CHAPTER 25

VENTILATION

25-1 TYPES OF VENTILATION

There are several types of ventilation and each has different uses. Several previous chapters discussed the need for ventilation. Chapter 16 identified the need for ventilation to keep flammable gases and vapors below the lower flammable limit (LFL). Chapter 18 discussed the role of air movement in reducing heat stress. Chapter 24 identified a requirement to keep toxic contaminants at or below certain concentrations and noted the importance of ventilation in making confined spaces safe for entry.

Ventilation can reduce odors in a room and can dilute cigarette smoke. Older air quality standards found in building codes have their origin with studies of acceptable levels of body odor and cigarette smoke.[1] Ventilation can control microorganisms, dusts, and other particulates in hospitals and clean rooms. Some clean rooms use laminar flow to prevent particulates from getting distributed in the room.

There is also a need to use ventilation to limit carbon dioxide buildup in a closed, occupied space. One inspires oxygen and expires carbon dioxide as a product of cellular combustion. A person expires approximately $0.7\,\text{ft}^3$ of CO_2 per hour. If the standard CO_2 content of air is 0.03% and the upper limit is 0.6%, then the amount of ventilation air required is $4\,\text{ft}^3/\text{min}$ per person. This amount is very small. Infiltration of outdoor air into a building often provides enough air to meet this requirement, but tightly sealed buildings may not.

Thermal Control

One will recall from Equations 18-2 and 18-4 that air velocity is one of the key physical parameters contributing to control of heat stress. Air velocity strongly influences convective and evaporative cooling. When it is warm indoors and cool outdoors, we may open a window in a building to let air move through. Not only is there a temperature difference, but there is air movement. We turn on a fan or set a fan in a window to increase air velocity. Most often we use thermal comfort ventilation to provide cooling. However, if the conditions are right, ventilation can be used to warm a space and its occupants.

General or Dilution

General ventilation and dilution ventilation are the same. They refer to the process of using clean air (often outside air) to reduce the level or concentration of contaminants in a building or space.

Dilution ventilation reduces the concentration of flammable or combustible gases and vapors below the LFL. When used for this purpose, a factor of safety is applied to the

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Safety and Health for Engineers, Second Edition, by Roger L. Brauer

air requirement, because concentrations may not be uniformly distributed. The rate of contaminant generation may vary. The gases or vapors may be lighter or heavier than air and tend to concentrate locally. Factors of safety range from 3 to 10. High values apply to those contaminants with high toxic or flammable hazards, whereas low values apply to those contaminants with low toxic or flammable hazards.

There are practical limits to dilution ventilation. They include cost, effectiveness, and risk. If a contaminant is generated at a high rate, a very large amount of air is required to keep the contaminant at or below the LFL or below some allowable toxic concentration. It is expensive to move large quantities of air, and it is often more expensive to heat, cool, or remove moisture from entering air.

General ventilation does not always reach local sites in a space, particularly near contaminant sources, where concentrations may exceed safe levels for fire or health.

General ventilation may move contaminated air to locations that are not otherwise contaminated and it could expose more people by moving toxic mixtures into breathing zones of people. Contaminants may evaporate at varying rates because of varying process temperatures or particular use activities. General ventilation works best where contaminant generation is uniform and the rate of generation is low.

If contaminants are highly toxic or very flammable, then dilution ventilation is not a good choice for contaminant control. Failure to keep concentrations below limits can have serious consequences. A system failure could produce very dangerous conditions. Local concentrations could exceed limits and lead to injury, fire, or explosion. Someone could interfere with planned circulation and air flow patterns and produce a dangerous condition. For example, someone could stack supplies near a work station, restrict air movement and dilution, and cause local conditions to exceed limits.

Principles There are several principles for dilution ventilation arrangements. Contaminated air should move away from occupants and fresh air should pass by occupied areas first as it moves toward a source of contaminants. Supply air should be as widely dispersed as possible to be sure that all areas of a space receive fresh air and to reduce the possibility of local concentration buildup.

Units of measure for dilution ventilation are units of air flow, such as cubic feet per minute. Air changes per hour are not appropriate, because they reflect room volume only. Dilution ventilation requirements should be based on the amount of air needed to control some contaminant level or rate of contaminant generation. When computing the ventilation required, one normally adjusts data to standard temperature (0°C) and pressure (460 mmHg).

Steady-State Concentrations One can compute the dilution ventilation air, V_r, required to keep some evaporating solvent below a prescribed limit [lower flammable limit (LFL) or threshold limit value (TLV)] from

$$V_r = \frac{403 \times \text{specific gravity} \times 10^6 \times E \times K}{\text{molecular weight} \times L}, \tag{25-1}$$

where

V_r is in ft^3/min,

E is the constant evaporation rate in pints/hr,

K is a safety factor (normally from 3 to 10),

L is the limiting concentration (LFL or TLV) in parts per million, and the specific gravity and molecular weight are properties of the solvent. If the evaporation rate is in pounds per minute, the coefficient in Equation 25-1 is 387 instead of 403.

Example 25-1 Suppose workers apply adhesive in a certain operation. The adhesive has a solvent base, methyl ethyl ketone (MEK). If the process allows 6 p of MEK to evaporate per hour, how much dilution air is required to prevent combustion? The molecular weight of MEK is 72. Referring to Table 16-3, the specific gravity of MEK is 0.8. The LFL is 1.8, and because this is fairly low and therefore quite flammable, a high value (8) for a factor of safety, *K*, is selected. From Equation 25-1, we find that the required dilution air is

$$\begin{aligned} V^{\mathrm{r}} &= \frac{403(0.8)(10^6)(6)(8)}{72(1.8\times 10^4)} \\ &= 11{,}940\ \mathrm{ft}^3/\mathrm{min}. \end{aligned}$$

Concentration Buildup Suppose a contaminant is evaporating at some rate in a space that initially contains clean air. Also suppose there is a fixed rate of dilution air for the space. The concentration of the contaminant in the space may increase over time. One can determine what the concentration is after a period of time from

$$\ln\frac{G-\left(\frac{Q}{K}\right)C}{G}=\frac{\left(\frac{Q}{K}\right)t}{V} \tag{25-2a}$$

or

$$\frac{G-\left(\frac{Q}{K}\right)C}{G}=e^{\frac{-(Q/K)t}{V}}, \tag{25-2b}$$

where

- C is the concentration of gas or vapor at time t,
- G is the rate of generation of the contaminant,
- Q is the rate of ventilation,
- K is the factor of safety to allow for incomplete mixing, and
- V is the volume of the room or space.

Example 25-2 A process of degreasing metal furniture starts into operation. Initially, the air in the 20,000-ft^3 dryer is free of solvent vapors. The ventilation rate in the dryer is 2,500 ft^3/min, and there is a factor of safety $K = 4$. The degreasing solvent evaporates at a rate 0.8 ft^3/min. How long will it take for the concentration to reach 500 ppm?

One can rearrange and apply Equation 25-2a to determine the time from no solvent to a concentration of 500 ppm:

$$\begin{aligned} t &= -\frac{VK}{Q}\left\{\ln\left[G-\frac{\left(\frac{Q}{K}\right)C}{G}\right]\right\} \\ &= -\frac{20{,}000(4)}{2{,}500}\times\left\{\ln\left[\left(0.8-\frac{\left(\frac{2{,}500}{4}\right)(500\times10^{-6})}{0.8}\right)\right]\right\} \\ &= 15.85\ \mathrm{min}. \end{aligned}$$

Example 25-3 For the process in Example 25-2, what is the concentration after 1 hr?

Rearranging Equation 25-2b, the concentration is

$$\begin{aligned}C &= \frac{G - Ge^{\frac{-(Q/K)t}{V}}}{\frac{Q}{K}}\\ &= \frac{0.8 - 0.8e^{\left[\frac{-\left(\frac{2,500}{4}\right)(60)}{20,000}\right]}}{\frac{2,500}{4}}\\ &= 1,084\,\text{ppm}.\end{aligned}$$

Purging If the space is contaminated at some concentration and ventilation is started, the concentration will decrease. The rate of purging is

$$\ln\left(\frac{C_2}{C_1}\right) = \frac{-Q(t_2 - t_1)}{VK}, \tag{25-3}$$

where

C_1 is the initial concentration at the time ventilation starts, t_1, and

C_2 is the final concentration at time t_2.

Example 25-4 For the dryer in Example 25-2, assume that the degreasing line stops. No more furniture enters the dryer. The generation of contaminants stops. At that time, t_1, the concentration in the dryer is 50 ppm. If the ventilation continues, how long will it take to reduce the concentration in the dryer to 10 ppm?

Applying Equation 25-3,

$$\begin{aligned}(t_2 - t_1) &= -\frac{VK}{Q} \times \ln\left(\frac{C_1}{C_2}\right)\\ &= -\frac{20,000(4)}{2,500} \times \ln\left(\frac{50}{10}\right)\\ &= 51.5\,\text{min}.\end{aligned}$$

Local Exhaust

The main purpose of local exhaust ventilation is capturing contaminants at their source before they contaminate a room or work station. The captured contaminants are moved through ducts to another location. It may be necessary to remove the contaminants before dumping the air outdoors or before recirculating the air. Figure 25-1 illustrates the key components in a local exhaust ventilation system. Later sections of this chapter give more details about local exhaust ventilation systems.

One advantage of local exhaust ventilation is complete or nearly complete capture of contaminants. The capture is independent of the rate of contaminant generation, toxicity, flammability, or the type of contaminant. Another advantage of local exhaust ventilation is the relatively low volume of air required compared with dilution ventilation.

Disadvantages of local exhaust ventilation systems are complexity of design, system cost, and difficulty in modifying or moving them. Failures of both dilution ventilation and local exhaust ventilation systems could create dangerous conditions. Because local exhaust

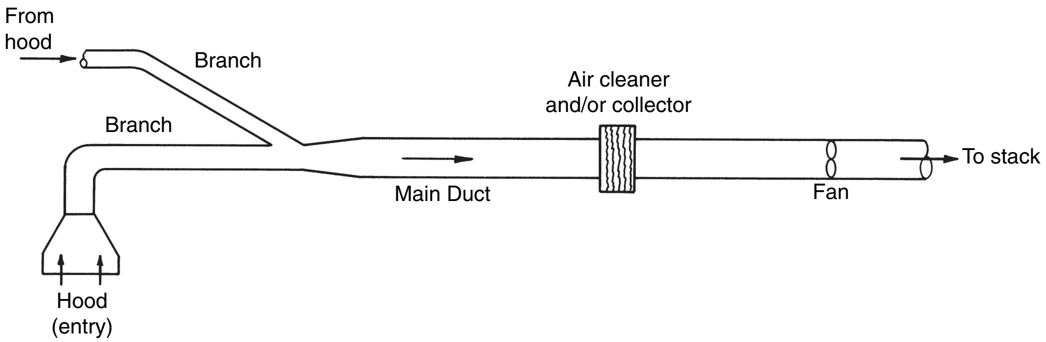

Figure 25-1. Key components of a local exhaust system. If a local exhaust system is used to exhaust toxic contaminants, an alarm may be important to alert people when there is an interruption of air flow.

systems are well suited for toxic contaminants, an alarm may be important to alert people when there is an interruption of air flow or a dangerous contaminant level.

25-2 PRINCIPLES OF VENTILATION

Air Flow

Air moves when there is a pressure difference between two locations and the air moves from the high pressure location to the low pressure one. The quantity of air flow Q is

$$Q = VA, \tag{25-4}$$

where

Q is cubic feet per minute,

V is the velocity in feet per minute, and

A is the cross-sectional area through which air flows in square feet.

This is a restatement of Equation 10-6 and principles related to it.

For a pipe or duct of constant cross-sectional area, the velocity of air moving in it is constant over its entire length. If the cross-sectional area changes over the length of a pipe, the velocity is different at each different area of the pipe. The amount of air flowing is constant over the length of a pipe, regardless of cross-sectional changes.

The pressure creating air movement is the total pressure, TP. Total pressure has two components: static pressure, SP, and velocity pressure, VP. For air flow, all three are normally measured in inches of water. The three pressures are related:

$$TP = SP + VP. \tag{25-5}$$

Figure 25-2 illustrates the measurement of the three pressures.

Static pressure is the potential pressure exerted in all directions by a fluid at rest. In a duct, static pressure tends to expand or collapse a pipe, depending on whether static pressure is positive or negative. Static pressure is measured normal to the direction of air flow.

Velocity pressure is the kinetic pressure that causes a fluid to flow at some velocity. It is always positive and acts in the direction of air flow. It exists only when air is in motion.

The velocity pressure is related to air velocity as follows:

$$V = 4{,}005(VP)^{\frac{1}{2}}, \tag{25-6}$$

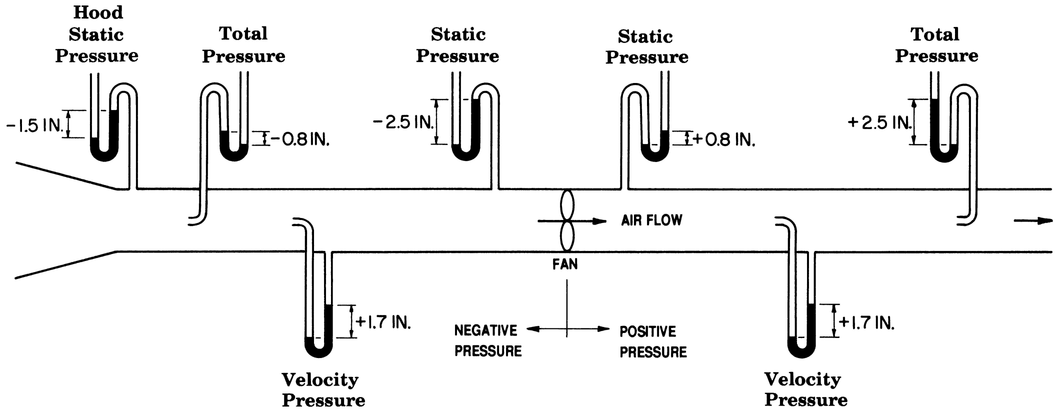

Figure 25-2. Relationships among total pressure, static pressure, and velocity pressure.

where

V is in feet per minute and

VP is in inches of water.

Losses in Systems

When air moves, there are pressure losses because some of the energy involved in potential flow is converted to heat. There are several types of losses, each resulting from different phenomena.

One type of loss is friction loss. As air moves through a pipe, the surfaces create some friction. The rougher the surfaces, the greater the friction loss; the higher the velocity, the greater the friction loss. Friction loss in a pipe or duct varies directly with pipe length, inversely with pipe diameter, and directly with the square of the velocity. Friction losses are often given per unit of pipe length.

Another kind of loss is dynamic loss. Turbulence results when there is a bend in a pipe or the cross section changes. Dynamic losses increase with increasing abruptness of the bend or change. Dynamic losses are expressed in units of equivalent pipe length. A bend or transition has the same loss as that resulting from friction loss over some length of pipe or duct of the same size. Sometimes, dynamic losses are reported as a fraction of the velocity pressure. For example, a loss for an elbow might be $0.13VP$.

Dynamic losses also result from acceleration of air at rest. Most often this occurs at the entrance into an exhaust system. Turbulence at the entry to the system adds to dynamic losses. The coefficient of entry, C_e, is a measure of the efficiency at the entry of a hood or pipe. The efficiency indicates how well static pressure is converted to velocity pressure.

Not only are there friction losses along pipe walls and dynamic losses at the system entry and at each bend or transition, but there are also losses at filters or other air cleaning devices that are part of the system. In summary, Bernoulli's equation (Equation 10-8) applies to air flow in ducts. A related form for the equation is the sum of the static pressure and velocity pressure of a point upstream in a ventilation system is equal to the sum of the static pressure, the velocity pressure and friction losses (FL) and dynamic losses (DL) at a point downstream in the system:

$$SP_1 + VP_1 = SP_2 + VP_2 + FL + DL. \qquad (25\text{-}7)$$

One must expend energy to create a pressure difference between the ends of the system. A fan normally creates the pressure difference for an exhaust system by creating a static pressure great enough to overcome the resistance of the system.

Flow of Jets

A jet of air, blown from a small pipe into a space or room with a large volume of still air, can penetrate a limited distance into the large space. If the velocity of the air jet is V as it leaves a pipe of diameter d, the velocity at a distance $30d$ from the face of the pipe is approximately $0.1\,V$ (see Figure 25-3).

Flow at Pipe Entry

If the flow is reversed so that air enters a pipe of diameter d with a velocity of V at the pipe face, the velocity of air drops off rapidly as a function of distance upstream from the pipe face. For a plain pipe, the velocity at a distance of $1\,d$ from the pipe face is less than $0.075\,V$ (see Figure 25-4). Placing a flange around the pipe entrance extends the velocity profile only a small amount.

Make Up Air

Regardless of the purpose for ventilation, the air used in ventilation must be supplied from somewhere. Make-up air replaces air removed by a ventilation system. If the volume of make-up air is less than the volume of exhausted air for a given space, there will be a negative pressure in the space. Conversely, if the volume of make-up air is greater than the volume of exhausted air in a space, there will be a slight positive pressure. In general, it is desirable to have a negative pressure in a contaminated space or in a space where there is a source of contaminants. The negative pressure will draw air from adjacent spaces through cracks in windows, doors, ducts, or pipes and the contaminants will stay in the contaminated space. If there are contaminants in adjacent spaces, tight seals between spaces will prevent transfer of the contaminants between spaces. The presence of a positive pressure in a contaminated space will spread contaminated air to adjacent spaces.

Cleaning Air

When air is removed from a space through dilution or local exhaust, the contaminants are moved elsewhere, usually outdoors. Outdoor air quality standards limit the dumping of contaminants. As a result, it is common to clean the contaminants from the exhausted air. Some contaminants collected by local exhaust systems may have economic value. There

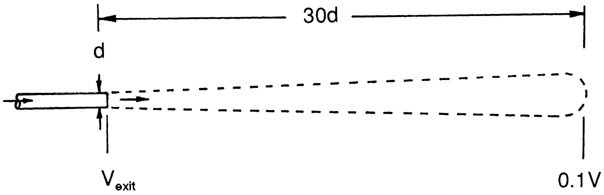

Figure 25-3. A jet of air can penetrate deeply into a space. Air exiting a pipe has approximately 10% of the exit velocity at a distance of $30d$ from the exit.

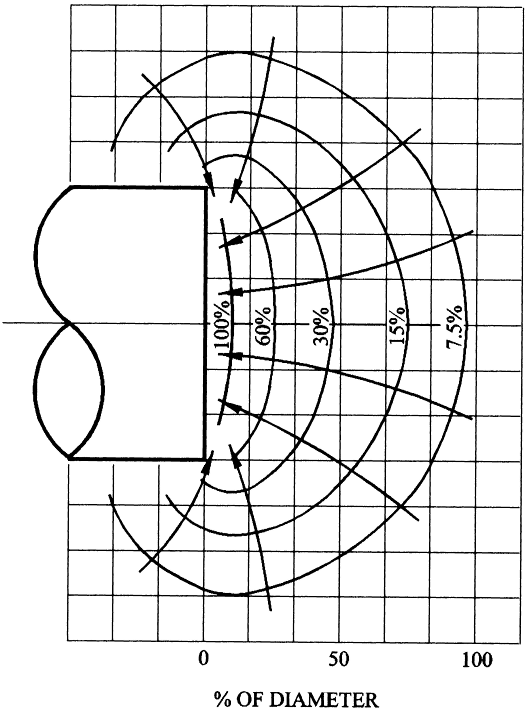

Figure 25-4. The velocity of air entering a pipe or hood decreases rapidly with distance from the pipe entrance.

are several types of equipment for removing airborne particulates and gases or vapors from exhausted air (see Section 25-6).

Recirculating Air

Because it is expensive to heat, cool, or remove moisture from ventilation air, it may be more economical to clean exhaust air and recirculate it. In deciding on recirculation, one must consider the possible effects of recirculation on occupants. If the contaminated air has potential health consequences, recirculation is not normally recommended, even if the cleaning process adequately removes contaminants. The more dangerous a contaminant, the more care one should take in deciding on recirculation. Failures in the system and inadequate maintenance can lead to hazardous conditions, and the more dangerous a contaminant, the greater the protection needed to ensure that system failures will not circulate hazardous air into occupied areas.

If air is recirculated and there is a health hazard from a potential failure in the cleaning process, several design factors must be met.

1. Contaminants in recirculated air that have a health hazard should not exceed recommended concentrations. One can estimate the permissible concentration, C_r, of a contaminant in air exiting a cleaning device prior to mixing with air in a workspace from

$$C_r = 0.5(\text{TLV} - C_o)\left(\frac{Q_T}{Q_R}\right)\left(\frac{1}{K}\right), \qquad (25\text{-}8)$$

where

C_o is the concentration of contaminant in a worker's breathing zone when local exhaust is discharged outdoors,

Q_T is the total ventilation flow through the affected space (cubic feet per minute),

Q_R is the recirculated air flow (cubic feet per minute),

K is a factor of safety related to incomplete mixing (range is 3 to 10), and

TLV is the threshold limit value of the concentration.

For recirculation of nuisance contaminants, the applicable coefficient in Equation 25-7 is 0.9 instead of 0.5.

2. There must be a primary and secondary cleaning system in series, each with equal efficiency. An alternative to a secondary cleaning system is a fail-safe monitoring system that must monitor the level of contaminant in the cleaned air being recirculated.
3. There must be a warning system that indicates problems in the cleaning systems. A problem may be inefficiency or failure of the secondary system or excessive levels of contaminants exiting the system.
4. If the warning system indicates a problem, either the recirculated air must be diverted immediately to the outdoors or the contaminant generating process must be completely shut down.
5. Periodic testing of recirculated air is necessary to ensure that the system is working properly.
6. Warning signs must tell occupants of the potential danger from a failure of the recirculation system. It must explain the meaning of a warning signal and the actions required for protection. AGCIH[2] gives additional factors to consider in designing recirculation systems.

Location of Exhaust Vents and Inlets

Local exhaust systems often have exhaust vents located on roofs of buildings where there are also inlets for air conditioning and air recirculation systems. When inlet and exit vents are close to each other and when wind conditions are just right, exhausted contaminants may travel directly to inlets and return to the building interior. There should be adequate separation of exhaust vents from any type of air inlet to ensure that contaminants do not reenter the building.

Protecting the Breathing Zone

Protecting the breathing zone of occupants is a basic concept for design of any type of ventilation system. Air flow patterns must move contaminated air away from a breathing zone, not near or through a breathing zone. If air is moved through a breathing zone, it should be clean air.

25-3 CAPTURING PARTICULATES AND GASES

Flow Requirements for Capture

The main idea of local exhaust ventilation is capturing contaminants at their source. One can accomplish this most easily by enclosing the source as much as possible. Enclosures increase the efficiency of capture, reduce operating cost, and require less air flow to capture contaminants. If the source of contamination cannot be enclosed, the entry (hood) to the local exhaust system should be as close to the source as possible. The farther a hood is from the source of contaminants, the less efficient it will be. Air volume required to accomplish capture increases with distance between a contaminant source and the face of a hood. The shape of a hood also can affect the likelihood of capture. The profile of air movement at the entry extends farther upstream from the hood for certain types of hoods.

The force on contaminants created by moving air must overcome other forces acting on contaminants. For gases, vapors, and particulates, the forces include thermal air currents, room air currents, and motion created by a process or operator. Diffusion, buoyancy, and gravity also apply to gases and vapors. Buoyancy acts on gases lighter than air, and gravity acts on gases heavier than air. Both buoyancy and gravity produce small forces on gases and vapors compared with other sources. Depending on their size and mass, particulates may act differently than gases and vapors. Very small particulates have little mass, act much like gases, and remain entrained in air, whereas large particulates settle out of the air because of gravity. Forces from processes that place particulates in motion, such as grinding, may be difficult to overcome with air movement. Capture is more effective if the process motion is in the same direction as air movement for capture.

The velocity of air required to capture contaminants varies with contaminants and processes. Table 25-1 lists a range of capture velocities. Capture velocity is the air velocity at any point in front of a hood or at a hood opening necessary to overcome opposing air currents and to capture contaminant air at that point by causing it to flow into the hood.

Types of Hoods and Hood Properties

Hoods can be plain openings of round or square pipe, can have flanges, can have very narrow slots, and can enclose a process or form a canopy over a tank or process. For most, the air velocity at some distance in front of the hood is a function of the shape and air

TABLE 25-1 Range of Capture Velocities[a]

Condition of Dispersion	Examples	Capture Velocity of Contaminant (ft/min)
Released with practically no velocity into quiet air	Evaporation from tanks; degreasing, etc.	50–100
Released at low velocity into moderately still air	Spray booths; intermittent container filling; low speed conveyor transfers; welding; plating; pickling	100–200
Active generation into zone of rapid air motion	Spray painting in shallow booths; barrel filling; conveyor loading; crushers	200–500
Released at high initial velocity into zone	Grinding; abrasive blasting	500–2,000

In each category above, a range of capture velocity is shown. The proper choice of values depends on several factors:

Lower End of Range	Upper End of Range
1. Room air currents minimal or favorable to capture	1. Disturbing room air current
2. Contaminants of low toxicity or of nuisance value only	2. Contaminants of high toxicity
3. Intermittent, low production	3. High production, heavy use
4. Large hood, large air mass in motion	4. Small hood, local control only

[a] *Industrial Ventilation*, 25th ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 2004.

TABLE 25-2 Properties of Various Hood Types[a,b]

Type	Aspect Ratio (W/L)	Air Volume	C_e
Plain opening: square, rectangular, and round	≥0.2	$Q = V(10x^2 + A)$	0.72
Flanged opening: square, rectangular, and round	≥0.2	$Q = 0.75V(10X^2 + A)$	0.82
Slot (rectangular)	<0.2	$Q = 3.7LVX$	
Flanged slot (rectangular)	<0.2	$Q = 2.8LVX$	
Booth	To suit work	$Q = VA = VWL$	
Canopy	To suit work	$Q = 1.4PDV$	

[a] From *Industrial Ventilation*, 25th ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 2004.

[b] W = width of rectangular opening, ft; L = length of rectangular opening, ft; C_e = entry coefficient; X = distance in front of hood face, ft; A = cross-sectional area, ft^2; P = perimeter of work or tank, ft; D = height above work or tank to canopy face, ft.

flow. Table 25-2 lists properties of various hood types. Slots (small aspect ratio openings) help to distribute uniformly the velocity of air in front of a larger hood face. The face velocity is the air velocity at the hood opening.

Example 25-5 A flanged opening rectangular hood (W = 4 in and L = 16 in) is placed 6 in from a contaminant source. The contaminant is released at low velocity into moderately still air. (a) What volume of air is required to capture the contaminant? (b) If the opening dimensions were W = 2 in and L = 32 in, what volume of air would be required?

From Table 25-1, the upper recommended capture velocity is 200 ft/min. For (a), the rectangular hood has an aspect ratio more than 0.2 (4/16 = 0.25). From Table 25-2, the applicable flow equation for this hood is $Q = 0.75\,V(10X^2 + \mathrm{A})$. The area of the opening is $(4 \times 16)/144 = 0.444\,\text{ft}^2$. The flow required is $200\{(6/12)^2 + 0.444\} = 104\,\text{ft}^3/\text{min}$.

For the alternate hood (b), the aspect ratio is less than 0.2 (2/32 = 0.06). The flow equation from Table 25-2 is $Q = 2.8LVX$. Although the face area is the same as the previous case, the volume of required air is $Q = 2.8(32/12)(200)(6/12) = 747\,\text{ft}^3/\text{min}$.

As air moves into a hood, the area of moving air decreases and velocity increases. Changing static pressure (in velocity pressure) causes a loss at the entry. The coefficient of entry, C_e, represents that loss. For standard air, the static pressure at the hood throat is

$$Q = 4005AC_e(SP_h)^{1/2}, \tag{25-9}$$

where

SP_h is the hood static pressure in inches of water,

V is in feet per minute,

C_e is dimensionless,

A is the area of the hood opening in square feet, and

Q is the air flow rate in cubic feet per minute.

25-4 FLOW IN PIPES AND DUCTS

Flow Requirements in Pipes

After being captured, a contaminant moves from the hood through ducts to a point of discharge. Particulates may settle out of the flowing air and collect in the ducts, causing plug-

TABLE 25-3 Design Velocities for Moving Contaminants in Ducts

Velocity Nature of Contaminant	Examples	Design (ft/min)
Vapors, gases, and smoke	All vapors, gases, and smokes	Any velocity (1,000–2,000 is common)
Fumes	Zinc and aluminum oxide fumes	1,400–2,000
Very fine, light dust	Cotton lint, wood flour, litho powder	2,000–2,500
Dry dusts and powders	Fine rubber dust, Bakelite modeling powder dust, jute lint, cotton dust, shavings (light), soap dust, leather shavings	2,500–3,500
Average industrial dust	Sawdust (heavy and wet), grinding dust, buffing lint (dry), wool jute dust (shaker waste), coffee beans, shoe dust, granite dust, silica flour, general material building, brick cutting, clay dust, foundry (general), limestone dust, packaging and weighing asbestos dust in textile industries	3,500–4,000
Heavy dusts	Metal turnings, foundry tumbling barrels and shakeout, sand blast dust, wood blocks, hog waste, brass turnings, cast iron boring dust, lead dust	4,000–4,500
Heavy or moist dusts	Lead dust with small chips, moist cement dust, asbestos chunks from transite pipe cutting machines, buffing lint (sticky), quick-lime dust	4,500 and up

ging. The duct velocity is the air velocity in the duct, and it must be high enough to prevent settling and plugging. Table 25-3 lists design velocities for ducts. Duct velocities that are too high can cause denting, damage as particles impinge on duct walls, and possible leaks. Some airborne materials are sticky or have electrostatic properties that cause clinging to duct surfaces. Velocity will not overcome these problems.

Designing Ducts and Pipes

A designer must size ducts, select bends and elbows, combine several ducts into one system, select fans and motors, and move air through cleaning devices and on out through exhaust stacks. The design process requires detailed analysis through each element of the system. Different operations, types of contaminant, and degrees of hazard all impact design decisions. This text does not cover the design process in detail. In general, a designer must ensure that design velocities are maintained along the system. A design should have sufficient pressure at each location to ensure that there is proper air movement in each branch and at each hood.

25-5 FANS

Fans, blowers, or ejectors provide air movement in local exhaust systems. Fans are most common. Normally, they are located downstream of air cleaning devices. Ejectors are pneumatic conveyors that prevent contaminants from flowing through an air-moving device.

Types of Fans

There are many kinds of fans. Some are combined with stacks or other elements of a duct system and sold as a package. Some fans include motors; others require separate selection of motors. Some fans have enclosed motors to prevent ignition of flammable dusts, gases, and vapors (see Chapters 12, 16, and 17). Table 25-4 lists types of fans and some key features of each.

Fan Selection and Fan Laws

Manufacturers rate fans for flow and static pressure produced. A designer must match system flow and pressure requirements to fan rating curves. The resistance of an exhaust system may vary during its operation. For example, the cleaning device may plug up and significantly increase losses. A design must include anticipated changes in operating characteristics. Changing the speed of a motor may compensate for the additional losses and maintain the velocity and flow required.

Flow rate, pressure produced, and horsepower vary with fan speed. However, fan speed has a different relationship with each parameter. These relationships are fan laws (refer to Equations 25-10 through 25-12). Flow rate varies directly with fan speed, whereas total pressure (TP) and fan static pressure (FSP) vary with the square of fan speed. Air

TABLE 25-4 Types of Fans and Key Features[a]

Type of Fan	Key Features
Axial Flow	
Propellar fan	Moves large quantities of air; low static pressure; used for relatively clean air and no duct resistance; common for general ventilation
Tubeaxial (duct) fan	Fabricated in a round duct; used for condensable fumes, pigments, and other materials that collect on blades; larger diameters at slow speeds are better for abrasives and accumulating material
Vane axial fan	Develops higher pressures than other axial flow fans; more economical in horsepower and space
Centrifugal	
Forward-curved blade	Squirrel cage wheel; leading edges curve toward the direction of rotation; develops low to moderate static pressure; not recommended for dusts or fumes that adhere to blades (causes imbalance and is difficult to clean)
Straight or radial blade	Paddle wheel; most commonly used fan in exhaust systems; used for materials that clog a fan wheel; medium tip speed; medium noise factor; used for heavy dust load
Backward blade	Blades are inclined in opposite direction from fan rotation; high tip speed, high fan efficiency; blade shape is conducive to buildup of material; not suited to condensable fumes or vapors.
Special	
Airfoil-backward curved	Airfoils vary with manufacturer; quiet; high efficiency; blade usually has low vibration
In-line flow centrifugal	Backward-curved blades; special housing to fit ducts
Power exhausters, power roof ventilators	Packaged unit with fan, stack and weather; may be axial flow or centrifugal; various discharge patterns available
Combination fan and dust collector	Wide variety available; proper application important

[a] Derived from *Industrial Ventilation*, 25th ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 2004.

horsepower (AHP) or brake horsepower (BHP) varies with the cube of fan speed. Selecting components and applying fan laws to achieve an efficient and economical to operate system is a complex process, particularly when the properties of the system vary with time.

$$\mathrm{FSP} = SP_{\mathrm{out}} - SP_{\mathrm{in}} - VP_{\mathrm{in}}, \tag{25-10}$$

where

FPS is fan static pressure (inches of water),

SP is static pressure (inches of water), and

VP is vapor pressure (inches of water).

$$\mathrm{AHP} = \frac{5.2Q(TP)}{33{,}000} = \frac{Q(TP)}{6{,}350}, \tag{25-11}$$

where

Q is flow rate (cubic feet per minute) and

TP is total pressure (inches of water).

$$\mathrm{BHP} = \frac{5.2Q(TP)}{33{,}000(\mathrm{E})} = \frac{\mathrm{AHP}}{E}, \tag{25-12}$$

where *E* is mechanical efficiency (dimensionless).

25-6 AIR CLEANING DEVICES

Very often a local exhaust ventilation system must include a capability to remove contaminants before air is dumped to the outdoors. Cleaning is essential if air is to be recirculated. There are several types of air cleaning devices. Figure 25-5 illustrates properties of aerosols and related cleaning equipment.

Types of Air-Cleaning Devices

The main types of air-cleaning equipment are mechanical separators, filtration devices, wet collectors, electrostatic precipitators, gas adsorbers, and combustion incinerators.

Efficiency ratings for air-cleaning devices can be misleading. If efficiency is based on mass, collecting only a few large particles can achieve high efficiency even if nearly all small particles pass through. Efficiency data is most accurately represented by a curve showing the portion of each size of particle actually captured. For gases passing through an adsorption bed, efficiency varies with the concentration of the gas. Low concentrations have lower efficiencies per pass than do high concentrations, and efficiency drops as the adsorption bed loads up with contaminants.

Mechanical Separators One type of mechanical separator is a gravity chamber. Air moves through an enclosure and, because its cross-sectional area is large, the air velocity is very slow. Gravity acts on the suspended particles as they pass through the chamber and pulls them to the bottom of the enclosure, where they stay until removed. Particles smaller than 40 μm in diameter pass through a gravity chamber and are not collected. Gravity chambers are low-cost collection devices for large particles.

Impingement separators are another type of mechanical separator where dust-laden air passes through a network of baffles. Because the air changes direction quickly, partic-

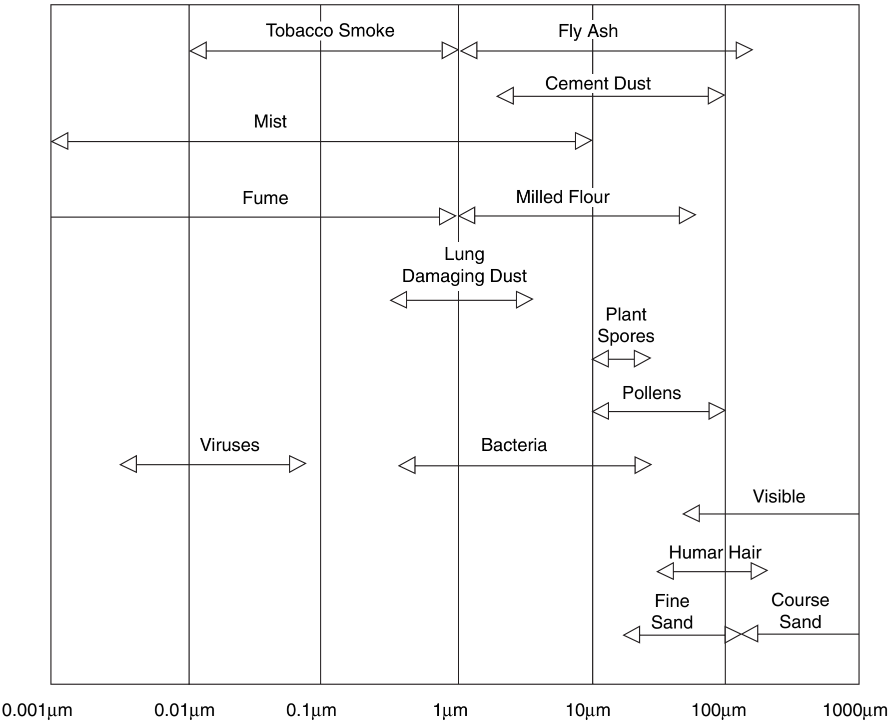

Figure 25-5. Examples of particle sizes.

ulates have more momentum and cannot make the quick turns. Consequently, they impinge on the baffles, and the baffles direct them to one side of the flow. The clean air separated from the particulates passes out the less contaminated side of the baffles. Overall efficiency depends on particle size, gas velocity, and particle density. Particles smaller than 20 μm are not collected. An advantage for impingement separators is low cost.

Cyclone collectors or separators are a common mechanical collector. Contaminated gas enters tangentially into a circular chamber. The rotating gas causes particulates to move to the outside of the rotating column. The particulates fall to the bottom and exit through a port. The partially cleaned air escapes through a vent at the top and center of the cylinder. The rotation can generate forces on the particles many times the force of gravity, and efficiency increases as the radius of a cyclone separator decreases. These separators have relatively low cost. Particles smaller than 5 μm are not collected and impinging materials will erode the cylinder walls.

Filtration Devices There are several forms of filtration devices. Mat filters are very porous and have low efficiency. Some filters, like those made of glass fibers, are disposable; others are washable. Ultrafiltration filters, such as high-efficiency particulate air filters (HEPA), remove a wide range of particles, but they require considerable maintenance and have high-pressure drops across them.

The most common filtration devices are fabric filters. There are many kinds of fabrics. The type of contaminant and the temperature of the air are but two factors that affect selection. Some filters are in the form of tubes or stockings; others have an envelope or pleated form. Air moves through the fabric bags and dust collects inside them. The more material that collects, the greater the efficiency, the smaller the particles collected, and the higher the pressure drop across the filter. Many of the large fabric filters are self-cleaning. For some, cleaning is accomplished by agitation or motion that shakes off the collected material and cleans the filters; for others, reverse air flow knocks material loose. Air from an exhaust system must be diverted to an alternate collector during the self-cleaning cycle of a collector.

Wet Collectors The idea of wet collectors is to put contaminants in contact with a liquid, usually water. After being trapped in the liquid, the contaminants may accumulate in it. For some collectors, the contaminants and liquid may pass through cleaning elements in the wet collector system. Examples of wet collectors are spray chambers, wet centrifugal collectors, wet filters, orifice collectors, venturi collectors, and packed towers. Some wet collectors, like packed towers, also may contain adsorption material for collecting contaminant gases and vapors. Wet collectors have advantages, such as constant pressure drop, capability to handle high temperatures and humidities, compact design, and moderate cost. Some wet collectors remove 90% of 1-μm particles. Water used in wet collectors may need treatment before disposal.

Electrostatic Precipitators Air containing solid or liquid particles passes through a bank of discharge electrodes that place a high negative charge on the particles. Collecting electrodes or plates with the opposite charge attract the charged particles. Some precipitators have more than one stage. Electrostatic precipitators have high efficiencies, even for small particulates, and they have very little pressure drop, but they are expensive to operate compared with other devices.

Gas Collection There are both absorbing and adsorbing gas collectors. Gas passing through a liquid may react with or dissolve in the liquid. This is absorption. Some materials, like activated carbon and alumina, adsorb certain gases and vapors at the surface of the material. The adsorbing medium may hold up to half its weight in captured gases and vapors. The medium can be reactivated by heating it to drive off the captured gases and vapors. If the gases and vapors have economic value, collecting or condensing them may be desirable. The efficiency of gas collection varies somewhat with concentration of gas or vapor in the air. Another means for removing gases and vapors from air is cooling and condensation. The incoming air is cooled to form condensation and the resulting liquids are removed.

Combustion Incineration Combustion incinerators use oxidation to convert gases and vapors into less harmful material. However, not all gases and vapors end up in a harmless form. Combustion may involve direct flame or catalytic combustion. For some gases and vapors, efficiencies may reach 98%.

Selection of Air-Cleaning Devices

There are many factors to consider in selecting air-cleaning devices. Volume of air flow, concentration of contaminants, kind of contaminant and contaminant properties, temperature, pressure drop, contaminant hazards, and other things are important. National, state, and local pollution control laws affect the choice of collection device as well.

25-7 VENTILATION MEASUREMENT

There are many instruments for assessing air flow and distribution patterns of moving air.

Smoke tubes are hand-help pumps that disperse smoke or powder visible to the eye. One can watch the movement of the smoke to see what movement patterns exist in a space or near an exhaust hood. Smoke-producing candles also are useful.

Anemometers measure air velocity. Some anemometers have a small impeller moved by the air. The impeller drives a gauge that displays velocity. Another type of anemometer has a vane that moving air deflects. An indicator connected to the vane gives air velocity. Most anemometers are very directional. They must be in line with the direction of air flow for proper readings.

Heated wire, thermocouple, or thermistor anemometers measure air velocity, temperature, or static pressure. Some brands are not directional, others are directional.

A pitot tube is a tube inserted into an airstream to measure total, velocity, or static pressure. For correct readings, the mouth of the tube must be pointed against the airstream. The position varies with the pressure of interest. The tube involves a water manometer, water gage, or other readout device. Figure 25-2 illustrates a basic pitot tube.

25-8 STANDARDS

OSHA Standards

OSHA has several standards requiring ventilation. They involve ventilation for abrasive blasting, electrostatic spraying, grinding, polishing, buffing, spray finishing, spraying operations, powder coating, textiles, asbestos, and other activities. There are ventilation requirements for bulk oxygen systems, bulk plants, confined spaces, dip tanks, laundries, open surface tanks, processing buildings, sawmills, exhaust duct systems, storage rooms, and open surface and other tanks. 29 CFR 1910 contains these regulations. In 29 CFR 1926, there are ventilation regulations for tunnels and shafts, compressed air, preservative coatings, temporary heating devices, welding, and cutting.

ACGIH

A long-standing publication of the ACGIH is *Industrial Ventilation*. It is the primary reference for design of general and local exhaust ventilation systems.

Others

The American National Standards Institute, the National Fire Protection Association, and other organizations have standards on ventilation. The Mine Safety and Health Administration details requirements for ventilation of mines in 30 CFR 75.300. One can also refer to the ASHRAE Handbook[3] for standards, procedures, and design information relating to ventilation systems and associated components.

EXERCISES

1. A flanged slot hood exhausts particulates in an operation. The flow volume for the exhaust system is 10,000 ft^3/min. The hood is 6 ft wide × 1 ft long.
   - **(a)** What is the velocity at a distance 2 ft in front of the hood face?
   - **(b)** Neglecting entry losses, what is the face velocity for the hood?
   - **(c)** If the exhaust duct has a 2.5 ft diameter, what is the velocity in the duct?

2. A flexible, round, plain-opening pipe removes welding fumes. The pipe is 8 in in diameter and is positioned so the pipe face is 8 in from the welding. Assume the capture velocity produced is 200 ft/min at the point of welding.
   - **(a)** What is the flow rate in the pipe?
   - **(b)** Estimate the velocity at the face of the pipe?
3. A canopy hood hangs over an automated welding operation. The welding table and hood are both 4 ft wide and 3 ft long. The hood is 3 ft above the welding operation and the capture velocity is 200 ft/min. What flow rate is required in the hood?
4. For the following particle sizes, which type(s) of air cleaners are likely to be effective and economical?
   - **(a)** 50 μm
   - **(b)** 15 μm
   - **(c)** 1 μm
5. A solvent leaks into a production room of 125,000 ft^3. Personnel are evacuated and an exhaust fan is set up in an external doorway that is sealed with a plastic sheet with an opening just large enough for the fan. A window is opened across the room to provide make-up air. If the fan moves air at 4,000 ft^3/min and the solvent concentration is 125 ppm when the fan is turned on, how long will it take to reduce the concentration to 20 ppm? Assume a factor of safety of 3 and that no additional amount of solvent has leaked into the room and evaporated after the fan is started.
6. Investigate how different brands of home, room-type air-cleaning devices work. Compare the brands in terms of efficiencies based on the amount of air cleaned per hour and based on the size of particle collected by the device.

REVIEW QUESTIONS

1. Name three purposes for ventilation.
2. What are the two major types of ventilation for controlling airborne contaminants?
3. Name two principles that dilution ventilation systems should meet.
4. What are the main components in a local exhaust system?
5. Define the following:
   - **(a)** static pressure
   - **(b)** velocity pressure
   - **(c)** total pressure
   - **(d)** friction loss
   - **(e)** dynamic losses
   - **(f)** make up air
   - **(g)** recirculated air
   - **(h)** capture velocity
   - **(i)** face velocity
   - **(j)** duct velocity
6. Compare the velocity of air from a jet blowing into a space and the movement of air being drawn into an exhaust entry.

7. What factors should be considered in deciding if air should be recirculated?
8. What factors should be included in design of an air recirculation system when the air contains contaminants with health hazards?
9. What are the fan laws?
10. Identify four types of air cleaning devices. Describe how each works. Identify an advantage or disadvantage for each.
11. What air-cleaning devices are suitable for gases and vapors?
12. Name four devices for measuring air flow or air distribution.

NOTES

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2 *Industrial Ventilation—A Manual of Recommended Practice*, 25th ed., American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 2004.

3 *ASHRAE Handbook*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA. Volumes on fundamentals, equipment, and systems and applications are updated regularly.

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  AIHA Z9.5 Laboratory Ventilation
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  AIHA Z9.7 Recirculation of Air from Industrial Process Exhaust Systems
  ASHRAE 62 Ventilation for Acceptable Indoor Air Quality
  ASHRAE 62.2 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings
  UL 441 Gas Vents
  UL 680 Emergency Vault Ventilators and Vault-Ventilating Ports
  UL 705 Power Ventilators

National Fire Protection Association, Quincy, MA:
  NFPA 91 Exhaust Systems for Air Conveying of Gases, etc.
  NFPA 96 Ventilation Control and Fire Protection of Commercial Cooking Operations
  NFPA 211 Chimneys, Fireplaces, Vents, and Solid Fuel Burning Appliances

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