rho c_p)_{w,F}\left(\frac{l_m}{l_F}\right)^{0.9} \tag{51.8}$$

Because scaling thermal properties have only a secondary effect on fluid flow, considerations of convenient construction and flow visualization may require that some or all surface materials in the model are different from those selected based on thermal property scaling.

Example 1 A physical scale model is proposed to determine the equilibrium smoke layer position for the atrium depicted in Fig. 51.2. Because the horizontal cross-sectional area varies with height, algebraic equation and computer-based zone models are of limited value. The overall height of the atrium being studied is 30.5 m and the design fire is steady with a heat release rate of 5 MW. An exhaust fan capacity of 142 m^3/s is proposed. By applying the scaling relationships to formulate a small-scale model, the basic parameters for the scale model are

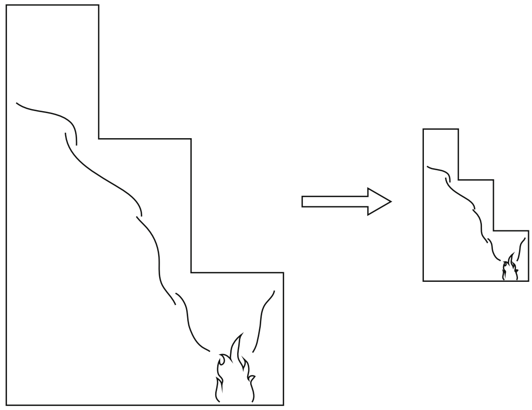

Fig. 51.2 Small-scale model of atrium

- Height: 3.8-m-tall model (1/8 scale)
- Fire size: 28 kW
- Fan capacity: 0.78 m^3/s

Analytical Models

Two categories of analytical models are zone and field models. A description of field models is outside the scope of this chapter. Zone models divide each compartment into a limited number of control volumes, typically an upper and a lower zone. Inherent in the zone approach is the assumption of uniform properties throughout each zone. In spaces with a large floor area, this assumption may be tenuous. Nonetheless, calculations associated with the zone model approach are relatively easy to perform and are often accepted for engineering purposes. Calculations following the zone model approach may be in the form of algebraic equations or a computer algorithm.

The zone model approach assumes that smoke from a fire is buoyant, rises to the ceiling, and forms a smoke layer. The buoyant nature of smoke is due to the decreased density of the heated smoke. As smoke rises in a plume, air is entrained to increase the mass flow rate in the plume. A decrease in the velocity and temperature of the smoke plume results from the increase in the plume mass flow rate, as dictated by

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conservation of momentum and energy. In addition, the entrained air dilutes the combustion products in the plume. The entire smoke layer is assumed to have uniform characteristics. As smoke is supplied to the smoke layer from the plume, the interface between the smoke layer and lower clear air zone descends. The additional smoke supplied by the plume also results in an increase in the smoke layer temperature, carbon monoxide concentration, and light obscuration.

Being a simplification, the zone model approach may not be applicable in some situations. One example includes a scenario with operating sprinklers, which may cool the layer and also entrain smoke from the upper layer into the water spray pattern descending into the lower zone. Another example consists of the case where smoke does not reach the ceiling as a result of a loss of buoyancy, where the pre-fire temperature near the ceiling of the atrium is greater than that near the floor. This situation is discussed in more detail later in this chapter. A third situation involves an atrium with a large cross-sectional area where the horizontal variation in conditions from one portion of the atrium to another is important to the analyst. Where localized conditions associated with the smoke plume or smoke layer need to be assessed, field models are more appropriate than zone models.

Two categories of fire scenarios for smoke management design in atria include (1) fires located in the atrium, and (2) fires located in a space adjacent and open to the atrium. This chapter concentrates only on fires within the atrium space. Methods to estimate conditions in any of the adjacent spaces, resulting from fires originating in the atrium or from fires in other adjacent spaces, are addressed elsewhere [2].

Smoke Filling Period

A smoke layer is formed once the smoke plume reaches the ceiling and the ceiling jet spreads horizontally to reach the bounding walls of the space. Subsequently, the smoke layer starts to descend in the space. In relatively small spaces with low ceilings, the smoke layer forms almost immediately. However, in large spaces with tall ceilings, the time required to form a smoke layer may be appreciable. The delay in forming a layer is attributable to the transport lag of the smoke. The smoke filling period continues until the properly sized smoke exhaust fans are actuated.

Transport Lag

The transport lag is composed of the time for a smoke plume to reach the ceiling (plume transport lag) and the time for the ceiling jet to reach the bounding enclosure (ceiling jet transport lag). These two time periods are depicted in Fig. 51.3.

Correlations for the plume and ceiling jet transport lag are available in the literature for both steady and t^2 fires [13, 14]. Because virtually all fires have a growth period before reaching a steady phase, the transport lag correlations for steady fires have little relevance.

Correlations for the plume transport lag for steady and t^2-fires are

Steady files:

$$t_{pl} = 0.67H^{4/3}/\dot{Q}^{1/3} \tag{51.9}$$

t^2 fires:

$$t_{\mathrm{pl}} = 0.1H^{4/5}t_g^{2/5} \tag{51.10}$$

Estimates of the plume transport lag from Equations 51.9 and 51.10 are provided in Fig. 51.4. As indicated in the figure, even the shortest plume transport lag for t^2 fires, associated with the fast t^2 fire, is greater than that for a modest-size steady fire.

Comparable correlations for the ceiling jet transport lag for steady and t^2 fires are

Steady files:

$$t_{\mathrm{c\,j}} = \frac{r^{11/6}}{1.2\dot{Q}^{1/3}H^{1/2}} \tag{51.11}$$

t^2 fires:

$$t_{\mathrm{c\,j}} = \frac{0.72rt_g^{2/5}}{H^{1/5}} \tag{51.12}$$

A comparison of the ceiling jet transport lag for a modest-size steady fire and t^2 fires is

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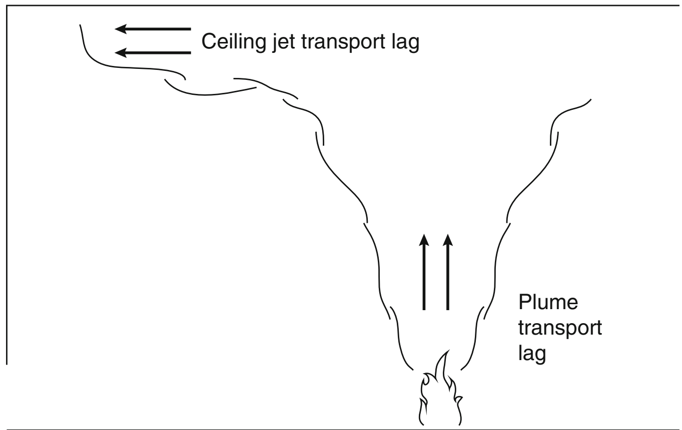

Fig. 51.3 Plume and ceiling jet transport lag

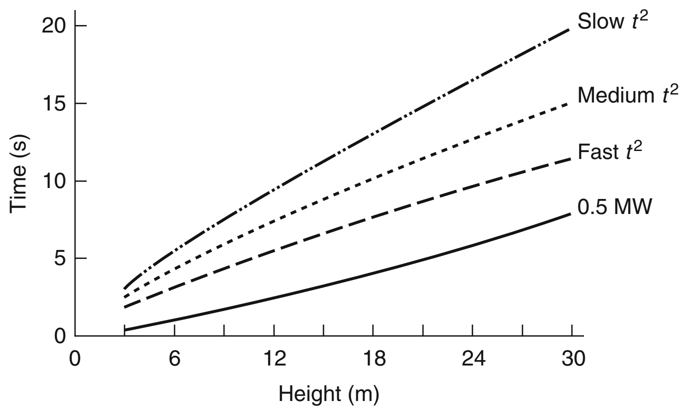

Fig. 51.4 Plume transport lag

presented in Fig. 51.5. Again, the transport lag associated with the steady fire is much less than that associated with any of the t^2 fires.

Many zone models do not account for transport lag. In low-height spaces with small compartments, this is likely to be inconsequential. In tall spaces with large cross-sectional horizontal areas, the lag may be important. In such cases, only models that incorporate transport lag are to be selected.

Smoke Layer Interface Position

Once the smoke layer has formed, the initial rate of descent of the layer is very rapid, slowing as the layer descends. This is attributable to the rate of smoke production being dependent on the height of the plume where entrainment occurs, i.e., the distance from the top of the fuel to the smoke layer.

Both empirical correlations and theoretically based methods are available to address conditions during the smoke filling period using a zone model approach [15]. Theoretically based methods use statements of conservation of mass and energy to determine the volume of the upper layer. Conservation of mass accounts for the smoke mass supplied from the plume to the smoke layer along with any smoke leaving the zone through ventilation openings. Conservation of energy is applied to address the energy being supplied by the plume along with heat losses from the layer.

Generally, the predicted smoke layer interface position determined by the two analytical

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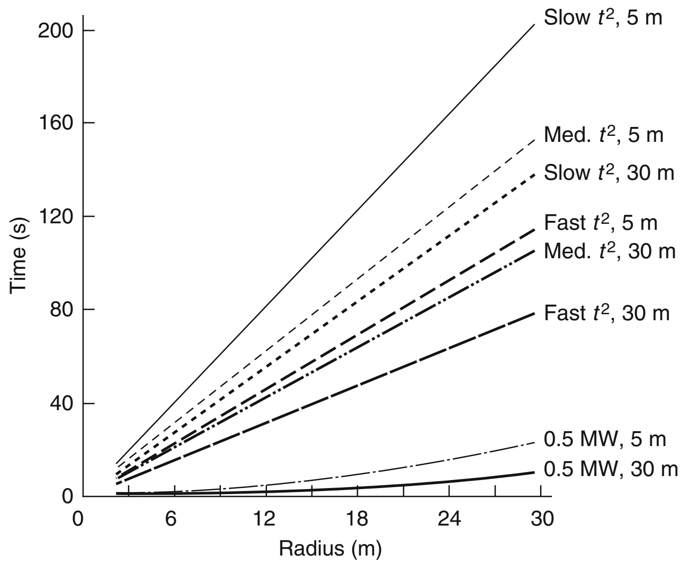

Fig. 51.5 Ceiling jet transport lag

methods differs. The smoke layer is comprised of the uppermost portion of the layer in which the conditions are relatively uniform at any elevation. Below that section is a transition zone, where the conditions decrease until they reach the bottom edge of the layer and are at their minimum value. The predictions from the empirical correlations relate to the position of the bottom edge of the transition zone as determined in an experimental program. In the theoretically based correlations, all of the smoke is considered to be in one layer with uniform properties. Combination of the transition zone and the upper portion into one uniform zone effectively results in the transition zone being compressed so as to have the same properties as the upper portion. As such, the theoretically based correlations relate to a thinner smoke layer than the empirical approach.

Empirical Correlations

Empirical correlations have been developed by Heskestad to determine the smoke layer interface position as a function of time for steady and t^2 fires. These correlations, included in NFPA 92 [1], are based on experimental data in large spaces. In the experimental efforts, the smoke layer interface position was established by a variety of means, including visual observations and measurements of temperature change, carbon dioxide concentration, or light obscuration.

The correlations are simple expressions with easily acquired input and minimal computations. The correlations provide conservative estimates of the smoke layer interface position (i.e., predicting the lower edge of the transition zone of the smoke layer which may include only 'wisps' of smoke) [16]. The correlations are applicable to simplified cases related to the fire and geometry of the space. Fire scenarios must be steady state or, if growing, follow a t^2 profile. The assumed geometrical configuration is a space of uniform cross-sectional area (i.e., rectangular or right cylindrical solids). In addition to the noted simplifications, second-order parameters such as environmental factors (e.g., stack effect, wind) and the effect of HVAC systems are neglected.

Steady Fires The position of the smoke layer interface for steady fires can be estimated using Equation 51.13 [16, 17]. Equation 51.13 is based on experimental data from fires in large-volume spaces with A/H^2 of 0.9–14 [18–20].

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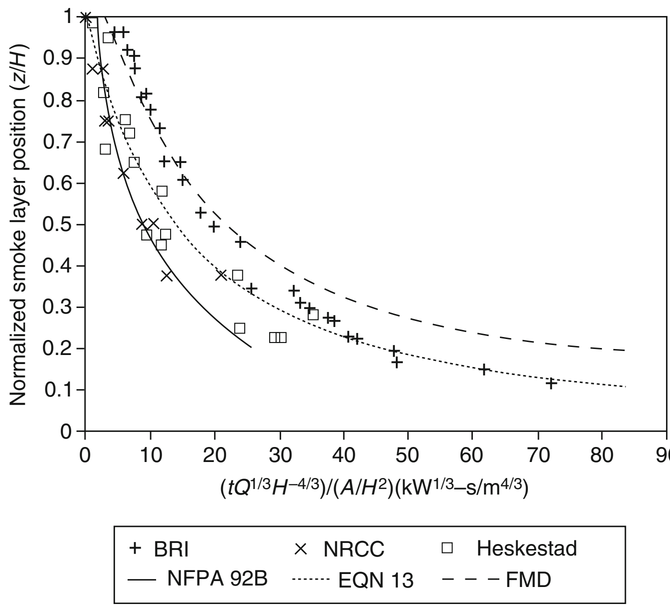
Fig. 51.6 Comparisons of smoke layer position—experimental data versus predictions



$$\frac{z}{H} = 1.11 - 0.28 \ln\left(\frac{t\dot{Q}^{1/3}H^{-4/3}}{A/H^2}\right) \quad (51.13)$$

Where $z/H \geq 0.2$.

Equation 51.13 is presented in non-dimensional form. The quantity $t\dot{Q}^{1/3}H^{-4/3}$ represents the normalized time from ignition. The significance of the normalized time parameter is to indicate that the same relative smoke layer position occurs for a long duration, low heat release rate fire in a tall ceiling height atrium, as for a short duration, large fire in an atrium with a short ceiling height. Different atrium geometries are accounted for by the non-dimensional shape factor, (A/H^2) [18, 19].

The limits noted for A/H^2 reflect the range of shape factors for the facilities in which the experiments were performed [18, 19]. Examples of atria within the noted range include atria with a cross-sectional area of 10,000 m^2 and a height of 105 m ($A/H^2 = 0.9$) or a height of 27 m ($A/H^2 = 14$). Comparisons of the predictions from Equation 51.13 to experimental data from fires in tall spaces are provided in Fig. 51.6 [20–22].

Transport lag, or the initial time period to form a smoke layer, is implicitly included in Equation 51.13. Evidence of this characteristic is obtained for short time durations where the resulting z/H is greater than 1.0 (otherwise $z/H > 1$ would literally mean that the smoke layer interface is *above* the ceiling). The lower limit for z/H of 0.2 relates to the lowest level where data were taken in any of the referenced experiments.

t^2 fires Equation 51.14 provides a correlation of the time-dependent smoke layer interface position for fires following a t^2-type profile [16]. Equation 51.14 is also based on experimental data in spaces with shape factors ranging from 0.9 to 14 [20, 23].

$$\frac{z}{H} = 0.91\left[t t_g^{-2/5} H^{-4/5} \left(A/H^2\right)^{-3/5}\right]^{-1.45} \quad (51.14)$$

Equations 51.13 and 51.14 both assume that the fire is located near the center of the atrium floor, remote from any walls. Smoke production is greatest for the centered configuration and thereby represents the worst-case condition.

Example 2 For a fast, t^2 fire in an atrium with a cross-sectional area of 800 m^2 and height of 20 m, determine the position of the smoke layer interface after 120 s.

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Solution Applying Equation 51.14 with $A/H^2 = 2.0$ and $t_g = 150$ s, z/H is 0.95 or $z = 19$ m.

Example 3 For a fast, t^2 fire in an atrium with a cross-sectional area of 800 m^2 and height of 20 m, determine the time for the smoke layer interface to reach 15 m above floor level.

Solution Re-expressing Equation 51.14 to solve for t,

$$t = 0.94 t_g^{2/5} H^{4/5} \left(A/H^2\right)^{3/5} (z/H)^{-0.69} \quad (51.15)$$

Applying Equation 51.15 with $A/H^2 = 2.0$ and $t_g = 150$ s, t is 140 s.

Reviewing the results from Examples 2 and 3, the smoke layer barely descends below the ceiling in the first 120 s. This is indicative of the lag time required for the plume to reach the ceiling and to form a layer. Then, after only another 20 s, the smoke layer descends 4 m, demonstrating the rapid initial descent rate of the smoke layer interface. The rapid descent is attributable to the significant quantity of smoke produced during the early stage of a fire in a tall ceiling space when the height available for entrainment is at its largest value. The predicted trend of rapid filling during the early stage of a fire has been reported by eyewitness accounts from four fires in atria [4, 24–26].

Theoretically Based Approach

Conservation of mass and energy can be applied to provide an estimate for the position of the theoretical smoke layer interface. Equation 51.16 expresses the conservation of mass, m_u, for the upper smoke layer, assuming no exhaust from the layer.

$$\frac{dm_u}{dt} = \dot{m} \quad (51.16)$$

Approximating the smoke as an ideal gas with properties of heated air, and assuming that the ambient pressure and specific heat are constant, the expression for conservation of energy for the smoke layer is

$$(\rho h)_u \frac{dV_u}{dt} = \dot{Q}_c + \dot{m} h_1 \quad (51.17)$$

Given the previously assumed conditions, ρh is a constant. Substituting the volumetric flow rate for the mass flow rate and simplifying,

$$\frac{dV_u}{dt} = \frac{\dot{Q}_c}{\rho h} + \dot{V} \quad (51.18)$$

The growth rate of the upper layer indicated in Equation 51.18 is dependent on two terms: (1) the volume supplied by the plume and (2) the expansion of the volume due to heating. For the case of an atrium with a constant cross-sectional area, A,

$$\frac{dV_u}{dt} = A \frac{dz_u}{dt} \quad (51.19)$$

As long as the smoke layer interface is well above the flaming region (see discussion later in this chapter), the plume mass entrainment rate can be estimated from [27].

$$\frac{dV_u}{dt} = \frac{\dot{m}}{\rho} = k_v \dot{Q}^{1/3} z^{5/3} \quad (51.20)$$

Several simplifications can be made for large clear heights (i.e., clear heights in excess of 10 m). The clear height is the distance from the top of the fuel to the bottom of the smoke layer. The magnitude of the second term is much less than the first. Generally, z is much greater than z_o. In addition, the volume increase of the upper layer supplied by the plume is appreciably greater than that due to expansion. With these simplifications and by substituting Equations 51.19 and 51.20 into Equation 51.18, an expression for dz_u/dt can be formulated

$$\frac{dz_u}{dt} = \frac{k_v \dot{Q} z^{5/3}}{A} \quad (51.21)$$

In Equation 51.21, k_v is the volumetric entrainment constant, defined as [36].

$$k_v = 0.076/\rho$$

The convective heat release fraction is the ratio of the convective heat release rate to the total heat release rate and is typically assumed

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to be on the order of 0.7–0.8. Throughout this chapter, a value of 0.7 is selected for the convective heat release fraction [1]. Assuming a plume entrainment constant of 0.076 kg $kW^{-1/3} \cdot m^{-5/3} \cdot s^{-1}$ and the density of ambient air as 1.2 kg/m^3, the volumetric entrainment constant is 0.064 $m^{4/3}\ kW^{-1/3}\ s^{-1}$.

An expression for the smoke layer position resulting from a steady fire as a function of time can be obtained by integrating Equation 51.9:

$$\frac{z}{H} = \left[1 + \frac{2k_v t \dot{Q}^{1/3}}{3(A/H^2)H^{4/3}}\right]^{-3/2} \qquad (51.22)$$

Alternatively, for a t^2 fire

$$\frac{z}{H} = \left[1 + \frac{4k_v t(t/t_g)^{2/3}}{(A/H^2)H^{4/3}}\right]^{-3/2} \qquad (51.23)$$

A comparison of the predictions from Equations 51.13 and 51.22 is provided in Fig. 51.6. One principal difference relates to the time delay for the smoke layer to form, i.e., transport lag. Transport lag is included implicitly in Equation 51.13. Equation 51.22 assumes that a smoke layer forms immediately. The transport lag can be accounted for separately [13].

Example 4 For a fast, t^2 fire in an atrium with a cross-sectional area of 800 m^2 and height of 20 m, determine the position of the smoke layer interface after 120 s.

Solution Applying Equation 51.23 with $A/H^2 = 2.0$ and $t_g = 150$ s, z/H is 0.72 or $z = 14.4$ m.

Vented Period

If a smoke control system has the capability to exhaust smoke, the descent of the smoke layer can be arrested if the volumetric rate of smoke exhaust from the smoke layer equals the volumetric rate of smoke supplied to the layer. Neglecting the effect of expansion, the layer descent is stopped when the mass exhaust rate is equal to the mass entrainment rate by the plume. Algebraic equations are available to estimate the properties of the smoke layer, including

1. Position of smoke layer interface
2. Temperature of smoke layer
3. Light obscuration in smoke layer and
4. Gas concentration in smoke layer

Equilibrium Smoke Layer Interface Position

The exhaust rate necessary to arrest the descent of the smoke layer can be estimated based on knowledge of the mass entrainment rate into the plume. The mass entrainment rate depends on the configuration of the plume. Plume configurations reviewed in this chapter are

1. Axisymmetric plume
2. Wall plume
3. Corner plume
4. Balcony spill plume

Axisymmetric Plume Axisymmetric plumes are formed from fires involving fuel packages remote from any walls (i.e., near the center of the atrium floor). Being remote from any walls, air is entrained around all of the plume perimeter along the entire clear height of the plume. The functional relationship of the mass entrainment rate to the heat release rate and clear height is [28].

$$\dot{m} = f\left(\dot{Q}_c^{1/3} z^{5/3}\right) \qquad (51.24)$$

One set of equations for the mass entrainment rate was originally derived by Heskestad [27]. One of the equations in the pair developed by Heskestad applies to estimating the entrainment in the flaming portion of the plume and another deals with the overall plume, including flaming portion and upper portion where flames are absent.

The limiting height is defined as the height of the continuous flaming region, (i.e., where flames are present 50 % of the time). The limiting height may be estimated as [27].

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$$z_f = 0.166\dot{Q}_c^{2/5} \tag{51.25}$$

For clear heights less than the limiting height, i.e., where flames extend into the smoke layer, the entrainment rate is estimated using Equation 51.26

$$\dot{m} = 0.032\dot{Q}_c^{3/5} z \tag{51.26}$$

For clear heights greater than the limiting height, i.e., where the flaming region ends prior to reaching the smoke layer, the entrainment rate is estimated using Equation 51.27:

$$\dot{m} = 0.071\dot{Q}_c^{1/3} z^{5/3} + 0.0018\dot{Q}_c \tag{51.27}$$

Equation 51.27 is a simplified version of the original expression developed by Heskestad (see Chap. 13, with z_o from the original expression set equal to zero. The validity of neglecting z_o in Equation 51.27 is based on the observation that z_o is typically small, compared to z [2]. The location of the virtual origin of an assumed point source can be estimated as [27].

$$z_o = 0.083\dot{Q}^{2/5} - 1.02d_o \tag{51.28}$$

For noncircular fuels, an equivalent diameter needs to be defined. The definition of an equivalent diameter is based on a circle that has an area equal to the floor area covered by the fuel. Considering a wide range of diameters and heat release rates associated with a variety of typical fuel packages, the virtual origin ranges from 0.5 to −5 m. Negative values are obtained when the second term is greater than the first (i.e., for fuel commodities with modest heat release rates spread over a large area).

Originally, Equations 51.26 and 51.27 were developed to describe plumes from horizontal, circular flammable liquid pool fires. However, these equations have been shown to be applicable to more complex fuels, as long as the limiting height is greater than the diameter of the fuel, and the fire only involves the surface of the material (i.e., is not deep-seated) [27].

The mass rate of smoke production estimated by Equations 51.26 and 51.27 is independent of the type of materials involved in the fire, other than indirectly in terms of the heat release rate. This is due to the mass rate of entrained air being much greater than the mass rate of combustion products generated, which is true as long as sufficient air is available for combustion. As a result of the fire being approximated as a point source in the entrainment equations, the shape or form of the fuel is not of primary importance. Thus, the parameters associated with a detailed description of the fuel package are relegated to a level of secondary importance.

In both Equations 51.26 and 51.27, the mass entrainment rate is dependent on the clear height, where the mass entrainment rate increases with increasing values of the clear height. During the early stages of the fire, the clear height has its maximum value thereby providing the maximum smoke production rate. This is especially true if the flame height is well below the smoke layer, where the smoke production rate is proportional to $z^{5/3}$.

In most engineering applications, the smoke production (or exhaust) rate is expressed in terms of a volumetric rate rather than a mass rate. In order to accommodate this preference, the relationship between the volumetric rate and mass rate is expressed as Equation 51.29.

$$\dot{V} = \frac{\dot{m}}{\rho} \tag{51.29}$$

Assuming smoke to have the same properties as air, the density of smoke may be evaluated as the density of air at the temperature of the smoke layer [3]. Graphs relating the volumetric smoke production rate to the clear height for selected total heat release rates ranging from 1000 to 10,000 kW are provided in Fig. 51.7.

Example 5 A fire has a total heat release rate of 5000 kW and is located at the center of the atrium floor. The smoke layer interface is 35 m above the floor. Determine the mass and volumetric rates of smoke being supplied by the plume to the smoke layer (i.e., at the location of the smoke layer interface).

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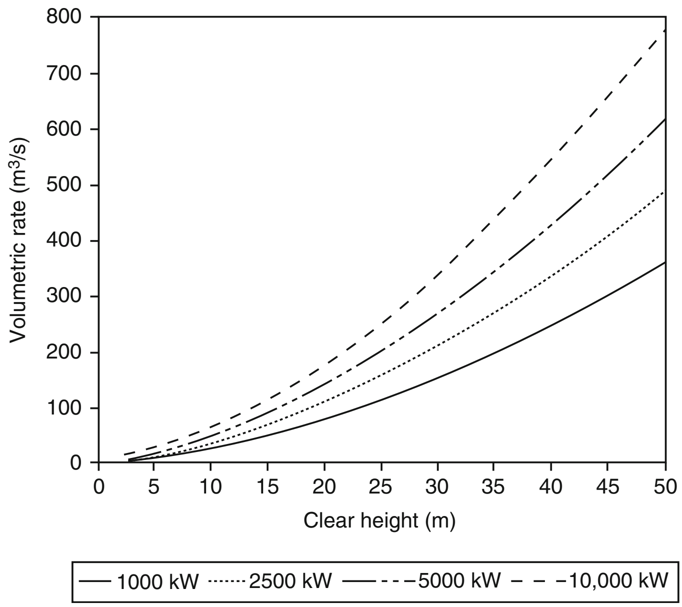

Fig. 51.7 Smoke production rate for axisymmetric plumes

Solution First, the limiting height is evaluated using Equation 51.25 to determine the applicable equation for the mass rate of entrainment, assuming the convective heat release fraction is 0.7, $z_f = 4.3$ m. Because $z > z_f$, Equation 51.27 is the applicable equation for determining the mass rate of smoke production. Neglecting z_o, the mass smoke production rate is 410 kg/s. The associated volumetric rate (from Equation 51.29, assuming 20 °C and 1 atm pressure) is 340 m^3/s.

Wall and Corner Plumes Fires located near walls and corners principally entrain air only along the surface of the plume away from the walls or corner. Consequently, the amount of smoke production is reduced for these locations, compared to the axisymmetric plume remotely located from the walls. Using the concept of reflection, the smoke production rate from wall and corner plumes can be estimated [29, 30].

A plume generated by a fire located against a wall only entrains air from approximately half of its perimeter, as indicated in Fig. 51.8. According to the concept of reflection, the smoke production rate is estimated as half of that from a fire that is twice as large (in terms of heat release rate) (note: having half of the entrainment does not cancel out the impact of considering twice the fire size as the entrainment is proportional to the one-third power of the heat release rate).

Similarly, a plume generated by a fire located near a corner of a room is referred to as a corner plume (see Fig. 51.8). Using the concept of a reflection, the smoke production rate from corner plumes, where the intersecting walls form a 90° angle, is estimated as one-quarter of that from a fire that is four times as large.

Example 6 A fire located on the floor of an atrium has a total heat release rate of 5000 kW. The smoke layer interface is 35 m above the floor. Compare the mass rates of smoke being supplied by the plume to the smoke layer, given an axisymmetric, wall, or corner plume configuration.

Solution In Example 5, $z_f = 4.3$ m and the smoke production rate for the axisymmetric plume using Equation 51.27 is 410 kg/s. Applying the same equation for the wall plume, the smoke production rate for a fire size of 10,000 kW is estimated as 520 kg/s. Dividing that rate by two provides the smoke production rate for the wall plume (260 kg/s). Similarly, for

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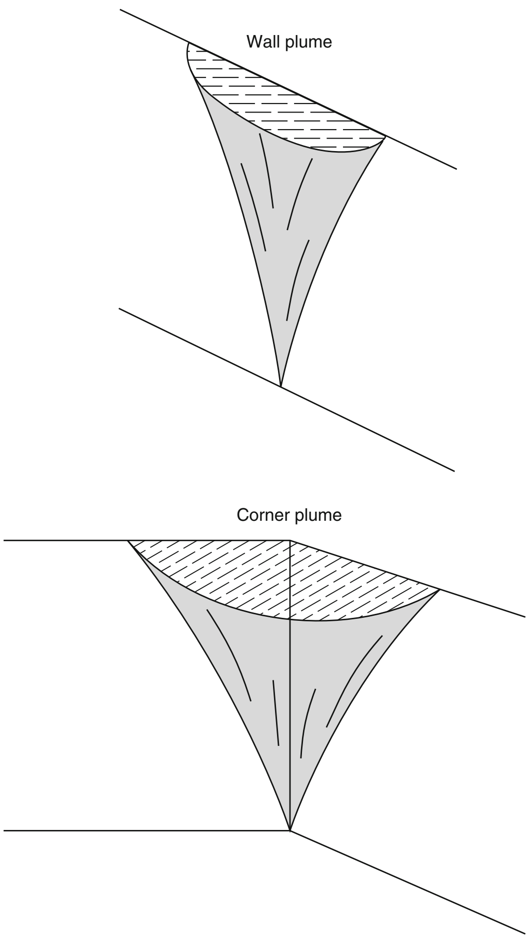

Fig. 51.8 Wall and corner plume diagrams

the case of the corner plume, the smoke production rate is 170 kg/s (considering one-quarter of the smoke production rate from a 20,000 kW fire).

Comparing the smoke production rates for the three plumes (axisymmetric, wall, and corner plumes), the smoke production rate is greatest for the axisymmetric plume (410 kg/s) compared to 260 and 170 kg/s for the wall and corner plumes, respectively. Thus, conservative hazard assessments should assume an axisymmetric plume is developed from a fire that is located away from the walls, near the center of the space.

Balcony Spill Plume A balcony spill plume is generated in cases where smoke reaches an intermediate obstruction, such as a balcony, travels horizontally under the obstruction, and then turns and rises vertically. Scenarios with balcony spill plumes involve smoke rising above a fire, reaching a ceiling, balcony, or other significant horizontal projection, then traveling horizontally toward the edge of the balcony. Characteristics of the resulting balcony spill plume depend on characteristics of the fire, width of the spill plume, and height of the ceiling above the fire. In addition, the path of horizontal travel from the plume centerline to the balcony edge is significant.

Several correlations on air entrainment into balcony spill plumes have been presented in the literature over several decades. A comprehensive review of the proposed correlations is provided by Harrison [31], Lougheed et al. [32] and Lim [33]. The correlations presented in NFPA 92 reflect the results obtained by Lougheed et al. from large-scale experiments and numerical simulations. One of the correlations in NFPA 92 has its roots back to Law's [34] interpretation of small-scale experimental data obtained by Morgan and Marshall [35]. This correlation is presented as:

$$\dot{m} = 0.36\left(\dot{Q}\dot{W}^2\right)^{1/3}(z_b + 0.25H) \qquad (51.30)$$

Lougheed et al. found that their large scale data was well described by this correlation for clear heights (z) in excess of 15 m. For lower heights, Lougheed et al. suggest the following correlation:

$$\dot{m} = 0.59\dot{Q}^{1/3}W^{1/5}(z_b + 0.17\dot{W}^{7/15}H + 10.35W^{7/15} - 15) \qquad (51.31)$$

The correlations presented in Equations 51.30 and 51.31, as well as others presented by numerous previous researchers, apply to balcony spill plumes of a specific configuration. The configuration considered is depicted in Fig. 51.9. As illustrated in the figure, the fire is located in a communicating space and the smoke flows under a soffit out from the room of fire origin, then under a short horizontal obstruction, i.e., balcony. The balcony is oriented perpendicular to the opening from the room. Any variations from

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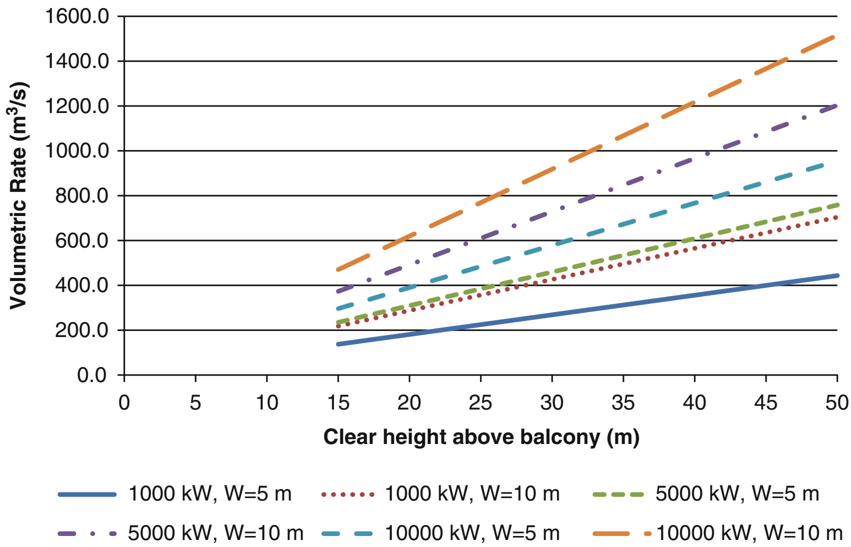

Fig. 51.9 Approximation of a balcony spill plume

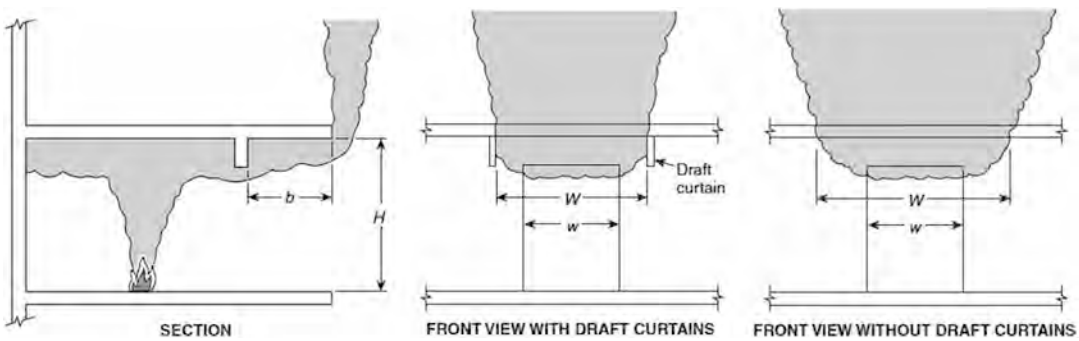

Fig. 51.10 Smoke production rate predictions for balcony spill plumes (H = 3 m)

this specific configuration have not been investigated and thus the balcony spill plume correlations presented as Equations 51.30 and 51.31 should not be applied for those situations. Instead, the application of CFD codes or small-scale models should be applied to assess those situations.

Predictions of the smoke production rate using Equation 51.30 for the balcony spill plume are included in Fig. 51.10. The calculations represented in the figure consider a 3-m height to the underside of the balcony.

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A comparison of the smoke production rate for axisymmetric and balcony spill plumes is provided in Fig. 51.11. The results from both Equations 51.30 and 51.31 are depicted in Fig. 51.11 and are the reason for the points of inflection at a clear height of 15 m. The heat release rate for both fires is a steady state 5000 kW, and *H* is 3 m for the balcony spill plume. For short heights, the smoke production

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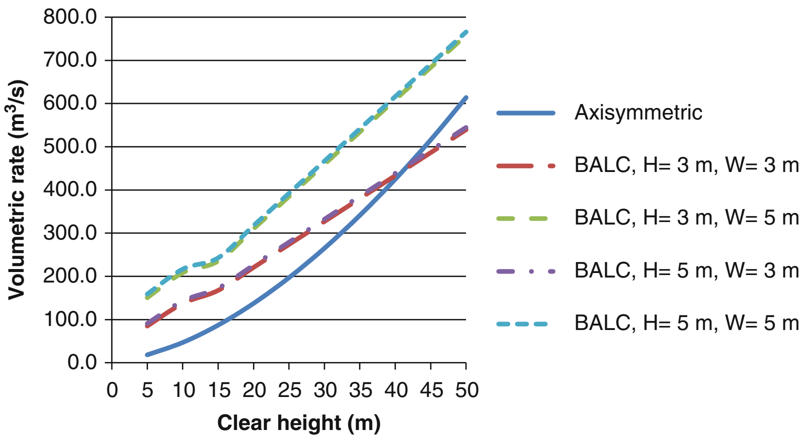

Fig. 51.11 Comparison of smoke production rate for axisymmetric and balcony spill plumes

rate for the balcony spill plume is appreciably greater than that for the axisymmetric plume. However, with increasing height, the smoke production rates from the two plumes become comparable. Eventually, the two curves intersect, suggesting that, at some height, the balcony spill plume behaves in the same manner (i.e., produces the same amount of smoke) as an axisymmetric plume. The point of intersection can be determined by setting the mass flow in Equation 51.27 equal to that in Equation 51.30.

The width of the plume, W, can be estimated by considering the presence of any physical vertical barriers attached to the balcony. The barriers act to restrict dispersion of the horizontal flow of smoke under the balcony. However, in the absence of any barriers, an equivalent width can be defined, based on results from visual observations of the width of the balcony spill plume at the balcony edge from the set of small-scale experiments by Morgan and Marshall [35]. The definition of an *equivalent confined plume width* is the width that entrains the same amount of air as an unconfined balcony spill plume. The equivalent width is evaluated using the following expression

$$L = w + b \tag{51.32}$$

Properties of Smoke Layer

Properties of the smoke layer are of interest both during the filling period of the fire and during the vented period. During the filling period, determination of the smoke layer properties is important to assess the level of hazard prior to actuation of a mechanical smoke control system. During the vented period, smoke layer properties are of interest to assess the level of hazard associated with those cases where occupants are exposed to smoke (i.e., the highest walking level is submerged in the smoke layer). The smoke layer properties of interest include temperature, light obscuration, and gas species concentration.

Temperature Rise in Smoke Layer The temperature of the smoke layer can be determined based on an energy balance for the volume of the smoke layer. Energy is supplied to the layer by the fire. Energy may be lost from the layer to the enclosure (walls, ceiling) of the space. During the filling period, the resulting expression is [1].

$$T = T_o \exp\left(\frac{(1-\chi_l)Q}{Q_o}\right) \tag{51.33}$$

Estimates for χ_l (heat loss fraction from the smoke to enclosure) vary appreciably. Some of the design guides suggest assuming that the smoke layer is adiabatic (i.e., setting $\chi_l = 0$), in order to be conservative [1]. Walton suggested values for χ_l between 0.6 and 0.9 for relatively small spaces of near cubic shape [36]. In many of the large spaces with tall ceiling heights, the temperature rise anticipated for the smoke layer is relatively modest such that convection and radiation heat transfer to an

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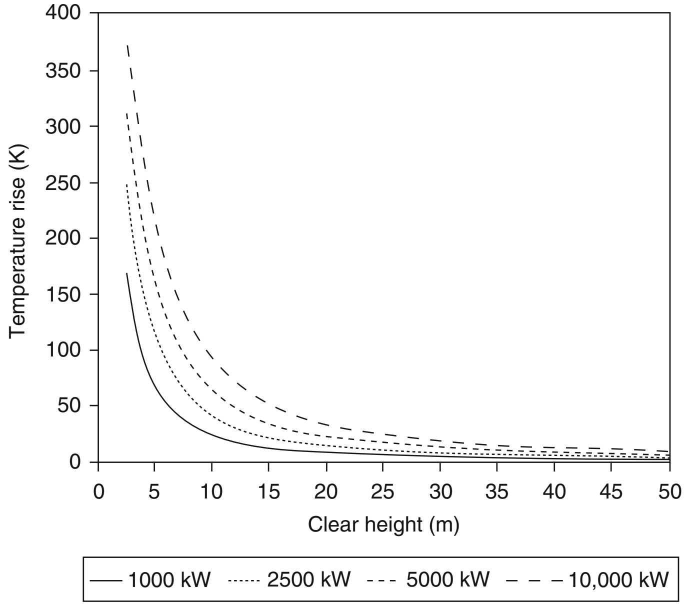

Fig. 51.12 Temperature rise of smoke layer for axisymmetric plumes

enclosure will also be modest. Consequently, in such applications, the adiabatic assumption will provide reasonable predictions of the temperature rise. However, in low ceiling spaces (under approximately 10 m) the temperature may be significantly overestimated by applying the adiabatic assumption.

Similarly, the equilibrium smoke layer temperature during venting can be approximated by applying an energy balance to the smoke layer. In this case, energy is also lost from the layer due to smoke being exhausted from the atrium. Equation 51.34 can be used to determine the temperature rise of the smoke layer under adiabatic conditions.

$$\Delta T = \frac{(1 - \chi_l)\dot{Q}_c}{c_p \dot{m}} \tag{51.34}$$

If the adiabatic assumption is applied, the smoke layer temperature will be overestimated, providing a conservative estimate of the hazard. In reality, some heat is lost from the upper smoke layer to the surrounding walls and ceiling. However, no elementary method is available to estimate the overall proportion of heat that is lost to the surroundings [37, 38]. Some zone and field computer fire models account for heat losses to the boundary, thereby avoiding the need to specify the heat loss fraction [19, 39]. The adiabatic smoke layer temperature for a range of fire sizes is presented in Fig. 51.12.

The degree of overestimation can be assessed by comparing the estimated smoke layer temperature with the plume centerline temperature. For thermodynamic reasons, the smoke layer temperature cannot exceed the plume centerline temperature. The plume centerline temperature, T_c, can be evaluated using Equation 51.35 [40]

$$T_c = 0.08 T_o \dot{Q}_c^{2/3} z^{-5/3} + T_o \tag{51.35}$$

The volumetric venting rate for other heat release rates or temperature rises may be determined using Equation 51.36 considering that the specific heat is virtually constant for the expected temperature range of interest

$$\frac{\dot{Q}_{c_1}}{\dot{Q}_{c_2}} = \frac{V_1}{V_2} \frac{\Delta T_{\mathrm{ad}_1}}{T_{\mathrm{ad}_2}} \frac{T_2}{T_1} \tag{51.36}$$

As can be observed from Equation 51.36, doubling the volumetric venting rate for the same size fire reduces the temperature rise by approximately 50 % (the temperature rise is not precisely halved, since the absolute temperature of the smoke layer in both instances is not exactly the same).

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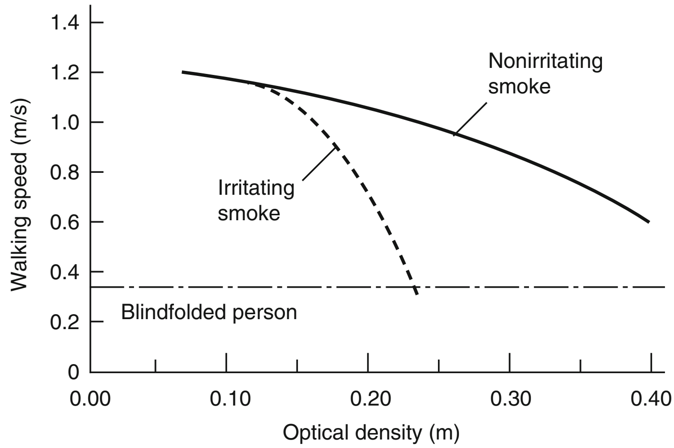

Fig. 51.13 Relationship between visibility through smoke and walking speed

Light Obscuration The visibility distance through smoke can be related to the optical density per unit pathlength via empirical correlations [41, 42]. The experimental basis for the correlations consists of tests with humans viewing objects through smoke. However, the participants were not directly exposed to the irritating effects of smoke. Consequently, the reported correlations are likely to overestimate the visibility distance.

In addition to the light obscuration quality of the smoke, the visibility of an object is dependent on the light source for the object being viewed as well as ambient lighting conditions [42, 43].

The optical density of the smoke layer can be determined considering that all of the particulates generated by the fire are transported to the layer via the plume and accumulate in the layer. Such an approach neglects any deposition of soot on enclosure surfaces, thereby overestimating the optical densities. The expressions for the smoke filling and vented periods are provided as Equations 51.37 and 51.38 [16].

$$\text{Smoke filling}: \quad D = \frac{D_m Q}{\chi_a H_c A(H - z)} \tag{51.37}$$

$$\text{Vented}: \quad D = \frac{D_m \dot{Q}}{\chi_c \Delta H_c \dot{m}/\rho} \tag{51.38}$$

The mass optical density is dependent on the fuel, burning mode, ventilation conditions, and operation of sprinklers. The mass optical density can vary by orders of magnitude for different ventilation conditions.

Although a reduction in visibility is not directly life-threatening, it does reduce the walking speed of individuals, thereby increasing the exposure time to toxic gases and elevated temperatures. In addition, the reduction in visibility may lead to an increased susceptibility to occupants tripping or falling. The relationship between visibility and movement speed is indicated in Fig. 51.13.

Carbon Monoxide Concentration The concentration of gas species contained in the smoke layer can be determined considering that all of the mass that is supplied to the layer via the plume accumulates in the layer. No absorption by the enclosure is assumed. The resulting expressions for the smoke filling and vented periods are [16].

$$\text{Smoke filling}: \quad \Upsilon_i = \frac{f_i Q}{\rho_o \chi_a H_c A(H - z)} \tag{51.39}$$

$$\text{Vented}: \quad \Upsilon_i = \frac{f_i Q}{\dot{m} \chi_a H_c} \tag{51.40}$$

In order to express the gas species concentration in units of ppm, Equation 51.41 needs to be applied

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$$ppm_i = \frac{MW_{\text{air}}}{MW_i}\gamma_i \times 10^6 \quad (51.41)$$

Input for evaluating the gas species concentration includes the yield fraction and heat of combustion, both of which are fuel dependent parameters. The yield fraction is dependent on the burning mode and oxygen concentration. Most of the information tabulated on the yield fraction, such as that by Khan (see Chap. 36), assumes well-ventilated, flaming combustion. Most of the fires of interest in large spaces will involve flaming combustion and are likely to be well ventilated. However, fires in small, connected spaces may become underventilated. Caution needs to be exercised in properly identifying ventilation conditions when predicting these parameters because the yield fraction can vary by orders of magnitude for different ventilation conditions. Also, the yield fractions noted by Tewarson are relevant only to cases where sprinklers are not operating [44].

Example 7 Estimate the steady-state smoke layer properties (temperature, visibility to an internally illuminated exit sign, and CO concentration) during the vented period, given the following situation:

1. The smoke layer interface is maintained 35 m above floor level.
2. The rate of heat release of the flaming fire is a steady state 5000 kW.
3. The fuel is comprised principally of polyurethane foam.

SOLUTION *Smoke Layer Temperature*
Equation 51.34 can be applied to determine the adiabatic smoke layer temperature rise. In Example 5, a mass rate of smoke production of 410 kg/s was determined. Thus, assuming an adiabatic smoke layer, a convective heat release rate fraction of 0.7 and specific heat of air of 1.0 kJ/kg·K, the temperature rise is 8.5 °C.

Visibility Visibility during the vented period is estimated using Equation 51.38. Fuel-related parameters are obtained in Chaps. 36, 24.

$$D_m = 260 \text{ m}^2/\text{kg}$$
$$H_c = 12,400 \text{ kJ/kg}$$

Considering smoke layer density, ρ, at the temperature of the smoke layer to be 1.17 kg/m^3, the optical density is 0.32 m^{-1} and the associated visibility is 8.5 m.
CO Concentration CO concentration for the vented period is estimated using Equations 51.40 and 51.41, with the fuel-related properties again evaluated from, Appendix C.

f_{CO} for polyurethane is~$0.030 \text{kg}_{\text{co}}/\text{kg}_{\text{fuel}}$

The resulting CO concentration in the smoke layer is 31 ppm.

Comparison of Mechanical Exhaust and Natural Venting Designs

Design Aspects of Mechanical Venting Systems

Most smoke control systems for covered malls and atria in the United States use mechanical venting systems. Mechanical venting systems need to be designed to exhaust the amount of smoke needed to satisfy design objectives. The volumetric flow of smoke needs to be adjusted for temperature, using the methods discussed previously in this chapter.

Mechanical exhaust systems are relatively immune to environmental effects because the energy associated with the fan is able to provide a sufficient force for smoke movement and, thus, is not relying as much on the buoyancy of the smoke or stack effect. Protection from wind effects can be accommodated by hardware.

Response time is a principal limitation for mechanical exhaust systems. The response time is the sum of the time for detection and the time for the system to reach capacity (which may be up to a minute). This combined time may be longer than the time for the smoke layer to reach the critical height established by design goals. Also, because the capacity of a mechanical venting system is sized considering a particular

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size of design fire (see Equations 51.26, 51.27, 51.30 and 51.31), if an actual fire has a greater heat release rate than considered in the design, the capacity of the mechanical exhaust will not be sufficient.

In addition, mechanical exhaust systems are susceptible to plugholing, a situation in which a hole is created in the smoke layer below the exhaust inlet by a high-capacity exhaust system. This results in a reduction in efficiency of the exhaust system because air from beneath the smoke layer is being extracted, thereby the desired quantity of smoke is not being extracted, causing the smoke layer to deepen. Plugholing is addressed later in this chapter.

The limitations of mechanical venting systems can be overcome in some cases by providing detection devices that minimize the time required for detection and by using several small capacity exhaust fans to avoid plugholing. However, despite these measures, it is still possible that design goals will not be able to be achieved by mechanical venting designs. Thus, the feasibility of such goals may need to be evaluated. Alternative smoke management approaches may be sought, for example, providing physical barriers at upper levels to reduce the required clear height or considering opposed airflow at openings above the design smoke layer interface position.

Design Aspects of Natural Venting Systems

Natural venting removes smoke by taking advantage of the buoyancy of the smoke. In the United States, natural venting systems are primarily found only in facilities such as industrial or warehouse structures. Outside of the United States, natural venting is often utilized in many applications.

The key advantages of natural venting systems are the self-correcting aspect of the vents in case the design fire is inappropriately defined and the simplicity of the operation of natural vents. These advantages will be described as part of the continuing discussion in this section.

The engineering principles that apply to vent operation addressed in this section consider the scenarios depicted in Fig. 51.14. Because smoke filling along the underside of the ceiling in a curtained area is similar to that in a compartment, additional information on compartment fire scenarios is presented in Chap. 33. If the draft curtains are deep enough, they can be thought of as simulating the walls of a single compartment.

The description of engineering principles of natural vents will be provided from the perspective of a two-layer zone model. The overall building compartment is assumed to have near-floor inlet vents that are large enough to maintain the area below the smoke layer at outside-ambient conditions. The upper smoke-layer thickness will change with time, but at any instant it is assumed to be uniform in space, with absolute temperature, T, and density, ρ.

Mass and energy are transferred continuously to and from the upper and lower layers. Conservation of energy and mass along with the Ideal Gas Law is applied to the layers, which leads to equations that require estimates of components of heat transfer, enthalpy flow, and mass flow to the layers. Qualitative and some key quantitative features of these phenomena are described and presented below. The reader is referred to Chap. 15, for a general discussion on the topic of flow through vents. Considering a vent in a wall or ceiling, flow is driven through such a vent mainly by cross-vent hydrostatic pressure differences from the high- to the low-pressure side of the vent. The traditional means of calculating vent-flow rates is by using an orifice-type flow calculation.

Assuming relatively quiescent conditions in the areas on both sides of the vent, the pressure in each space can be described as the hydrostatic pressure. The mass flow through a vent is derived from Bernoulli's equation, where the buoyancy pressure is related to the dynamic pressure at the vent:

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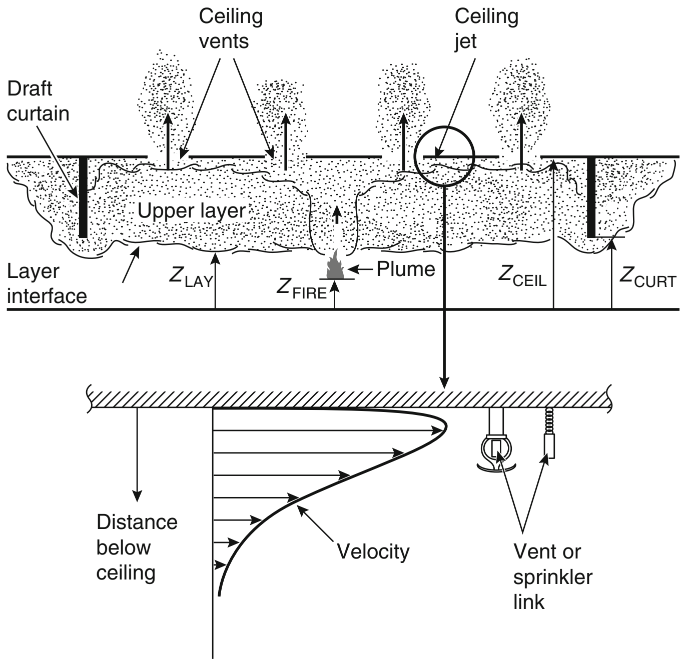

Fig. 51.14 Fire in a building space with draft curtains and ceiling vents

$$\frac{1}{2}\rho_o u^2 = \Delta\rho g d \tag{51.42}$$

where

ρ = Density of smoke (kg/m^3)

ρ_o = Density of ambient air (kg/m^3)

$\Delta\rho = \rho_o - \rho$ (kg/m^3)

Relating the mass flow through the vent to the velocity of the gases

$$\dot{m} = \rho A_v u \tag{51.43}$$

where

$\dot{m}$ = Mass flow rate through vent (kg/s)

A_v = Flow area of vent (m^2)

Replacing the densities with temperatures using the ideal gas law:

$$\dot{m} = \left(2\rho_o^2 g\right)^{1/2}\left(\frac{T_o \Delta T}{T}\right)^{1/2} A_v d^{1/2} \tag{51.44}$$

As indicated in Equations 51.42–51.44, the capacity of natural vents is related to the pressure difference caused by the buoyancy of the smoke layer. As such, the flow rate of smoke through the vent increases with increasing smoke-layer temperature and depth.

$$\dot{m} = \left(2\rho_o^2 g\right)^{1/2}\left(\frac{T_o \Delta T}{T^2}\right)^{1/2} \frac{A_v d^{1/2}}{\sqrt{1 + \frac{C_{d,v}^2 A_v^2 T_o}{C_{d,i}^2 A_i^2 T_o}}} \tag{51.45}$$

For vents installed in sloping roofs, the design position of the smoke layer should be at least below the bottom of the vent. To ensure that only smoke is exhausted from that vent and not any air from below the layer, the smoke layer position should be at least 10 % of the vertical distance from the top of the vent (Fig. 51.15). Then the distances d and z (recall that clear height is imbedded in the consideration of $\dot{m}$) are measured from the center of the vent.

Makeup Air Supply The effect of the inlet area on the flow rate through the vent can be assessed by recognizing that the pressure drop across the inlets associated with the inflow of replacement air must be subtracted from the buoyancy pressure causing the gases to flow through the vents. The effect of inlet pressure may be included in Equation 51.45 by replacing A_v by an effective vent area $\left(A_v^*\right)$ where

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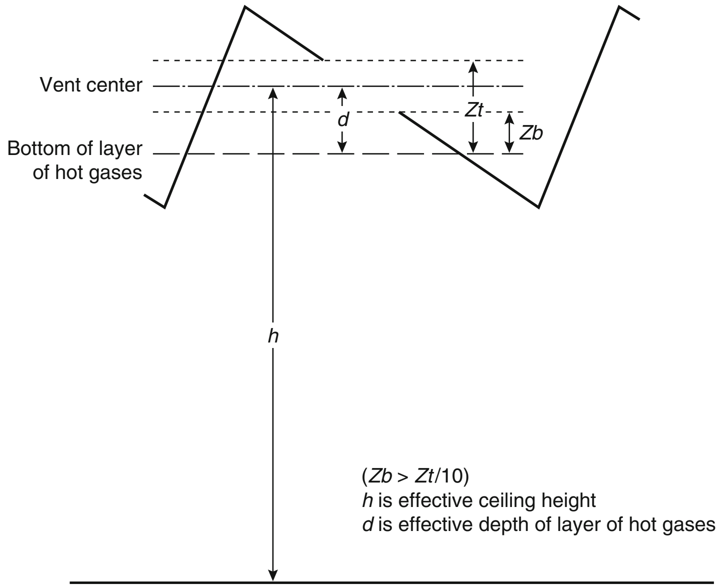

Fig. 51.15 Design position of gas layer versus vent

$$\frac{1}{A_v^{*2}} = \frac{1}{A_v^2} + \frac{1}{A_i^2}\left(\frac{T_o}{T}\right) \tag{51.46}$$

As such, the ratio of the actual vent area to the effective vent area, K, is given as

$$K = \frac{A_v}{A_v^*} = \left[1 + \left(\frac{A_v}{A_i}\right)^2 \frac{T}{T_o}\right]^{1/2} \tag{51.47}$$

The effect of vent ratio (ratio of outlet to inlet areas) on the effectiveness of natural venting is presented in Fig. 51.16 with a design fire of 2.5 MW and a ceiling height of 15 m. As indicated in the figure, with a vent ratio of 0 (having infinite inlet area), the clear height is slightly greater than when the outlet to inlet areas are equal. Thus, as with mechanical systems, the inlet area is an important consideration.

One of the principal advantages of natural venting systems is the relative insensitivity of the equilibrium smoke-layer position with the fire size, as indicated in Fig. 51.15. The graphs in Fig. 51.17 indicate that for two different ceiling heights (15 and 30 m), the equilibrium smoke-layer temperature is virtually identical for the two significantly different fire sizes. This similarity is due to the bigger fire size producing a smoke layer with a greater temperature. The hotter smoke will be more buoyant, thereby increasing the buoyancy force at the vent leading to an increase in the mass flow rate through the vent to reduce the amount of smoke accumulating under the ceiling.

The ability of a vent to perform similarly for two different fire sizes is a significant benefit of natural vents. Unlike mechanical exhaust, for natural vents if an error is made such that an actual fire is greater than the defined "design fire," the natural vents should still able to provide near-satisfactory performance.

Limitations The limitations of natural venting systems are related to the forces affecting smoke movement: principally a lack of buoyancy and wind effects. The smoke must be buoyant relative to the ambient environment in order for natural venting systems to be effective. Smoke may lose its buoyancy either due to cooling from sprinkler operation or dilution from entrained, cool air. Because the mass flow is strongly dependent on the difference in the smoke-layer temperature and outdoor temperature, if the smoke-layer temperature rise is only slightly different than the ambient temperature, then the flow from a vent will also be modest. As such, in tall spaces with relatively small fire sizes, the

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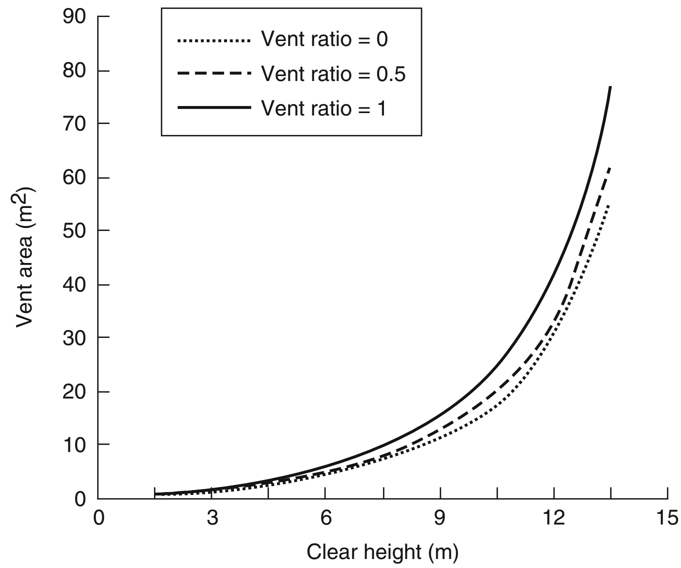

Fig. 51.16 Effect of vent ratio on natural venting

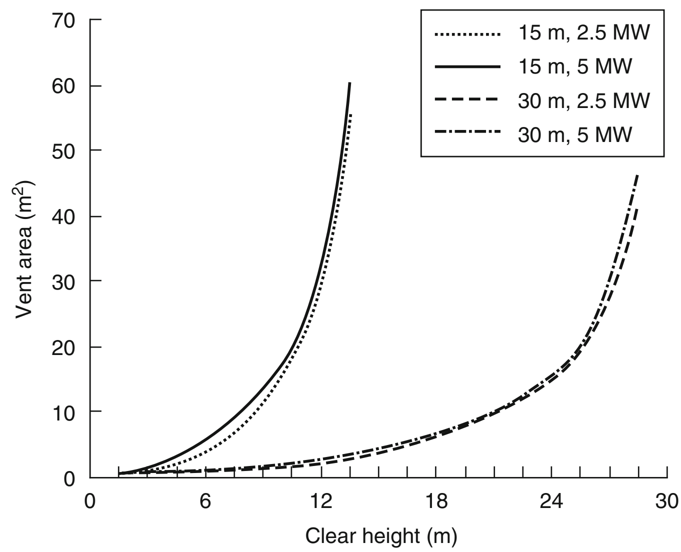

Fig. 51.17 Effect of vent ratio on natural venting for two ceiling heights (15, 30 m) and fire sizes (2.5 MW, 5 MW)

modest capacity of natural vents may constrain the ability to achieve design objectives, necessitating that mechanical ventilation be used.

To consider the effect of outside wind conditions, pressures on the outside of the building in the vicinity of the vent need to be assessed. The pressure on the building depends on the wind speed at the elevation of the vent, wind direction relative to the outside building geometry, and proximity and geometry of neighboring buildings. Wind effects on buildings are addressed in Klote et al. [2].

If the building vents are open and if vent areas are relatively small compared to the building surface area, then pressures near the vent openings will be substantially unchanged from the above-mentioned, closed-vent pressure distribution, except near any local through-vent flows that may develop. Also, although the

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exterior pressures generally vary from vent to vent, they will be relatively uniform for any particular vent. Under these conditions, a determination of flow rates into and/or out of vents and through the interior of the building is based on an interior building flow analysis, with pressure-specified boundary conditions at the open vents.

A Single, Open Inlet Vent or Multiple Openings at the Same Pressure If there is only one open inlet vent on the upwind side of the building that experiences a relatively high pressure differential above the local hydrostatic pressure or if there are several open vents, all at locations on the outside surface of the building where pressures are substantially identical, then, the wind will have no effect on the inflow or outflow through the vents. Thus, if the air inside the building is uniformly at the outside air temperature and if there is no mechanical ventilation, then the effect of the wind will be simply to bring the interior hydrostatic pressure at the location of the vent(s) to the aerodynamic-flow-specified value; the interior of the building will be "pressurized" as a result of the open vent(s), but there will be no wind-induced interior flows. If there is a fire in the room with the open vent (e.g., the vent is a broken window), then, in the usual way, there will be fresh air inflow into the room toward the bottom of the vent and buoyant smoke outflow toward the top of the vent, all this taking place at an aerodynamic-flow-specified, elevated hydrostatic pressure within the room.

If the open vent is in a side of the building with a negative wind coefficient (e.g., facing downwind or on roofs near the upwind side), the pressure at the vent will be relatively low, and the local hydrostatic pressure will be *reduced* by an amount only on the order of $\rho_o u^2/2$. Again, no wind-induced flow at the vent is expected.

Two Inlet Vents, One on the Upwind Side and One on the Downwind Side of the Building If there are two inlet vents in the walls of the building, one upwind and one downwind (ignoring heating and mechanical ventilation), then there *will* be wind-induced flow through the vents and within the building. Inlet air will be provided at the high-pressure upwind vent and outlet air at the low-pressure downwind vent, with levels of through-vent flows and of interior hydrostatic pressures determined by an appropriate analysis that accounts for conservation of momentum (i.e., Bernoulli's equation) and mass at the exterior vents and at room-to-room vents within the interior of the building. The changes in hydrostatic pressures within the rooms of the building, over and above the hydrostatic pressures that would be present in a quiescent environment, would be somewhere between the wind-induced pressures at the locations of the high-pressure vent and the low-pressure vent.

Wind-Modified Pressures at Roof Surfaces and Wind-Modified Action of Ceiling Vents Roof surfaces of flat-roofed buildings tend to have negative, wind-induced pressure coefficients, unless the buildings are very long in a direction parallel with the wind direction. Sloping roofs may have pressure coefficients that can be positive or negative, depending on wind direction. Therefore, if the interior, wind-induced hydrostatic pressures are greater than those associated with a quiescent environment (e.g., the result of open vents in the upwind side of the building), then the flow of smoke through ceiling vents can be enhanced significantly by virtue of increased, favorable, cross-vent pressures. However, for reduced interior pressures (e.g., as a result of open vents on the downwind side of the building), the effect of wind conditions can substantially disrupt the desired smoke-removing action of ceiling vents, even reducing the *direction* of the cross-vent pressures and, as a result, the direction of the flow through the vents (i.e., making the flow travel from the outside to the inside).

Thermal Activation of Vents

Convective heating and thermal response of near-ceiling-deployed fusible links or other near-ceiling thermal sensor devices (including thermoplastic vent covers designed to soften

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and "drop out" at specified actuation design temperatures) are determined from the local time-dependent distributions of ceiling jet velocity and temperature. These distributions will depend on vertical distance below the ceiling and radial distance from the fire-plume axis. Once the operating temperature of the thermal element is reached, the device or devices operated by the element will be actuated. Characteristics of ceiling jets are described in Chap. 14.

The mathematical fire model LAVENT (fusible-*L*ink-*A*ctuated *VENT*s) [22–24] was developed and is available to simulate most of the phenomena described above. The LAVENT model can be used to simulate on a time-dependent basis and to study parametrically a wide range of scenarios with natural vents. Full documentation for LAVENT, including its theoretical basis [22], a user guide for the computer code [23], and sample problems using the code are included in Annexes B, C, and D of NFPA 204 [45]. In its current form, LAVENT does not account for wind effects, the reduced effectiveness of vents as a result of limited-area inlet vents, or the presence of mechanical systems [22]. Input data on the thermal response characteristics of the link will be needed for such an analysis. The use of LAVENT has not been validated for estimating the response of "drop out" vents.

Sprinklers and Vents

Vents and sprinklers provide different fire safety benefits. The level of fire safety in a facility would be enhanced if both sets of benefits could be achieved systematically. However, simply providing the two technologies following design rules independent of each other will not necessarily lead to a combination of their respective benefits. Potential problems may occur as a result of the interaction of the two technologies (i.e., operation of the smoke and heat vents can modify sprinkler performance and the operation of the sprinklers can modify smoke and heat vent performance). As an example of the latter, consider the case in which water spray from a sprinkler system cools the smoke, thereby reducing the buoyancy of the smoke. The reduced buoyancy reduces the mass flow rate through a vent, thereby resulting in a deeper smoke layer. However, the sprinkler discharge can also dramatically reduce the fire size resulting in a decreased production of smoke.

Numerous research projects have been conducted to address the interaction between vents and sprinklers (see Annex A of NFPA 204 and Beyler and Cooper [46] for a thorough review of the previous research). The previous projects have sought to demonstrate the level of impact that one system has on the other's performance, either by indicating that it is always significant, always insignificant, or significant only if a particular set of conditions is provided. Projects have also attempted to identify design changes necessary if both systems are present (i.e., perhaps larger vent sizes could be installed in sprinklered buildings to counteract the reduced mass flow of cooled smoke). To date, none of the previous projects have been able to provide the conclusive results that provide definitive information illustrating the degree of influence that one system has on the other for all situations.

Past Studies of Combined Vent/Sprinkler Systems A review of 34 papers evaluated the validity of generic claims and counterclaims on the benefits of combined vent/sprinkler systems [46]. A listing of these claims and counterclaims and a summary of conclusions on their validity follow.

Claims and Counterclaims [46] In the literature, claims that have been made in favor of vent/sprinkler systems can be reduced to the following three:

1. Smoke and heat vents limit the distribution of products of combustion in the facility whether deployed sprinklers are operative or inoperative.
2. Smoke and heat vents decrease the number of activated sprinklers.

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3. Smoke and heat vents assist the fire department in identifying the location of the fire within the facility and in reducing the need for manual roof venting.

In the literature, claims that have been made *against* vent/sprinkler systems can be reduced to the following four:

1. Smoke and heat vents cause enhanced burning rates.
2. Smoke and heat vents delay sprinkler activation.
3. Smoke and heat vents increase the number of activated sprinklers.
4. Smoke and heat vent flow rates are insufficient to realize any benefit.

Validity of Claims for and Against Combined Vent/Sprinkler Systems After evaluating reports of studies of combined vent/sprinkler systems, Beyler and Cooper [46] came to the following conclusions:

- Venting does not have a negative effect on sprinkler performance.
- If a fire is directly beneath a vent, activation of the first sprinklers may be delayed slightly, but there is no evidence that this delay will have a significant impact on overall sprinkler performance.
- Venting does limit the spread of smoke by removing smoke from the building near the source of the fire (within the curtained compartment of fire origin), improving visibility for building occupants while evacuating and for fire fighters during fire control operations.
- By limiting the spread of smoke and heat, venting reduces smoke and heat damage to the building.
- In the event that sprinklers do not operate, venting remains a valuable aid in controlling the fire manually.
- In many fires, current vent design practices, for example, those of NFPA 204 [45], are likely to limit the number of vents operated to one and, in successful sprinkler operations, vents may not operate at all.
- Design practices should use methods that ensure early operation of vents; vent operation should be ganged so that the benefit of roof vents is fully realized.
- When deployed with vents and draft curtains, a sprinkler design needs to take full account of draft curtains as obstructions to ceiling jet flows and sprinkler discharge.
- Draft curtains should be placed in aisles rather than over storage.

Considerations for the Design of Combined Vent/Sprinkler Systems Taking Beyler and Cooper's conclusions into account and drawing on current knowledge of basic physical phenomena involved in vent/sprinkler interactions, the design of combined sprinkler/vent systems should seek to satisfy the following general criteria:

1. A successful vent design, whether deployed with or without sprinklers, is one that leads to the benefits of improved visibility and safety during a fire by limiting the descent of the upper smoke layer to a specified height (i.e., eye level of occupants and fire fighters).
2. When draft-curtain compartmentation is included in the vent design, a significant additional possible benefit results from the smoke being contained within the curtained compartment of fire origin by action of the venting.

Interaction of Sprinkler Spray and Smoke Layer The action of sprinkler sprays on a smoke layer includes a combination of evaporative cooling and dilution of the smoke. Dilution occurs due to entrainment of the relatively cool and uncontaminated lower-layer gases and the upper layer by the spray [47–59]. Provided the sprinkler spray–reduced smoke temperature and associated loss of buoyancy are not too great, the effect of evaporative cooling of the smoke, even if accompanied by moderate sprinkler spray–driven mixing, could be offset by additional vent capacity. However, even without significant evaporative cooling, sprinkler spray–driven mixing action can be so significant that it leads to a precipitous increase in the volume of smoke and thus a deeper smoke-layer. If and when the latter vigorous mixing occurs, then even impractically large increases in vent capacity are unlikely to lead to any significant

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improvement. The latter phenomenon is commonly referred to as *smoke logging*. As such, a vent design that is developed to meet the above general criteria must be based on an analysis that accounts for and avoids the phenomena of smoke logging.

There is experimental evidence that smoke logging can be controlled by venting [60], and a preliminary analysis to explain the phenomenon has been provided [47, 48]. Thus, it has been reported that "preliminary tests in [a] . . . large-scale mall . . . showed that, under some conditions, [a] . . . smoke layer could be brought down by a manually operated sprinkler spray, [and that] smoke logging then occurred rapidly, with a high smoke density at low level. However, under some conditions, the smoke layer was not disturbed by a sprinkler spray" [48].

Computer Simulations of Sprinkler Spray–Driven Cooling, Mixing, and Smoke Logging A computer model could be applied to address the issue of sprinkler spray–driven cooling, mixing, and smoke logging. However, the past experimental studies have not led to an understanding of the complex phenomena of sprinkler spray cooling and sprinkler spray–driven smoke transport and mixing that causes the temperature reduction that could be used as a basis for such a model. What is known through anecdotal accounts of visual observations is that spray-driven mixing and transport of an initially stable and growing upper smoke layer can and often does lead to onset of smoke logging, whereby the mixing actions of sprinkler sprays are so vigorous as to effectively and continuously mix any newly generated smoke from the fire plume with the smoke already present in the smoke layer to fill the entire space.

Analytic fire-modeling has been employed to assess a generic interaction of a downward-directed sprinkler spray and a two-layer fire environment can be used to resolve the above issues [59]. The model simulated the action of the sprinkler spray, including the effects of evaporative cooling and the spray-driven mixing of the elevated-temperature, upper smoke layer and the relatively cool and uncontaminated lower layer. The analysis led to the identification of six possible modes of sprinkler/layer interaction [58, 59]. The mode that prevailed at any time during the development of a particular fire was found to depend mainly on the thickness and temperature of the upper smoke layer and on the momentum, spread angle, and characteristic droplet size of the sprinkler spray. In any particular fire scenario, the action of open vents and/or draft-curtain compartmentation could provide some control of the thickness and temperature of the layer and, therefore, of sprinkler/layer interactions that prevail.

Of the six above-referenced modes of sprinkler/vent interaction, four were found to be particularly favorable in the sense that they would *maximize* the success of a combined sprinkler/vent design. Thus, with proper vent design the favorable modes could lead to the desired control of the smoke-layer depth while minimizing smoke mixing to the lower layer to the point that any smoke there is only in a highly dilute state. Thus, for a given set of sprinkler spray characteristics, if the smoke layer is kept relatively thin and/or not too buoyant (i.e., its temperature is not too high), then the rates of both mass and enthalpy flow entrained into the upper-layer part of the sprinkler's "spray cone of influence" would be relatively insignificant compared to the corresponding rates associated with the fire-plume flow to the upper layer. In the early part of a typical fire scenario and immediately subsequent to one or more rapid-response sprinkler discharges, the condition of a relatively thin and not-too-high-temperature upper smoke layer should be prevalent. As a result, the combined action of cooling and momentum exchange in the spray cone would be strong enough to transport the entrained smoke through the layer interface and well into the depth of the lower layer to be mixed eventually, with negligible consequences, into the rest of the lower-layer gases.

In contrast to the above, there were two particularly *unfavorable* modes of sprinkler/vent interaction that would *minimize* the likely success of a combined sprinkler/vent design. These configurations could lead to relatively vigorous

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mixing between the smoke layer and the lower layer, leading to a rapid growth of the upper smoke layer and possibly to smoke logging.

Resolving the Problem of Sprinkler Skipping and Vent Skipping In terms of achieving vent/sprinkler design objectives, it is important to identify a possible means of resolving problems associated with the phenomena known as *sprinkler skipping* and *vent skipping*.

If ceiling jet–convected water droplets strike a sprinkler link or bulb, then, because of effects of evaporative cooling, there will be a significant reduction of its rate of heating, which can lead to a significant delay in sprinkler discharge. It is the resulting, unpredictable, and deleterious delay in sprinkler discharge that is referred to as *sprinkler skipping*.

Although research has been conducted to characterize the spray from sprinklers, a general description of all aspects of the spray is beyond the current state of knowledge. Such a description would be needed to provide a reliable model that can be used to predict the phenomenon.

Accounting for Sprinkler Skipping and Vent Skipping in Design In the design of sprinklers without vents, the effects of sprinkler skipping on the ability of a sprinkler system to control a fire are taken into account by the empirically based design standard, NFPA 204. In contrast, when vents and sprinklers are used *together*, the random and unpredictable effects of vent skipping are not accounted for in the design of automatic vent systems as outlined in NFPA 204.

In terms of combined vent/draft-curtain designs, and as an alternative to traditional automatic, fusible-link-actuated vents, which could involve the problem of vent skipping, a more controllable and reliable means of ensuring timely and effective vent action is available. One generic possibility would involve *ganging*, that is, opening together all or most vent units in the compartment of fire origin [61]. A ganging strategy that could be well integrated into a reliable, consensus sprinkler/vent design is one in which all vents of the fire compartment are ganged to open together immediately following first sprinkler discharge.

A Consensus Approach to the Design of Combined Sprinkler/Vent Systems

Using Mathematical Fire Models to Achieve Design Objectives The above discussion indicates that effective sprinkler/vent systems are feasible and that mathematical fire models with a proven capability for simulating sprinkler/smoke interactions can be used as the basis for a consensus approach to identify and establish effective sprinkler/vent system designs.
The capabilities of mathematical models to simulate sprinkler/smoke interactions have been reviewed [62, 63]. The models considered were those that are complete (i.e., they can simulate both isolated sprinkler/smoke interactions and full fire scenarios, where the latter would be used to establish the success of sprinkler/vent designs). Both zone-type and field model–type simulation approaches were found to be applicable for addressing the problem. In the usual way, the two approaches are complementary in the sense that the zone model approach is more applicable and appropriate for parametric studies and as a practical design tool and the field model approach is more applicable for simulating and studying the details of specific scenarios, for example, the discharge sequence of sprinklers and the effectiveness of a vent design where draft curtains are almost directly above the fire.

A sprinkler/vent design approach that uses zone-type fire model simulations might involve application of an advanced version of LAVENT that would include the sprinkler/smoke-interaction simulation model [59] discussed earlier. A successful preliminary implementation of this approach, with a revised prototype model called LAVENTS (fusible *L*ink-*A*ctuated *VENT*s and *S*prinklers), has already been presented [64]. Applications of the LES (*L*arge *E*ddy *S*imulation) model [65–68], the JASMINE model [69, 70], and others [71, 72] have also been reported.

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One of the difficulties in applying the above for design applications is the limited availability of input data to describe the initial sprinkler spray from a wide range of sprinklers and the response characteristics of the vent.

A Set of Example Guidelines for Design of a Consensus Sprinkler/Vent System As a summary to the above discussion, the following example guidelines are provided for the design of a sprinkler/vent system.

1. Establish the sprinkler design in the traditional way; that is, develop design parameters using full-scale testing involving effective, rapid, sprinkler-activation strategies in the absence of vents (in this context, "rapid" means that the design problem involves an effectively unconfined ceiling where smoke-layer buildup is negligible and does not affect the timing or sequence of early sprinkler discharge).
2. Establish a vent design objective. In cases in which sprinkler action is expected to control the fire (i.e., the fire will not exceed a specified, maximum energy-release rate), the design objective for scenarios as shown in Fig. 51.13 might be for the vents to maintain indefinitely the smoke from spreading beyond the curtained compartment of fire origin (i.e., the smoke-layer interface does not descend below the bottom of the draft curtains). If the latter design objective is too ambitious or in cases in which sprinkler action is expected only to slow but not to stop the growth of the fire, then the design objective would be for the vents to maintain the smoke from spreading beyond the curtained compartment of fire origin for a specified time interval (e.g., the time expected for the fire department to respond and initiate an attack on the fire).
3. Adopt a practical/achievable strategy of early opening of all vents in the compartment of fire origin, e.g., ganged operation of all vents in the curtained compartment of fire origin based on and subsequent to first sprinkler activation.
4. Using a fire model with a proven capability of simulating the time-dependent interaction of sprinklers, vents, and draft curtains, develop a vent design that meets the established design objectives.

Special Conditions

There are some aspects of smoke control system design that involve special attention. These aspects, which affect actuation of active smoke control systems and the efficiency of exhaust fans, are the following:

- Intermediate stratification
- Confined flow
- Plugholing
- Makeup air supply

Intermediate Stratification

The upward movement of smoke in the plume is dependent on the smoke being buoyant relative to the surroundings. Delays in activation may be experienced where ceiling-mounted initiating devices are present if the air near the ceiling is warmer than the rising smoke [2, 73]. Dillon [74] reported measurements of the difference in ambient temperature from floor to ceiling to be on the order of 50 °C in some atria with glazed ceilings. A prefire, warm air layer may be created due to a solar load where the ceiling contains glazing materials. In such cases, the smoke will stratify below this warm air layer and not reach the ceiling. Early after ignition, the maximum height to which the smoke plume will rise depends on the convective heat release rate and the ambient temperature variation in the open space.

Algebraic correlations may be applied to address two situations (Fig. 51.18):

1. The temperature of the ambient air is assumed constant up to a height above which there is discrete increase in temperature associated with a layer of warm air. This situation may occur if the upper portion of a mall, atrium, or other large space is unoccupied so that the air in that portion is left unconditioned.
2. The ambient interior air within the large space has a constant temperature gradient

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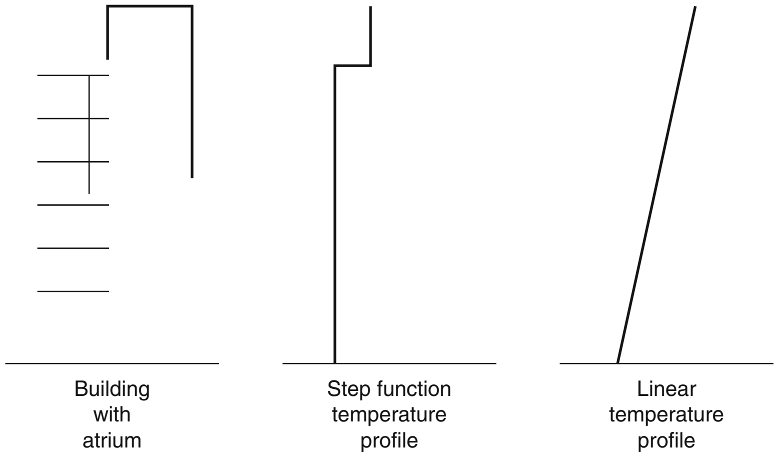

Fig. 51.18 Pre-fire temperature profiles

(temperature change per unit height) from floor level to the ceiling. This case is less likely than the first.

In the first case, where the interior air has a discrete temperature change at some elevation above floor level, then the potential for stratification can be assessed by determining the temperature of the plume at the height associated with the lower edge of the warm air layer. Where the plume centerline temperature is equal to the ambient temperature, the plume is no longer buoyant, loses its ability to rise, and stratifies at that height. One correlation for the plume centerline temperature was presented previously as Equation 51.35.

In the particular case where the ambient, pre-fire temperature increases uniformly along the entire height, the maximum plume rise can be determined from [19].

$$z_m = 3.79F^{1/4}G^{-3/8} \qquad (51.48)$$

where

$$F = g\dot{Q}_c/(T_o\rho_o c_p)$$

$$G = -(g/\rho_o)d\rho_o/dz$$

Assuming standard conditions and that the smoke in the space behaves as an ideal gas, the expressions for F and G are

$$F = 0.0277\dot{Q}_c$$

$$G = 0.0335dT_o/dz$$

Because dT_o/dz is a constant, $\Delta T_o/H$ may be substituted for the derivative. Substituting the simplified expressions for F and G into Equation 51.48 yields [73].

$$z_m = 5.54\dot{Q}_c^{1/4}(\Delta T_o/H)^{-3/8} \qquad (51.49)$$

By reformulating Equation 51.49 to solve for $\dot{Q}_c$, a minimum fire size can be determined that is just large enough to force the smoke to the ceiling of an atrium without prematurely stratifying due to the increasing ambient temperature.

$$\dot{Q}_c = 0.00118H^{5/2}\Delta T_o^{3/2} \qquad (51.50)$$

The results of an analysis of intermediate stratification are presented in Fig. 51.19. In one case, a step function is assumed to provide a 30 °C change in temperature 15 m above the floor due to the upper portion of the atrium being unconditioned. For the other case, a temperature gradient of 1.5 °C/m is arbitrarily assumed in an atrium with a ceiling height of 20 m. Plume centerline temperatures from two size fires are graphed based on Equation 51.35. As indicated in the figure, for the case with the uniform gradient, smoke is expected to stratify

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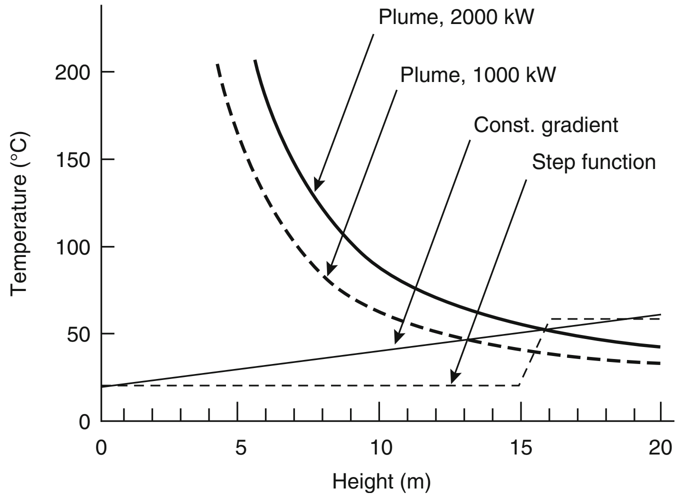

Fig. 51.19 Indoor air and plume temperature profiles with the potential for intermediate stratification

approximately 13 or 15 m above the floor, depending on the fire size. For the case involving the step function change in temperature, the smoke stratifies from both fire sizes at the height of the step change in temperature.

If the smoke is expected to stratify at an intermediate height below the ceiling, then a device other than ceiling-mounted detectors (such as projected beam detectors) needs to be considered to initiate the smoke control system. The beam detectors should be placed below the height of stratification to intercept the rising plume. In general, once the smoke control system operates, the warm air layer should be exhausted to permit the smoke to reach the ceiling.

Plume Width

As a plume rises it also widens as a result of the entrainment of additional mass into the plume. For tall, narrow spaces, the plume may fill the entire cross section of the atrium prior to reaching the ceiling. Above this position, air entrainment into the plume is greatly reduced due to the limited amount of air available. In such situations, initially the bottom of the smoke layer may be assumed to be located at this point of contact. Plume width is also important when determining the location of projected beam detectors intended to intercept the plume.

In order to determine the point of contact of the plume with the walls, the plume width must be expressed as a function of height. The width of the plume has been addressed theoretically and also experimentally.

Based on theory (see Chap. 13), the plume width is expected to be

$$d = 2.4\alpha z \qquad (51.51)$$

where $\alpha \cong 0.15$

$$\text{Thus,} \quad d = 0.36z \qquad (51.52)$$

Experimentally, the plume width is estimated by examining photographs [75] or the difference between the plume temperature and ambient temperature (i.e., temperature excess at various horizontal distances from the plume centerline) [30]. Using temperature measurements, the plume width is defined as the position where the temperature excess is one-half of the value at the centerline.

Handa and Sugawa [75] developed an empirical correlation of the width of the plume determined from photographs of the visual plume from wood crib fires

$$d = d_o z^{1/2} \qquad (51.53)$$

Heskestad [76] noted that the visible plume diameter was greater than that determined from the temperature excess. Consequently, Heskestad

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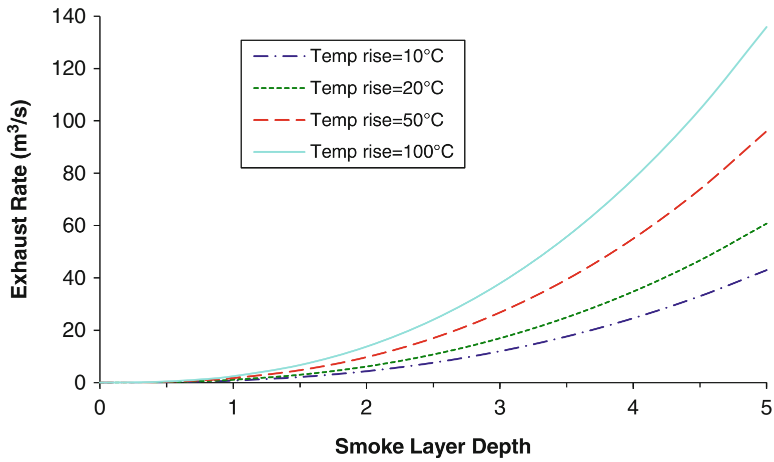
Fig. 51.20 Effect of smoke-layer depth and temperature rise on maximum exhaust capacity



estimated the visible plume diameter to be twice that determined by the excess temperature approach. Thus, the plume diameter is estimated as

$$d = 0.48\left(\frac{T_c}{T_o}\right)^{1/2} z \qquad (51.54)$$

As indicated in Equation 51.35, the plume centerline temperature decreases appreciably with increasing height. Thus, for tall spaces, the plume centerline temperature may be close to ambient. For example, at a height of 30 m with a fire size of 5000 kW and T_o of 293 K, T_c is 312 K. In this case $(T_c/T_o)^{1/2}$ in Equation 51.51 is only 1.03. Because of the rapid decline in T_c with increasing height, for engineering purposes $(T_c/T_o)^{1/2}$ can be approximated as being 1.0. Consequently, in many cases the total plume diameter may be approximated by considering the plume diameter to be approximately one-half of the height.

Considering the variety of analyses for plume width, the plume width is estimated to be 25–50 % of the height above the top of the fuel package, with the 36 % proportion from theory being near the middle of the range.

Plugholing

Plugholing occurs when the exhaust capacity at a single point is sufficiently large to draw air from the lower layer in addition to smoke. As such, less smoke is removed by the exhaust fans and a deeper layer results. Because a simple method to estimate the proportion of air drawn in from below the smoke layer by the fans is unavailable, an elementary method of estimating the smoke layer depth during plugholing is not available. As such, simple calculations can only be performed to assess the occurrence of plugholing, not the effect.

The original research on plugholing was done for natural vents. Recently, Lougheed and Hadjisophocleous demonstrated that the plugholing analysis for natural vents was also applicable to mechanical venting [77]. In order to avoid plugholing, the maximum exhaust capacity at an extract point is:

$$\dot{V}_{max} = 4.16\gamma d^{5/2}\left(\frac{\Delta T}{T_o}\right)^{1/2} \qquad (51.55)$$

Where γ is a factor relating to the location of the vent. If the vent is in the middle of the space, $\gamma = 1$ [1].

Results of applying Equation 51.56 are provided in Fig. 51.20 for a range of temperature rise values of the smoke. Where venting capacities greater than the maximum limit are needed to achieve smoke management objectives, multiple extract points need to be provided to avoid plugholing.

Assuming an axisymmetric plume, $\dot{m}$ can be replaced using Equation 51.20, and the smoke

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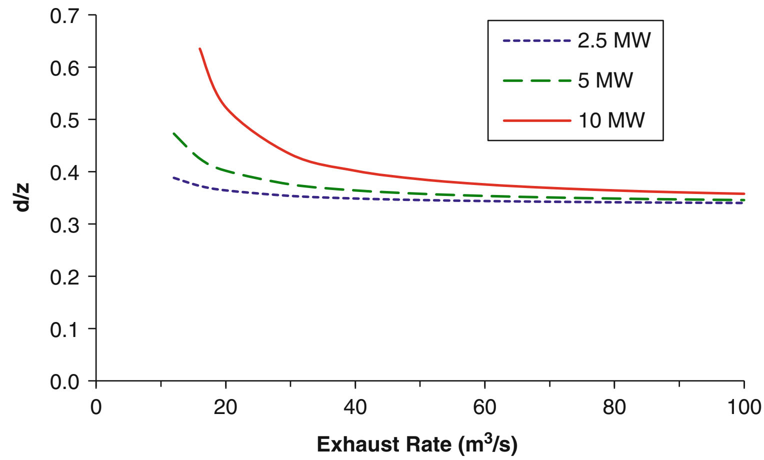

Fig. 51.21 Ratio of smoke-layer depth to clear height for single exhaust point

layer temperature can be replaced using Equation 51.34 (assuming adiabatic conditions) to express the minimum smoke layer depth in terms of the heat release rate and clear height as indicated in Fig. 51.21. For a single extract point, the minimum smoke layer depth is slightly less than 40 % of the clear height.

Makeup Air Supply

The makeup air supplied to the atrium should be

- Uncontaminated
- Introduced below the smoke layer
- Introduced at a slow velocity
- Supplied at a rate less than the required exhaust rate

Air that is not contaminated by smoke can be provided by locating intakes for the makeup air remote from the smoke exhaust discharge, preventing smoke feedback. To address the potential for smoke being introduced into the makeup air supply, a smoke detector should be provided to shut down the makeup air supply system. Selection of a smoke detector for this application should consider the operating conditions, range of temperatures, and installation within a duct.

All makeup air should be provided below the smoke layer interface. Any makeup air provided above the smoke layer interface merely adds mass to the smoke layer, which must be added to the required capacity of the smoke exhaust to prevent an increase in the smoke layer depth. If introduced near the smoke layer interface, the makeup air may increase the amount of mixing of clean air with the smoke to further add to the smoke layer.

Makeup air should be provided at a slow velocity so that the plume, fire, and smoke layer are not adversely affected. Makeup air supplied at a rapid velocity near the plume may deflect the plume to enhance the entrainment rate, thereby increasing the rate of smoke production. In addition, the burning rate of the fire may be increased by makeup air provided at an excessive velocity. Because the entrainment process induces an air velocity of approximately 1 m/s, the maximum makeup air velocity in the vicinity of the plume is often recommended to be 1 m/s. Because of the diffusion of air once past the diffuser, the makeup air velocity at the diffuser may be greater than 1 m/s.

Finally, the mass rate of makeup air supplied must be less than that being exhausted. Failure to follow this guideline may lead to the atrium being pressurized relative to the communicating spaces. Being at a positive pressure, smoke movement will be forced through any unprotected openings in physical barriers into the communicating spaces.

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Limited Fuel

In some cases smoke management objectives may be fulfilled without a dedicated smoke control system due to the intrinsic qualities of the atrium. The intrinsic qualities of the atrium include parameters, such as the composition and quantity of fuel and geometry of the atrium. As an example, a limited amount of fuel may be present that is unable to sustain a fire for a sufficient period of time to create conditions beyond the allowable limits. The amount of fuel consumed during the time period of interest depends on whether the fire is steady or unsteady. In the case of a steady fire, the fuel mass consumed in a given period of time is determined as

$$\dot{m}_f = \frac{\dot{Q}_t}{H_c} \tag{51.56}$$

Alternatively, for an unsteady, t^2 profile fire, the fuel mass consumed during a given period of time is given as

$$\dot{m}_f = 333\frac{t^3}{H_c t_g^2} \tag{51.57}$$

When analyzing the inherent ability of the atrium to fulfill the smoke management design goals, the time period should relate either to the performance of a fire protection system or to the development of smoke layer conditions in excess of acceptable levels. For example, in life safety–oriented designs, the time period may be either that required for evacuation, or for untenable conditions to be generated, whichever is less.

Opposed Airflow

Opposed airflow refers to systems where airflow is provided in a direction opposite to the undesired direction of smoke movement. Opposed airflow may be used in lieu of physical barriers to prevent smoke spread from one space to another (i.e., between the communicating space and the atrium). Opposed airflow limits smoke flow by countering the momentum of the smoke attempting to enter the adjoining space. A minimum airflow velocity at all points of the opening must be provided in order to prevent smoke migration through the opening. Empirical correlations to estimate the minimum average velocity for the entire opening are available, based on limited experimental data [78]. The calculated average velocity is greater than the actual minimum velocity required at an opening to oppose smoke propagation to insure that the minimum critical velocity is achieved at all points, considering the effects of turbulence caused by the edges and corners of the opening.

The minimum average velocity to oppose smoke originating in the communicating space is evaluated using Equation 51.59.

$$v_e = 0.64\sqrt{\frac{gH(T_s - T_o)}{T_s}} \tag{51.58}$$

Alternatively, if the smoke at the opening is part of a rising plume that is rising along the side of the atrium wall, then Equation 51.60 is applicable.

$$v_e = 0.057\left(\frac{\dot{Q}}{z}\right)^{1/3} \tag{51.59}$$

The opposed airflow velocity should not exceed 1 m/s. Above that limit, the airflow velocity may deflect the plume away from the wall, making more plume surface area available for entrainment. The increased area for entrainment will enhance the smoke generation rate. Consequently, the problem of propagation to the communicating space may be solved by an excessive average velocity; however, other problems may be created by the increased smoke production rate and a possible increase in the depth of the smoke layer in the atrium. The volumetric capacity of the mechanical equipment required to deliver the necessary velocity for opposed airflow can be approximated as

$$V_{oa} = A_o v_e \tag{51.60}$$

If several openings are protected with the opposed airflow approach using the same

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mechanical equipment, the cross-sectional area should be the sum of the areas for all of the openings. The opposed airflow technique may be infeasible due to the substantial amount of airflow capacity required to protect numerous openings having a large total area.

Where opposed airflow is utilized, the impact of the volume of air being introduced into the space with the fire must be assessed. For example, if the airflow is directed into the atrium and smoke exhaust equipment is also provided to maintain a constant position of the smoke layer interface in the atrium, then all of the additional air used for opposed airflow must also be exhausted. The additional air can be accounted for by increasing the required mass rate of exhaust in the atrium by the amount used for the opposed airflow. The additional air being exhausted will also affect the qualities of the smoke layer within the atrium (see Equations 51.34, 51.38, and 51.40). The smoke layer temperature, T_s(K), can be determined using Equation 51.61, based on an analysis included elsewhere [3].

$$T = 293 + \left[0.0018 + 0.072\dot{Q}_c^{-2/3} z^{5/3} + \frac{712A_o\sqrt{H(T-293)}}{\dot{Q}_c T^{3/2}}\right]^{-1} \quad (51.61)$$

Equation 51.61 must be applied iteratively to determine the resulting smoke layer temperature. In cases with large clear heights, the temperature of the air used for the opposed airflow strategy will be virtually equal to the temperature of the smoke layer to permit the addition of volumetric rates of air rather than mass rates.

Alternatively, if airflow is directed from the atrium into a communicating space, the communicating space must also be exhausted, otherwise the communicating space will become positively pressurized.

Example 8 Considering the atrium from Example 5. There are five 5-m-wide × 2.5-m-high openings to the communicating space. The bottom of the openings is 30 m above the floor of the atrium. Considering a 5000 kW fire in the center of the floor of the atrium, determine the following:

1. Minimum airflow velocity required for opposed airflow
2. Volumetric rate of air supply for opposed airflow
3. Capacity of the exhaust fans in the atrium to maintain the smoke layer interface at an elevation 25 m above floor level and also to accommodate the additional air from the opposed airflow approach

Solution The minimum opposed airflow velocity can be determined using Equation 51.60. However, the temperature of the smoke layer, T, is unknown. Thus, Equation 51.61 must be applied first. Solving iteratively, T is approximately 305 K. The minimum airflow velocity is 0.20 m/s. The volumetric supply capacity for the opposed airflow strategy for all five openings is 12.5 m^3/s. The associated mass flow rate is 15.0 kg/s.

Without the opposed airflow, the mass rate of smoke exhaust required to maintain the smoke layer interface height in the atrium at a height of 25 m is determined using Equation 51.27 to be 236 kg/s. Thus, the combined mass exhaust rate necessary is 251 kg/s. This mass flow rate corresponds to a volumetric rate of 209 m^3/s.

As a practical issue, this exhaust rate should be compared to that required to keep the smoke layer interface above the top of the openings (i.e., 32.5 m above floor level). Based on Equations 51.27 and 51.29, the required volumetric exhaust rate is 362 kg/s. Thus, in this situation, the combined exhaust rate with the opposed airflow strategy is less than that associated with the strategy to keep the smoke layer interface above the opening.

Nomenclature

A	Cross-sectional area of the atrium (m^2)
A_o	Cross-sectional area of opening (m^2)
b	Distance from the store opening to the balcony edge (m)

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C_{CO} Volumetric concentration of carbon monoxide (ppm)
c_p Specific heat (kJ/kg-K)
D Optical density per unit pathlength (m^{-1})
D_m Mass optical density (m^2/kg)
d Plume diameter (based on excess temperature) (m)
d_o Diameter of fire (m)
f_{CO} Yield fraction of CO (kg_{CO}/kg_{fuel})
f_i Yield fraction of species i (kg of species i per kg of fuel consumed)
g Gravitational acceleration (9.8 m/s^2)
H Height of ceiling above top of fuel surface (m)
H_b Height of balcony above top of fuel surface (m)
H_c Heat of combustion (kJ/kg)
$H_{c,conv}$ Convective heat of combustion (kJ/kg)
h Enthalpy
K Constant, depending on target being viewed (e.g., = 6 for lighted signs)[3]
k Thermal conductivity (W/m·K)
k_v Volumetric entrainment constant (0.065 $m^{4/3}$ kW $\cdot^{-1/3}\cdot$ s^{-1})
L Width of balcony spill plume (m)
l Characteristic length (m)
MW_i Molecular weight of species i (kg)
M_{CO} Molecular weight of carbon monoxide (28 kg)
M_{air} Molecular weight of air (29 kg)
m_u Mass of upper smoke layer (kg)
$\dot{m}$ Mass entrainment rate in plume (kg/s)
m_f Mass burning rate (kg/s)
Δp Pressure difference (Pa)
r Radius (i.e., horizontal distance from plume centerline (m)
Q $= \frac{1055}{t_g^2}\frac{t^3}{3}$ for t^2 fires (kJ)
$Q=$ $\dot{Q}\ t$ for steady fires (kJ)
$Q_o=$ $\rho_o c_p T_o A(H–z)$ (kJ)
$\dot{Q}$ Heat release rate of fire (kW)
$\dot{Q}_c$ Convective portion of heat release rate of fire (kW)
T_c Temperature at plume centerline (K)
T Temperature (K)
ΔT_{ad} Temperature difference between smoke layer and ambient air (°C)
ΔT_o Prefire temperature change from floor to ceiling of the ambient air (°C)
t Time (s)
t_{cj} Ceiling jet transport lag (s)
t_g Growth time (s)
t_{pl} Plume transport lag (s)
V Volumetric flow rate (m^3/s)
V_{oa} Volumetric capacity required for opposed air-flow (m^3/s)
V_u Volume of upper layer (m^3)
v Characteristic velocity (m/s)
v_e Opposed airflow velocity (m/s)
w Width of the balcony opening from the area of origin (m)
x Position (m)
Y_{CO} Mass fraction of CO (kg of species CO per kg of smoke)
Y_i Mass fraction of gas species i (kg of species i per kg of smoke)
z Clear height, position of smoke layer interface above the top of fuel surface (m)
z_b position of smoke layer interface above top of balcony (m)
z_f Limiting height above fuel (m)
z_m Maximum rise of plume (m)
z_o Virtual origin of plume (m)
χ_a Combustion efficiency
χ_l Heat loss fraction from smoke to enclosure
ρ Density (kg/m^3)

Subscripts

F Full-scale building
m Small-scale model
o Ambient air
w Wall, ceiling, or floor of enclosure

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کد آموزشی ۱۰۲	طراحی اعلام حریق Addressable Conventional	۱۶ ساعت
کد آموزشی ۱۰۳	مبانی و شناخت پمپ بوسترپمپ‌های آبرسانی و آتش نشانی به همراه بازدید از خط تولید	۱۶ ساعت
کد آموزشی ۱۰۴	طراحی تهویه و تخلیه دود همراه با آموزش نرم‌افزار Contam	۱۶ ساعت
کد آموزشی ۱۰۵	طراحی سیستم اعلان آدرس پذیر همراه با آموزش نرم افزار AlarmCAD	۱۶ ساعت
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کد آموزشی ۱۰۸	طراحی اطفاء حریق گازی FM200 & NOVEC CO_2	۱۶ ساعت
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کد آموزشی ۱۱۰	طراحی با نرم افزار Pyrosim	۱۶ ساعت
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کد آموزشی ۱۱۲	طراحی استخر، سونا و جکوزی	۱۶ ساعت

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