CHAPTER 33. INDUSTRIAL LOCAL EXHAUST SYSTEMS

INDUSTRIAL exhaust ventilation systems contain, collect, and remove airborne contaminants consisting of particulate matter (dusts, fumes, smokes, fibers), vapors, and gases that can create a hazardous, unhealthy, or undesirable atmosphere. Exhaust systems can also salvage usable material, improve plant housekeeping, and capture and remove excessive heat or moisture. Industrial exhaust systems must comply with ASHRAE *Standard* 62.1 and other standards as required [e.g., National Fire Protection Agency (NFPA) standards].

Special Warning: Certain industrial spaces may contain flammable, combustible and/or toxic concentrations of vapors or dusts under either normal or abnormal conditions. In spaces such as these, there are life safety issues that this chapter may not completely address. Special precautions must be taken in accordance with requirements of recognized authorities such as the National Fire Protection Association (NFPA), Occupational Safety and Health Administration (OSHA), and American National Standards Institute (ANSI). In all situations, engineers, designers, and installers who encounter conflicting codes and standards must defer to the code or standard that best addresses and safeguards life safety.

LOCAL EXHAUST VERSUS GENERAL VENTILATION

Local exhaust ventilation systems can be the most performance-effective and cost-effective method of controlling air pollutants and excessive heat. For many operations, capturing pollutants at or near their source is the only way to ensure compliance with occupational exposure limits that are measured within the worker’s breathing zone. When properly designed, local exhaust ventilation optimizes ventilation exhaust airflow, thus optimizing system acquisition costs associated with equipment size and operating costs associated with energy consumption and makeup air tempering. Chapters 2 and 3 in ACGIH (2013) also discuss this topic at length.

In some industrial ventilation designs, the emphasis is on filtering air captured by local exhausts before exhausting it to the outdoors or returning it to the production space. As a result, these systems are evaluated according to their filter efficiency or total particulate removal. However, if an insufficient percentage of emissions are captured, the degree of air-cleaning efficiency sometimes becomes irrelevant.

For a process exhaust system in the United States, the design engineer must verify if the system is permitted by the 1990 Clean Air Act. For more information, see the Environmental Protection Agency’s web site (www.epa.gov/air/caa/).

The pollutant-capturing efficiency of local ventilation systems depends on hood design, the hood’s position relative to the source of contamination, temperature of the source being exhausted, and the induced air currents generated by the exhaust airflow. Selection and positioning of the hood significantly influence initial and operating costs of both local and general ventilation systems. In addition, poorly designed and maintained local ventilation systems can cause deterioration of building structures and equipment, negative health effects, and decreased worker productivity.

No local exhaust ventilation system is 100% effective in capturing pollutants and/or excess heat. In addition, installation of local exhaust ventilation system may not be possible in some circumstances, because of the size, mobility, or mechanical interaction requirements of the process. In these situations, general ventilation is needed to dilute pollutants and/or excess heat. Where pollutants are toxic or present a health risk to workers, local exhaust is the appropriate approach, and dilution ventilation should be avoided. Air supplied by the general ventilation system is usually conditioned (heated, humidified, cooled, etc.). Supply air replaces air extracted by local and general exhaust systems and improves comfort conditions in the occupied zone.

Chapter 11 of the 2021 *ASHRAE Handbook—Fundamentals* covers definitions, particle sizes, allowable concentrations, and upper and lower explosive limits of various air contaminants. Chapter 31 of this volume, Goodfellow and Tahti (2001), and Chapter 2 of ACGIH (2013) detail steps to determine air volumes necessary to dilute contaminant concentration using general ventilations.

Sufficient makeup air must be provided to replace air removed by the exhaust system. If replacement air is insufficient, building pressure becomes negative relative to atmospheric pressure and allows air to infiltrate through open doors or window cracks, and can reverse flow through combustion equipment vents. A negative pressure as little as 0.05 in. of water can cause drafts and might cause backdrafts in combustion vents, thereby creating potential health and safety hazards. From the sustainability perspective, a negative plant static pressure can also result in excessive energy use. If workers near the plant perimeter complain about cold drafts, unit heaters are often installed. Heat from these units often is drawn into the plant interior, overheating the interior. Too often, this overheating is addressed by exhausting more air from the interior, causing increased negative pressure and more infiltration. Negative plant pressure reduces the exhaust volumetric flow rate because of increased system resistance, which can also decrease local exhaust efficiencies or require additional energy to overcome the increased resistance. Wind effects on building balance may also play a role, and are discussed in Chapter 24 of the 2021 *ASHRAE Handbook—Fundamentals*.

Positive-pressure plants and balanced plants (those with equal exhaust and replacement air rates) use less energy. However, if there are clean and contaminated zones in the same building, the desired airflow direction is from clean to dirty, and zone boundary construction and pressure differentials should be designed accordingly.

Exhaust system discharge may be regulated under various federal, state, and local air pollution control regulations or ordinances. These regulations may require exhaust air treatment before discharge to the atmosphere. Chapter 30 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* provides guidance and recommendations for discharge air treatment.

1. LOCAL EXHAUST FUNDAMENTALS

System Components

Local exhaust ventilation systems typically consist of the following basic elements:

- Hood to capture pollutants and/or excessive heat
- Ducted system to transport polluted air to air cleaning device or building exhaust
- Air-cleaning device to remove captured pollutants from the airstream for recycling or disposal
- Air-moving device (e.g., fan or high-pressure air ejector), which provides motive power to generate the hood capture velocity plus overcome exhaust ventilation system resistance
- Exhaust stack, which discharges system air to the atmosphere

System Classification

Contaminant Source Type. Knowing the process or operation is essential before a local exhaust hood system can be designed.

Hood Type. Exhaust hoods are typically round, rectangular, or slotted to accommodate the geometry of the source. Hoods are either enclosing or nonenclosing (Figure 1). **Enclosing hoods** provide more effective and economical contaminant control because their exhaust rates and the effects of room air currents are minimal compared to those for nonenclosing hoods. Hood access openings for inspection and maintenance should be as small as possible and out of the natural path of the contaminant. Hood performance (i.e., how well it captures the contaminant) should ideally be verified by an industrial hygienist.

A **nonenclosing hood** can be used if access requirements make it necessary to leave all or part of the process open. Careful attention must be paid to airflow patterns and capture velocities around the process and hood (under dynamic conditions) and to the process characteristics to make nonenclosing hoods effective. The use of moveable baffles, curtains, strip curtains, and brush seals may allow the designer to increase the level of enclosure without interfering with the work process. The more of the process that can be enclosed, the less exhaust airflow required to control the contaminant(s).

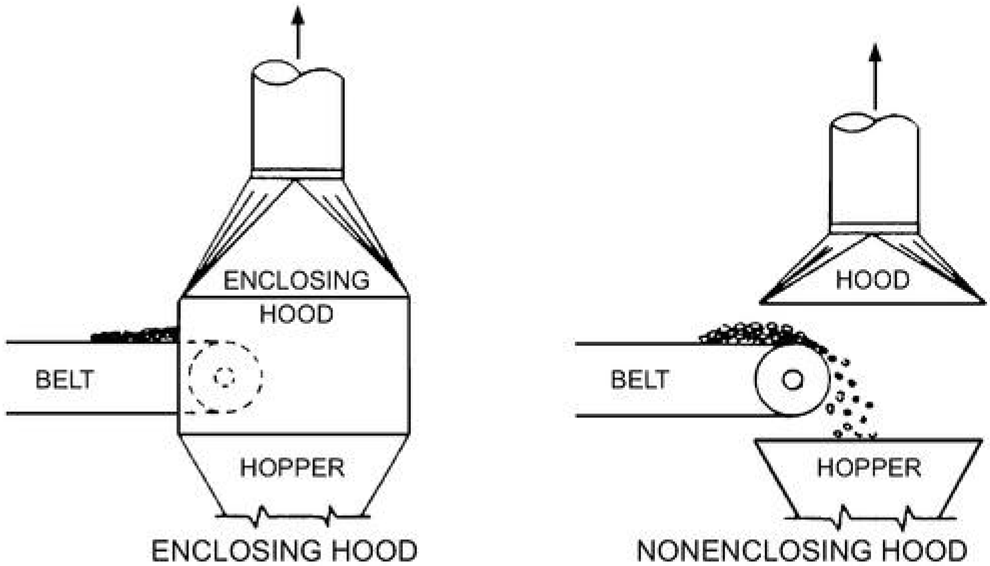

Figure 1. Enclosing and Nonenclosing Hoods (Adapted from ACGIH®, *Industrial Ventilation: A Manual of Recommended Practice*, 27th ed. Copyright 2010. Reprinted with permission.)

System Mobility. Local exhaust systems with nonenclosing hoods can be **stationary** (i.e., having a fixed hood position), **moveable, portable,** or **built-in** (into the process equipment). Moveable hoods are used when process equipment must be accessed for repair and loading and unloading of materials (e.g., in electric ovens for melting steel).

The portable exhaust system shown in Figure 2 is commonly used for temporary exhausting of fumes and solvents in confined spaces or during maintenance. It has a built-in fan and filter and an exhaust hood connected to a flexible hose. Built-in local exhaust systems are commonly used to evacuate welding fumes, such as hoods built into stationary or turnover welding tables. Lateral exhaust hoods, which exhaust air through slots on the periphery of open vessels, such as those used for galvanizing metals, are another example of built-in local exhaust systems.

Effectiveness of Local Exhaust

The most effective hood design uses the minimum exhaust airflow rate to provide maximum contaminant control without compromising operator capability to complete the work task. **Capture effectiveness** should be high, but it is difficult and costly to develop hoods with efficiencies approaching 100%. Makeup air supplied by general ventilation to replace exhausted air can dilute contaminants that are not captured by the hood. Enclosing more of the process reduces the need to protect against contaminant escape through cross drafts, convective currents, or process-generated contaminant momentum. In turn, this reduces the exhaust airflow required to control the contaminant(s).

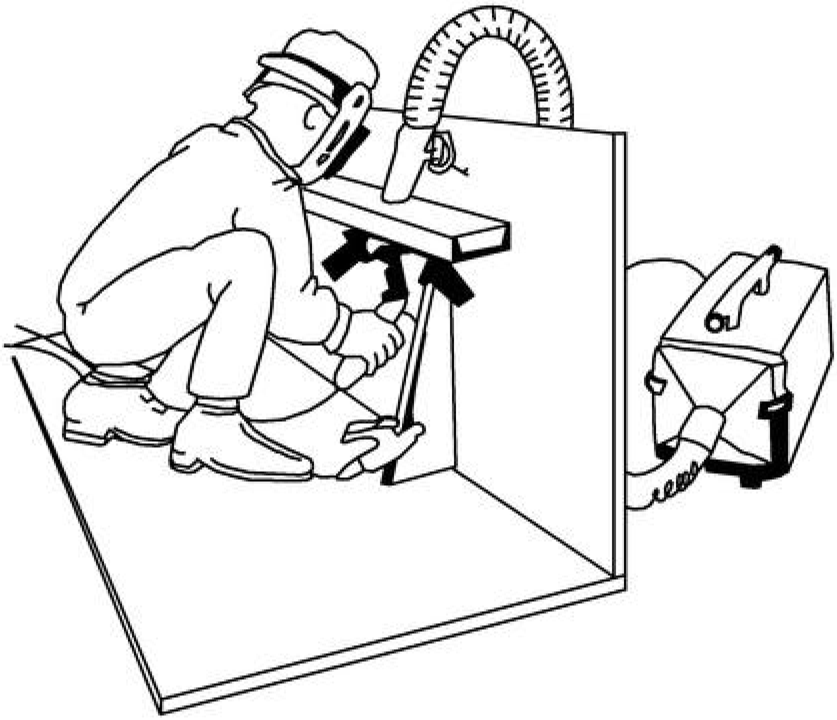

Figure 2. Portable Fume Extractor with Built-in Fan and Filter

Capture Velocity. Capture velocity is the air velocity required to entrain contaminants at the point of contaminant generation upstream of a hood. The contaminant enters the moving airstream near the point of generation and is carried along with the air into the hood. Designers use a designated capture velocity V_c to determine a volumetric flow rate to draw air into the hood. Table 1 shows ranges of capture velocities for several industrial operations. These figures are based on successful experience under ideal conditions. Once capture velocity upstream of the hood and hood position relative to the source are known, then the hood flow rate can be determined for the particular hood design. Velocity distributions for specific hoods must be known or determined.

Hood Volumetric Flow Rate. For a given hood configuration and capture velocity, the exhaust volumetric flow rate (the airflow rate that allows contaminant capture) can be calculated as

$$Q_o = V_o A_o \qquad \textbf{(1)}$$

where

Q_o = exhaust volumetric flow rate, cfm

V_o = average air velocity in hood opening that ensures capture velocity at point of contaminant release, fpm

A_o = hood opening area, ft^2

Table 1 Range of Capture (Control) Velocities

Condition of Contaminant Dispersion	Examples	Capture Velocity, fpm

Released with essentially no velocity into still air	Evaporation from tanks, degreasing, plating	50 to 100
Released at low velocity into moderately still air	Container filling, low-speed conveyor transfers, welding	100 to 200
Active generation into zone of rapid air motion	Barrel filling, chute loading of conveyors, crushing, cool shakeout	200 to 500
Released at high velocity into zone of very rapid air motion	Grinding, abrasive blasting, tumbling, hot shakeout	500 to 2000

Note: In each category above, a range of capture velocities is shown. The proper choice of values depends on several factors (Alden and Kane 1982):

Lower End of Range

1. Room air currents favorable to capture
2. Contaminants of low toxicity or of nuisance value only
3. Intermittent, low production
4. Large hood; large air mass in motion

Upper End of Range

1. Distributing room air currents
2. Contaminants of high toxicity
3. High production, heavy use
4. Small hood; local control only

Low face velocities require that supply (makeup) air be as uniformly distributed as possible to minimize the effects of room air currents. This is one reason replacement air systems must be designed with exhaust systems in mind. Air should enter the hood uniformly. Hood flanges, side baffles, and interior baffles are sometimes necessary (Figure 3).

Airflow requirements for maintaining effective capture velocity at a contaminant source also vary with the distance between the source and hood. Chapter 3 of ACGIH (2013) provides methodology for estimating airflow requirements for specific hood configurations and locations relative to the contaminant source.

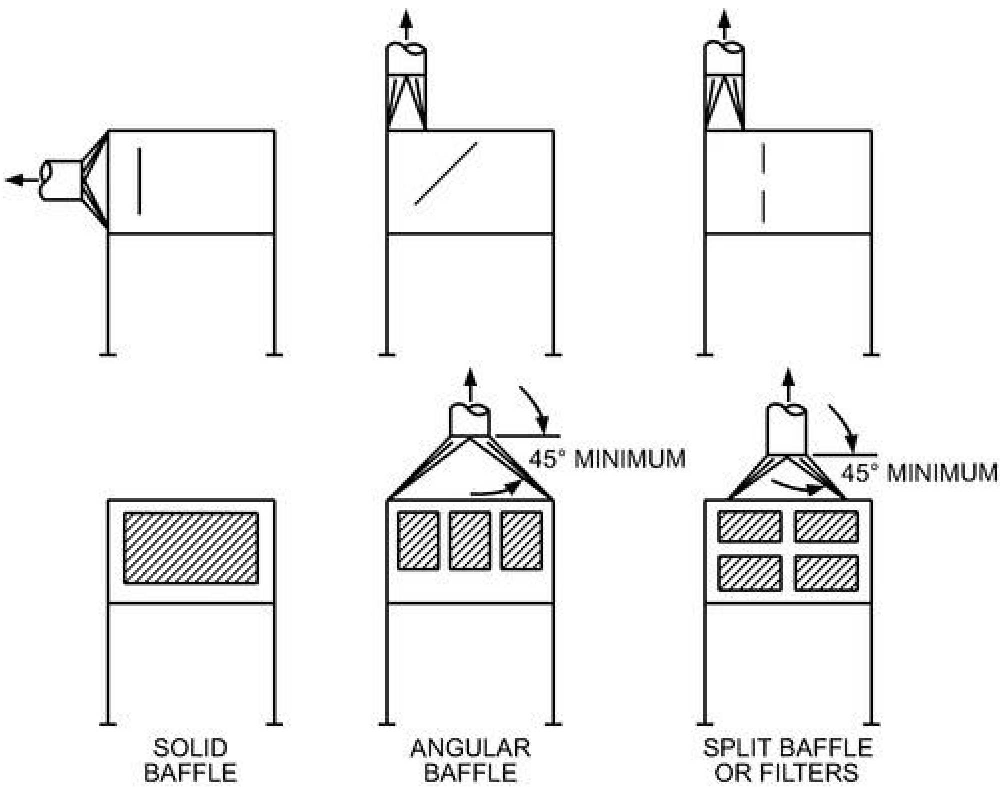

Figure 3. Use of Interior Baffles to Ensure Good Air Distribution

Airflow near the hood can be influenced by drafts from supply air jets (spot cooling jets) or by turbulence of the ambient air caused by jets, upward/downward convective flows, moving people, mobile equipment, and drafts from doors and windows. Process equipment may be another source of air movement. For example, high-speed rotating machines such as pulverizers, high-speed belt material transfer systems, falling granular materials, and escaping compressed air from pneumatic tools all produce air currents. These factors can significantly reduce the capturing effectiveness of local exhaust systems and should be accounted for in the exhaust system design.

Exhausted air may contain combustible pollutant/air mixtures. If it does, the amount by which the exhaust airflow rate should be increased to dilute combustible mixture must be verified to meet the requirements of National Fire

Protection Association (NFPA) *Standards* 86 and 329.

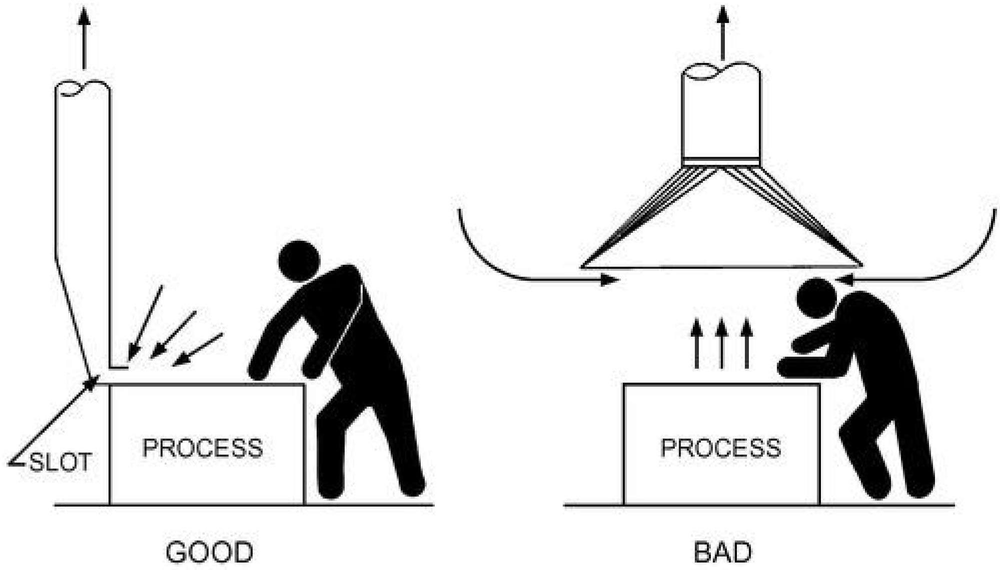

Figure 4. Influence of Hood Location on Contamination of Air in Operator's Breathing Zone (Adapted from ACGIH®, *Industrial Ventilation: A Manual of Recommended Practice*, 28th ed. Copyright 2013.)

Principles of Hood Design Optimization

Numerous studies of local exhaust systems and common practices have led to the following hood design principles:

- Hood location should be as close as possible to the source of contamination.
- The hood opening should be positioned so that it causes the contaminant to deviate the least from its natural path.
- The hood should be located so that the contaminant is drawn away from the operator's breathing zone.
- Hood size must be the same as or larger than the cross section of flow entering the hood. If the hood is smaller than the flow, a higher volumetric flow rate is required.
- Worker position with relation to contaminant source, hood design, and airflow path should be evaluated based on the principles given in Chapters 3 and 10 of ACGIH (2013).
- Canopy hoods (Figure 4) should not be used where the operator must bend over a tank or process (ACGIH 2013).

2. AIR MOVEMENT IN VICINITY OF LOCAL EXHAUST

Air capture velocities in front of the hood opening depend on the exhaust airflow rate, hood geometry, distance from hood face and surfaces surrounding the hood opening. Figure 5 shows velocity contours for an unflanged round duct hood. Studies have established the similarity of velocity contours (expressed as a percentage of the hood entrance velocity) for hoods with similar geometry (DallaValle 1952). Figure 6 shows velocity contours for a rectangular hood with an **aspect ratio** (width divided by length) of 0.333. The profiles are similar to those for the round hood but are more elongated. If the aspect ratio is lower than about 0.2 (0.15 for flanged openings), the flow pattern in front of the hood changes from approximately spherical to approximately cylindrical. Velocity decreases rapidly with distance from the hood; per DallaValle, velocity decreases on the order of 1/(distance from suction inlet squared).

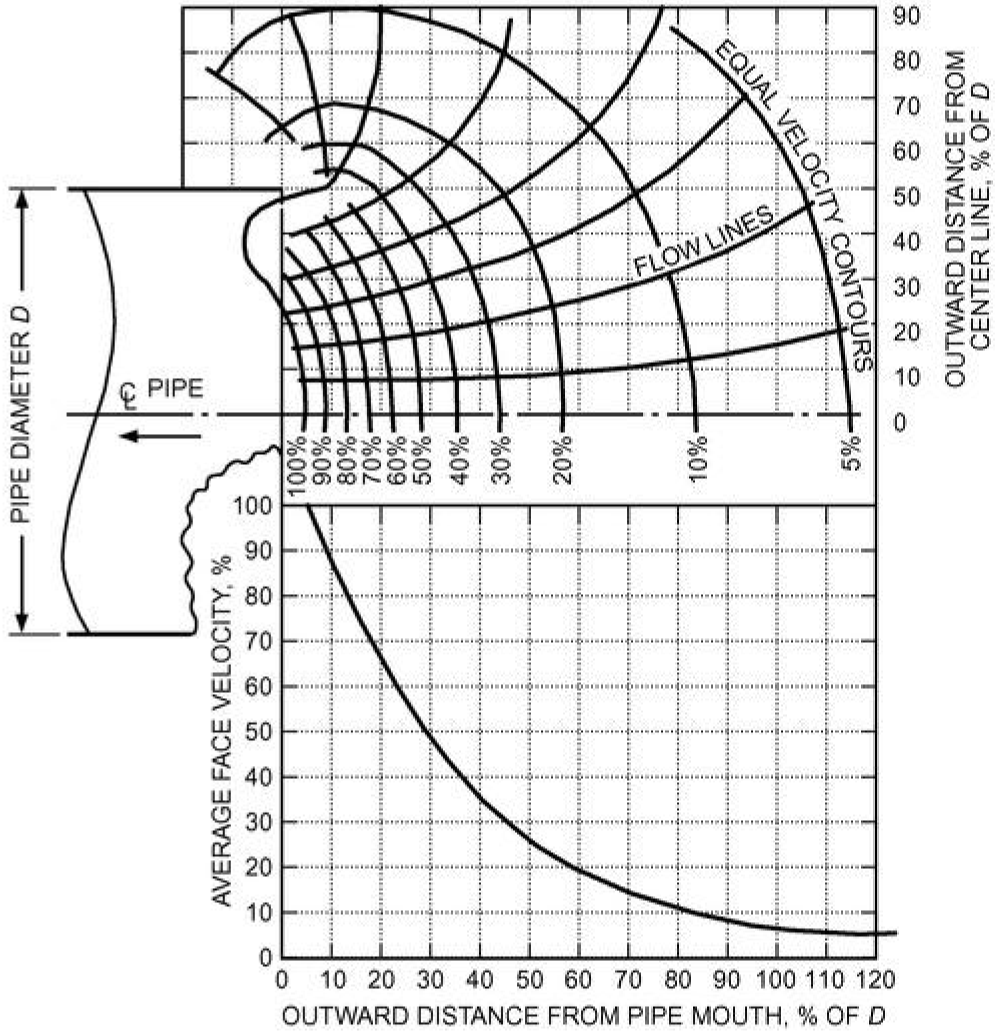

Figure 5. Velocity Contours for Plain Round Opening (Alden and Kane 1982; used by permission)

The design engineer should consider side drafts and other sources of air movement close to the capture area of a local exhaust hood. Caplan and Knutson (1977, 1978) found that air movement in front of laboratory hoods can cause contaminants to escape from the hood and into the operator's breathing zone. In industrial applications, it is common to see large fans blowing air onto workers who are located in front of an exhaust hood. This can render the local exhaust hood ineffective to the point that no protection is provided for the worker and/or their adjacent co-workers.

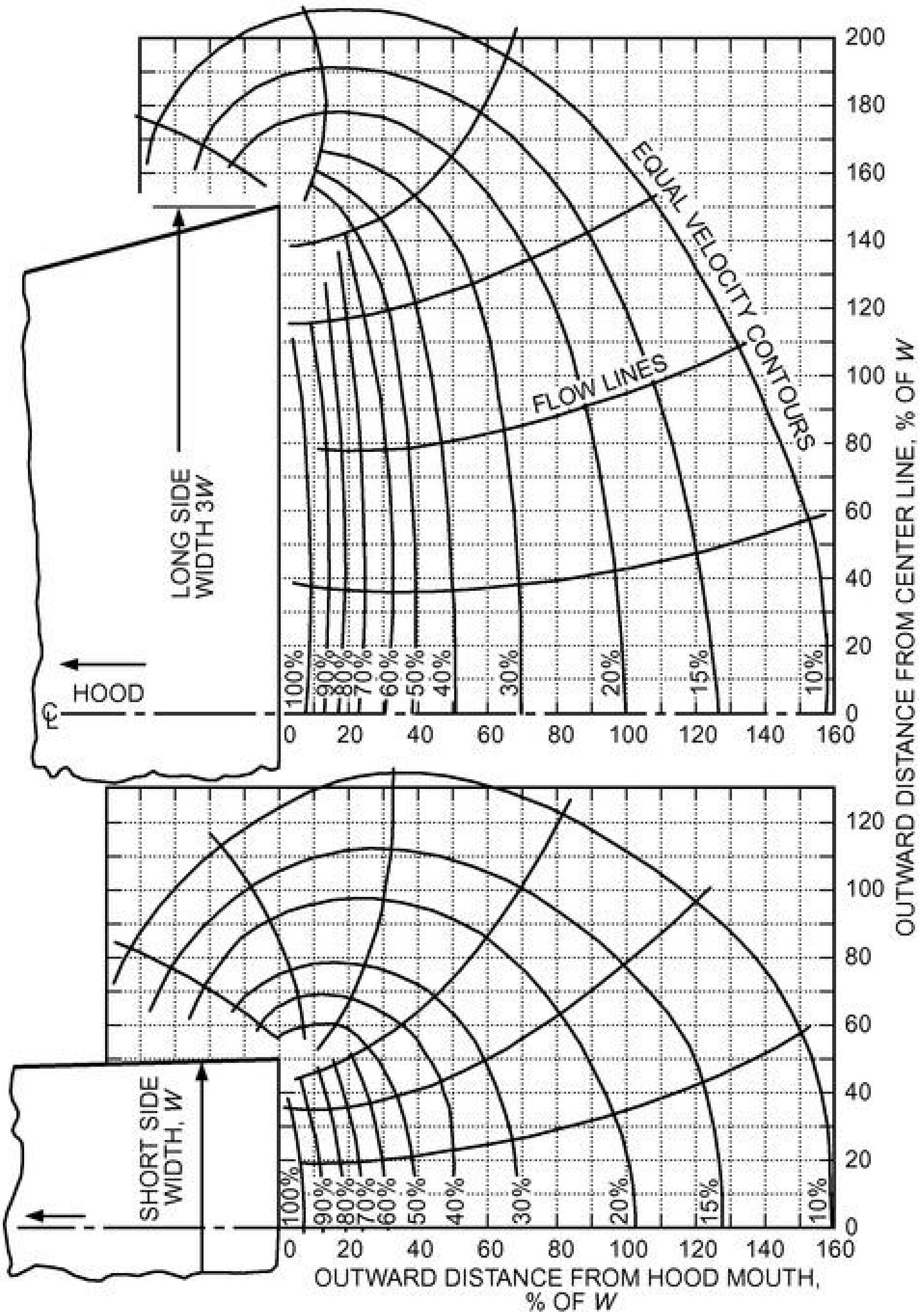

Figure 6. Velocity Contours for Plain Rectangular Opening with Sides in 1:3 Ratio (Alden and Kane 1982; used by permission)

Pressure Loss in Hoods and Ducts

A vena contracta forms in the entrance of the hood or duct and produces a pressure loss, which can be described using pressure loss coefficient C_o or a static pressure entry loss (ACGIH 2013). When air enters a hood, the pressure loss, called **hood entry loss**, may have several components, depending on the hood's complexity. Simple hoods usually have a single pressure loss coefficient C_L specified, defined as

$$C_L = \sqrt{\frac{P_v}{P_{s,h}}} \tag{2}$$

where

C_L	=	pressure loss coefficient depending on hood type and geometry, dimensionless
P_v	=	$K\rho V^2/2g_c$, dynamic pressure inside duct caused by moving airstream (constant in duct after vena contracta), where K is proportionality constant, in. of water, ρ is air density in lb/ft^3, and g_c is the gravitational acceleration constant, 32.2 $\text{lb}_m \cdot \text{ft/lb}_f \cdot \text{s}^2$
$P_{s,h}$	=	static pressure in hood duct because of velocity pressure increase and hood entry loss, in. of water

More information on loss factors and the design of exhaust ductwork is in [Chapter 21 of the 2021 *ASHRAE Handbook—Fundamentals*](), ACGIH (2013), and Brooks (2001).

The loss coefficient C_L is different from the hood entry loss coefficient. The entry loss coefficient C_o relates duct total pressure loss to duct velocity pressure. From Bernoulli's equation, hood total pressure is approximately zero at the entrance to the hood, and therefore the static pressure is equal to the negative of the velocity pressure:

$$P_s = -P_v \tag{3}$$

Static pressure in the hood/duct is the static pressure (velocity pressure) plus the head loss, which is expressed as a fraction of the velocity pressure, as

$$P_{s,h} = P_v + C_o P_v \tag{4}$$

Rearranged, the hood/duct static pressure $P_{s,h}$ (hood suction) for hoods is

$$P_{s,h} = (1 + C_o)P_v \tag{5}$$

and the change in total pressure is

$$\Delta P_t = P_{s,h} - P_v = C_o P_v \tag{6}$$

Loss coefficients C_o for various hood shapes are given in Figure 7. For tapered hoods, Figure 5 shows that the optimum hood entry angle to minimize entry loss is 45°, but this may be impractical in many situations because of the required transition length. A 90° angle, with a corresponding loss factor of 0.25 (for rectangular openings), is typical for many tapered hoods.

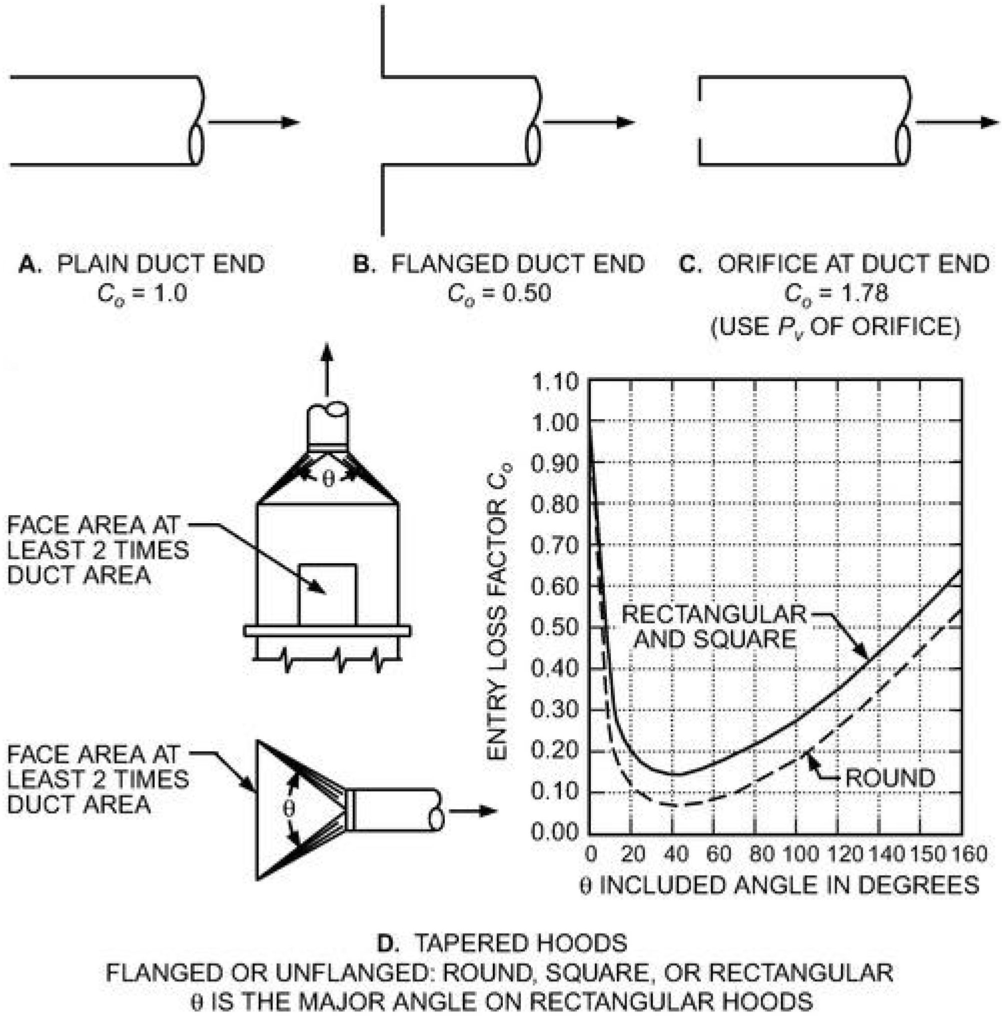

Figure 7. Entry Losses for Typical Hoods

Example 1. A nonenclosing side-draft flanged hood (Figure 8) with face dimensions of 1.5 by 4 ft rests on the bench. The required volumetric flow rate is 1560 cfm. The duct diameter is 9 in.; this gives a duct velocity of 3530 fpm. The hood is designed such that the largest angle of transition between the hood face and the duct is 90°. What is the suction pressure (static pressure) for this hood? Assume air density at 72°F.

Solution: The two transition angles cannot be equal. Whenever this is true, the larger angle is used to determine the loss factor from Figure 7. Because the transition piece originates from a rectangular opening, the curve marked "rectangular" must be used. This corresponds to a loss factor of 0.25. The duct velocity pressure is

$$P_v = \frac{\rho V^2}{2g_c} = \frac{(0.075)(3530)^2}{(2)(32.2)} \times \frac{12}{(62.4)(3600)} = 0.78 \text{ in. of water}$$

From Equation (5),

$$P_{s,h} = (1 + 0.25)(0.78) = 0.98 \text{ in. of water}$$

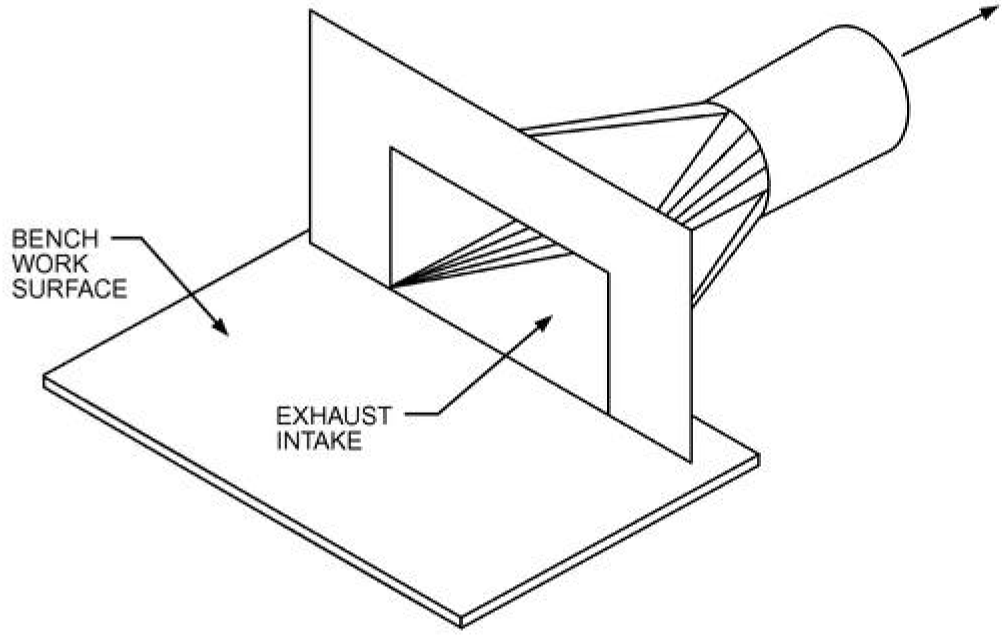

Figure 8. Hood on Bench

Compound Hoods. Losses for multislot hoods (Figure 9) or single-slot hoods with a plenum (compound hoods) must be analyzed somewhat differently. The slots distribute air over the hood face and do not influence capture efficiency. Slot velocity should be approximately 2000 fpm to provide required distribution at minimum energy cost; plenum velocities are typically 50% of slot velocities (approximately 1000 fpm). Higher velocities dissipate more energy and can cause hot spots in the face of the hood.

Losses occur when air passes through the slot and when air enters the duct. Because the velocities, and therefore the velocity pressures, can be different at the slot and at the duct entry locations, the hood suction must reflect both losses and is given by

$$P_{s,h} = P_v + (C_o P_v)_s + (C_o P_v)_d \tag{7}$$

where the first P_V is generally the higher of the two velocity pressures, s refers to the slot, and d refers to the duct entry location.

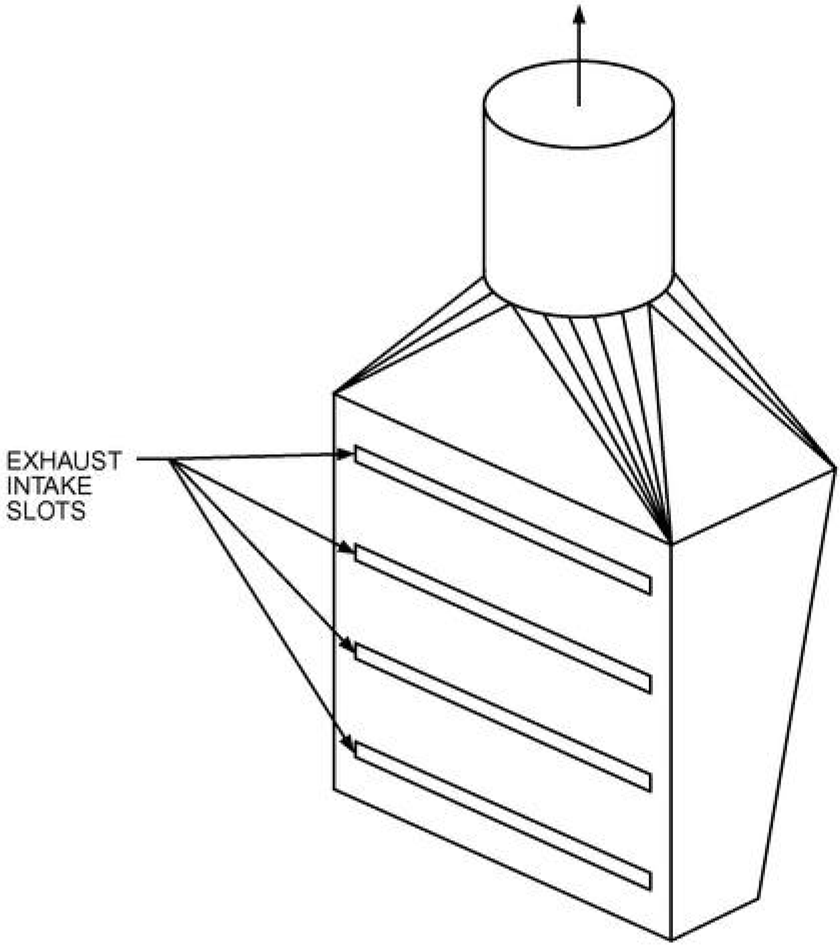

Figure 9. Multislot Nonenclosing Hood

Example 2. A multislot hood has three slots, each 1 by 40 in. At the top of the plenum is a 90° transition into the 10 in. duct. The volumetric flow rate required for this hood is 1650 cfm. Determine the hood suction (static pressure). Assume air density at 72°F.

Solution: The slot velocity V_s is

$$V_s = \frac{(1650)(144)}{(3)(40)(1)} = 1980 \text{ fpm}$$

which is near the minimum slot velocity of 2000 fpm. Substituting this velocity,

$$P_v = \frac{\rho V^2}{2g} = \frac{(0.075)(1980)^2}{(2)(32.2)} \times \frac{(12)}{(62.4)(3600)} = 0.24 \text{ in. of water}$$

The duct area is 0.5454 ft^2. Therefore, duct velocity and velocity pressure are

$$V_d = Q/A$$

$$V_d = \frac{1650}{0.5454} = 3025 \text{ fpm}$$

Substituting this velocity,

$$P_v = \frac{(0.075)(3025)^2}{(2)(32.2)} \times \frac{(12)}{(62.4)(3600)} = 0.57 \text{ in. of water}$$

For a 90° transition into the duct, the loss factor is 0.25. For the slots, the loss factor is 1.78 (Figure 7). The duct velocity pressure is added to the sum of the two losses because it is larger than the slot velocity pressure. Using Equation (7),

$$P_{s,h} = 0.57 + (1.78)(0.24) + (0.25)(0.57) = 1.14 \text{ in. of water}$$

Exhaust volume requirements, minimum duct velocities, and entry loss factors for many specific operations are given in Chapter 10 of ACGIH (2013).

Overhead Canopy Hoods

If a hot work process cannot be completely enclosed, place a canopy hood above the process so that the contaminant convectively moves toward the hood. Canopy hoods should be applied and designed with caution to avoid drawing contaminants across the operator's breathing zone (see Figure 4). The hood's height above the process should be minimized to reduce total exhaust airflow rate. Efficiencies in ventilation capture can be gained when ventilating heated processes with canopy hoods, because heated air naturally moves upward because of its reduced density (i.e., buoyancy). Canopy hoods are most effective when contaminant is released over a well-defined area, and the contaminant is entrained in the rising, buoyant plume. Room cross drafts can substantially deflect the rising plume when it is created by a low-temperature process, or when cross drafts are greater than 50 fpm between the process and the canopy inlet. When determining proper hood selection and design parameters, carefully consider process information, such as required worker access to the process, process-related material movement within the plume, and the hazard potential of the contaminants associated with the process.

Canopy hoods without side walls are the least effective and efficient method of controlling hot process plumes. The limitation of any hood design with distance between the hood face and surface of the source is the ability of cross drafts to interfere with capturing contaminants rising from the hot process. Where cross drafts greater than 50 fpm are present, hood designs should include side walls. At a minimum, one side wall should be included in the hood design on the side of the process where the cross draft originates (upstream side).

Canopy Hoods with Sidewalls

When side walls are included, or when the process is close to a structural wall, the plume may attach to the wall. In this event, the plume entrainment volume is reduced compared to that in an unbounded plume, and the resulting flow in the plume is reduced to half the flow of an unbounded plume. If there are two walls attached at a right angle, the flow is reduced to 1/4 of the unbounded plume flow (Nielsen 1993).

Low Canopy Hoods

Whenever the distance between a canopy hood and the hot source is within 3 ft or the source diameter, whichever is smaller, this hood is considered to be a low canopy hood. Its close proximity to the source does not allow sufficient time for the plume to expand; thus, the diameter or cross section of the hot air column is approximately the same as the source. Under this design scenario, the diameter or side dimensions of the hood need only be about 1 ft larger than the source diameter at its widest cross-section (Hemeon 1963, 1999). For rectangular sources, rising plumes may be better controlled if the hood shape reflects that of the source. In this circumstance, perform the hood airflow and design calculations as for a circular source, once for the length and once for the width dimensions.

High Canopy Hood Use as Redundant Control Measure

The high canopy hood without side walls is the least favorable canopy design. The design can be used as a redundant measure for controlling large-volume process plumes. High canopy hoods are not recommended as a primary control measure for heated processes, because of the large volumes of air displaced to remove pollutants from the workplace. For example, arc furnace charging has a limited duration, and restricted canopy hood use while the furnace is being charged reduces the required volume of replacement air. Ideally, high canopy hood faces without walls should be round, because rising air from point sources and compact shapes (i.e., not line sources) becomes circular in cross section as it rises (Bill and Gebhart 1975). This occurs because turbulence sweeps the plume edges inward to a minimal volume. However, it is more cost effective to manufacture and install square or rectangular hoods. Baffles are recommended at the face of rectangular canopy hoods to approximate the area of a round hood face.

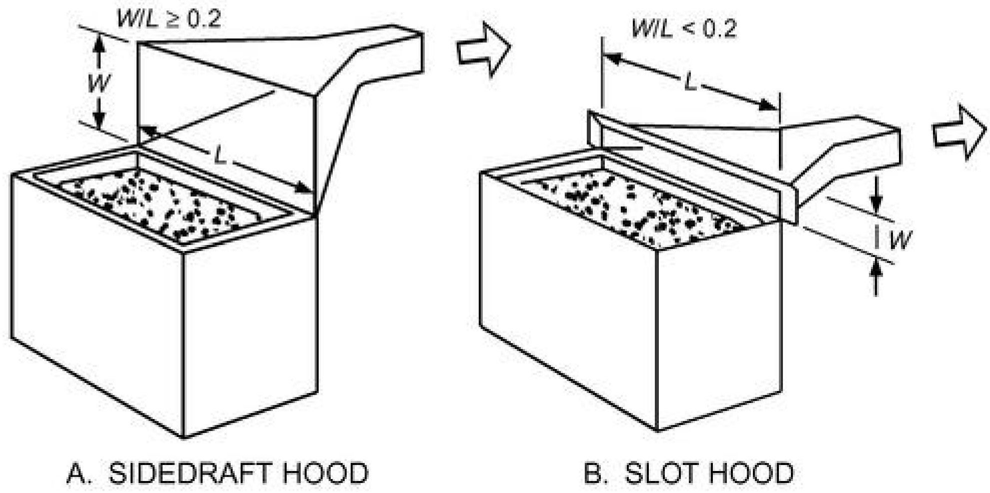

Figure 10. Sidedraft Hood and Slot Hood on Tank

Ventilation Controls for Large-Scale Hot Processes

Equations to approximate the velocity, area, and volumetric flow of rising air above a large-scale cylindrical heated process with excess air temperatures (Δt < 198°F) are available from several sources (ACGIH 2013; Goodfellow 1985; Hemeon 1963, 1999; U.S. Public Health Service 1973). These equations derive from compilation of empirical research by Hemeon and others, and are useful for traditional large-scale, high-temperature processes (e.g., arc furnaces, tapping operations).

Ventilation Controls for Small-Scale Hot Processes

New equations to approximate the velocity, area, and volumetric flow of the rising air above a small-scale heated process have been validated within a range of excess air temperatures (2°F < Δt < 54°F) (McKernan and Ellenbecker 2007; McKernan et al. 2007a, 2007b). These equations are based on modern research applicable to designing engineering controls for heated processes, as well as historic work by Hemeon and others (Goodfellow 1985; Hemeon 1963, 1999; U.S. Public Health Service 1973). They are particularly useful for approximating volumetric flow from discrete low-temperature sources. The historic equations of Hemeon and others continue to be useful for the traditional large-scale, high temperature processes (e.g., arc furnaces, tapping operations).

Sidedraft Hoods

Sidedraft hoods typically draw contaminant away from the operator's breathing zone. With a buoyant source, a sidedraft hood requires a higher exhaust volumetric flow rate than a low canopy hood. If a low canopy hood restricts the work process, a sidedraft hood may be more cost effective than a high canopy hood. Examples of sidedraft hoods include multislotted "pickling" hoods near welding benches (Figure 9) and slot hoods on tanks (Figure 10).

3. OTHER LOCAL EXHAUST SYSTEM COMPONENTS

Duct Design and Construction

Duct Considerations. The second component of a local exhaust ventilation system is the duct through which contaminated air is transported from the hood(s). Round ducts are preferred because they (1) offer more uniform velocity to resist settling of material, (2) can withstand the higher static pressures normally found in industrial exhaust systems, and (3) are easier to seal. When design limitations require rectangular or flat oval ducts, the aspect ratio (height-to-width ratio) should be as close to unity as possible.

Table 2 Contaminant Transport Velocities

Nature of Contaminant	Examples	Minimum Transport Velocity, fpm
Vapor, gases, smoke	All vapors, gases, smoke	Usually 1000 to 2000
Fumes	Welding	2000 to 2500
Very fine light dust	Cotton lint, wood flour, litho powder	2500 to 3000

Dry dusts and powders	Fine rubber dust, molding powder dust, jute lint, cotton dust, shavings (light), soap dust, leather shavings	3000 to 4000
Average industrial dust	Grinding dust, buffing lint (dry), wool jute dust (shaker waste), coffee beans, shoe dust, granite dust, silica flour, general material handling, brick cutting, clay dust, foundry (general), limestone dust, asbestos dust in textile industries	3500 to 4000
Heavy dust	Sawdust (heavy and wet), metal turnings, foundry tumbling barrels and shakeout, sandblast dust, wood blocks, hog waste, brass turnings, cast-iron boring dust, lead dust	4000 to 4500
Heavy and moist dust	Lead dust with small chips, moist cement dust, asbestos chunks from transite pipe cutting machines, buffing lint (sticky), quicklime dust	4500 and up

Source: Adapted from ACGIH (2013).

Minimum transport velocity is the velocity required to transport particles without settling. Table 2 lists some generally accepted transport velocities as a function of the nature of the contaminants (ACGIH 2013). The values listed are typically higher than theoretical and experimental values to account for (1) damage to ducts, which increases system resistance and reduces volumetric flow and duct velocity; (2) duct leakage, which tends to decrease velocity in the duct system upstream of the leak; (3) fan wheel corrosion or erosion and/or belt slippage, which could reduce fan volume; and (4) reentrainment of settled particles caused by improper operation of the exhaust system. Design velocities can be higher than minimum transport velocities but should never be significantly lower.

When particle concentrations are low, the effect on fan power is negligible. Using standard duct sizes and fittings decreases cost and delivery time. Information on available sizes and cost of nonstandard sizes can be obtained from the contractor(s).

Duct Losses. Chapter 21 of the 2021 *ASHRAE Handbook—Fundamentals* covers the basics of duct design and design of metal-working exhaust systems. Loss coefficients are found in the ASHRAE *Duct Fitting Database* CD-ROM (ASHRAE 2008).

For systems conveying particles, elbows with a centerline radius-to-diameter ratio (r/D) greater than 1.5 are the most suitable. If $r/D \le 1.5$, abrasion in dust-handling systems can reduce the life of elbows. Elbows, especially those with large diameters, are often made of seven or more gores. For converging flow fittings, a 30° entry angle is recommended to minimize energy losses and abrasion in dust-handling systems (Chapter 21 of the 2021 *ASHRAE Handbook—Fundamentals*).

Where exhaust systems handling particles must allow for a substantial increase in future capacity, required transport velocities can be maintained by providing open-end stub branches in the main duct. Air is admitted through these stub branches at the proper pressure and volumetric flow rate until the future connection is installed. Figure 11 shows such an air bleed-in. Using outside air minimizes replacement air requirements, though care must be taken to consider potential adverse effects of temperature or humidity extremes associated with the two air streams. The size of the opening can be calculated by determining the pressure drop required across the orifice from the duct calculations. Then the orifice velocity pressure can be determined from one of the following equations:

$$P_{v,o} = \frac{\Delta P_{t,o}}{C_o} \tag{8}$$

where

$P_{v,o}$ = orifice velocity pressure, in. of water

ΔT_o = total pressure to be dissipated across orifice, in. of water

C_o = orifice loss coefficient referenced to the velocity at the orifice cross-sectional area, dimensionless (see Figure 7)

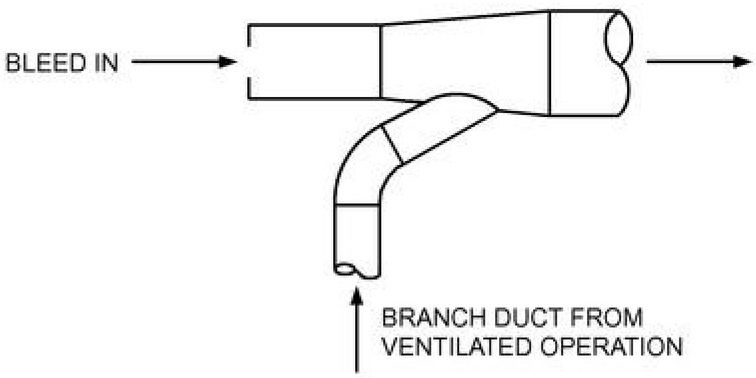

Figure 11. Air Bleed-In

Once the velocity pressure is known, orifice velocity and size can be determined.

Occasionally, a counterweighted backdraft damper or spring-loaded air admittance valve, configured to allow airflow into the duct but not out, is used as an air bleed in lieu of an orifice in systems that operate under varying airflow conditions. This ensures the proper quantity of transport airflow inside the duct, helping to eliminate material fallout and subsequent duct blockage.

Integrating Duct Segments. Most systems have more than one hood. If the pressures are not designed to be the same for merging parallel airstreams, the system adjusts to equalize pressure at the common point; however, the resulting flow rates of the two merging airstreams will not necessarily be the same as designed. As a result, the hoods can fail to control the contaminant adequately, exposing workers to potentially hazardous contaminant concentrations. Two design methods ensure that the two pressures will be equal. The preferred design self-balances without external aids. This procedure is described in the section on Industrial Exhaust System Duct Design in Chapter 21 of the 2021 *ASHRAE Handbook—Fundamentals.* The second design, which uses adjustable balance devices such as blast gates or balancing dampers, is not recommended, especially when abrasive material is conveyed.

Duct Construction. Elbows and converging flow fittings should be made of thicker material than the straight duct, especially if abrasives are conveyed. Elbows with $r/D > 2$ with replaceable wear plates (wear backs) in the heel are often used where particulate loading is extremely heavy or the particles are very abrasive. When corrosive material is present, alternatives such as special coatings or different duct materials (fibrous glass or stainless steel) can be used. Cleanout openings should be located to allow access to the duct interior in the event of a blockage. Certain contaminants may require washdown systems and/or fire detection and suppression systems to comply with safety or fire prevention codes. These requirements should be verified with local code officials and insurance underwriters. NFPA standards provide guidance on fire safety. Industrial duct construction is also described in Chapter 19 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*, and in Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) *Standard* 005-1999.

Air Cleaners

Air-cleaning equipment is usually selected to (1) conform to federal, state, or local emissions standards and regulations; (2) prevent reentrainment of contaminants to work areas; (3) reclaim usable materials; (4) allow cleaned air to recirculate to work spaces and/or processes; (5) prevent physical damage to adjacent properties; and (6) protect neighbors from contaminants.

Factors to consider when selecting air-cleaning equipment include the type of contaminant (number of components, particulate versus gaseous, moisture and heat in the airstream, and pollutant concentration), contaminant characteristics (e.g. volatility, reactivity), required contaminant removal efficiency, disposal method, and air or gas stream characteristics. Auxiliary systems such as instrument-grade compressed air, electricity, or water may be required and should be considered in equipment selection. Specific hazards such as explosions, fire, or toxicity must be considered in equipment selection, design, and location. See Chapters 29 and 30 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* for information on equipment for removing airborne contaminants. Consult an applications engineer when selecting equipment.

The cleaner's pressure loss must be added to overall system pressure calculations. In some cleaners, specifically some fabric filters, loss increases as operation time increases. System design should incorporate the maximum pressure drop of the cleaner, or hood flow rates will be lower than designed during most of the duty cycle. Also, fabric collector losses are usually given only for a clean air plenum. A reacceleration to the duct velocity, with the associated entry losses, must be calculated during design. Most other cleaners are rated flange-to-flange with reacceleration included in the loss.

Air-Moving Devices

The type of air-moving device selected depends on the type and concentration of contaminant, the pressure rise required, and allowable noise levels. Fans are usually used. Chapter 21 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* describes available fans; Air Movement and Control Association *Publication* 201 (AMCA 2002) describes proper connection of the fan(s) to the system. The fan should be located downstream of the air cleaner whenever possible to (1) reduce possible abrasion of the fan wheel blades and (2) create negative pressure within the air cleaner and the entire length of dirty duct so that air leaks into the exhaust system throughout its dirty side and control of the contaminant is maintained.

Fans handling flammable or explosive dusts should be specified as spark-resistant. AMCA provides three different spark-resistant fan construction specifications. Consult the fan manufacturer when handling these materials. Multiple NFPA standards give fire safety requirements for fans and systems handling explosive or flammable materials.

When possible, devices such as fans and pollution-control equipment should be located outside classified areas, and/or outside the building, to reduce the risk of fire or explosion.

In some instances, the fan is located upstream from the cleaner to help remove dust. This is especially true with cyclone collectors, for example, which are used in the woodworking industry. If explosive, corrosive, flammable, or sticky materials are handled, an injector (also known as an eductor) can transport the material to the air-cleaning equipment. Injectors create a shear layer that induces airflow into the duct. Injectors should be the last choice because their efficiency seldom exceeds 10%.

Energy Recovery to Increase Sustainability

Energy transfer from exhausted air to replacement air may be economically feasible, depending on the (1) location of the exhaust and replacement air ducts, (2) temperature of the exhausted gas, and (3) nature of the contaminants being exhausted. Heat transfer efficiency depends on the type of heat recovery system used.

If exhausted air contains particulate matter (e.g., dust, lint) or oil mist, the exhausted air should be filtered to prevent fouling the heat exchanger. If exhausted air contains gaseous and vaporous or volatile contaminants, such as hydrocarbons and water-soluble chemicals, their effect on the heat recovery device should be investigated. Chapter 26 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment* discusses air-to-air energy recovery systems.

When selecting energy recovery equipment for industrial exhaust systems, cross-contamination from the energy recovery device must be considered. Some types of energy recovery equipment may allow considerable cross contamination (e.g., some heat wheels) from the exhaust into the supply airstream, whereas other types (e.g., runaround coils) do not. The exhaust side of the energy recovery device should be negatively pressured compared to the supply side, so that any leakage will be from the clean side into the contaminated side. This is not acceptable for some applications. The material of the energy recovery device must be compatible with the pollutants being exhausted. If the exhaust airstream destroys the heat exchanger, contamination can enter the supply airstream and cause additional equipment damage as well as increase exposure to workers.

Exhaust Stacks

The exhaust stack must be designed and located to prevent reentraining discharged air into supply system inlets. The building's shape and surroundings determine the atmospheric airflow over it. Chapter 45 covers exhaust stack design. The typical code-required minimum stack height is intended to provide protection for workers near the stack, so discharged air is above their breathing zone. The minimum required stack height does not protect against reentrainment of contaminated exhaust into any outside air intakes.

If rain protection is important, a no-loss stack head design (ACGIH 2013; SMACNA *Standard* 005) is recommended. Weather caps deflect air downward, increasing the chance that contaminants will recirculate into air inlets, have high friction losses, and provide less rain protection than a properly designed stack head. Weather caps should never be used with a contaminated or hazardous exhaust stream.

Figure 12 contrasts flow patterns of weather caps and stack heads. Loss data for stack heads are presented in the *Duct Fitting Database* CD-ROM (ASHRAE 2008). Losses in straight-duct stack heads are balanced by the pressure regain at the expansion to the larger-diameter stack head.

Instrumentation and Controls

Some industrial exhaust systems may require positive verification of system airflow. Indicators of performance failure may require both audible and visual warning indicators. Other instrumentation, such as dust collector level indication, rotary lock valve operation, or fire detection, may be required. Selection of electronic monitoring instruments should consider durability expectations, maintenance, and calibration requirements. Interfaces may be required with the process control system or with the balance of the plant ventilation system. Electrical devices in systems conveying flammable or explosive materials or in a hazardous location may need to meet certain electrical safety and code requirements. These requirements are determined by the owner, process equipment manufacturer, federal and state regulations, local codes, and/or insurance requirements.

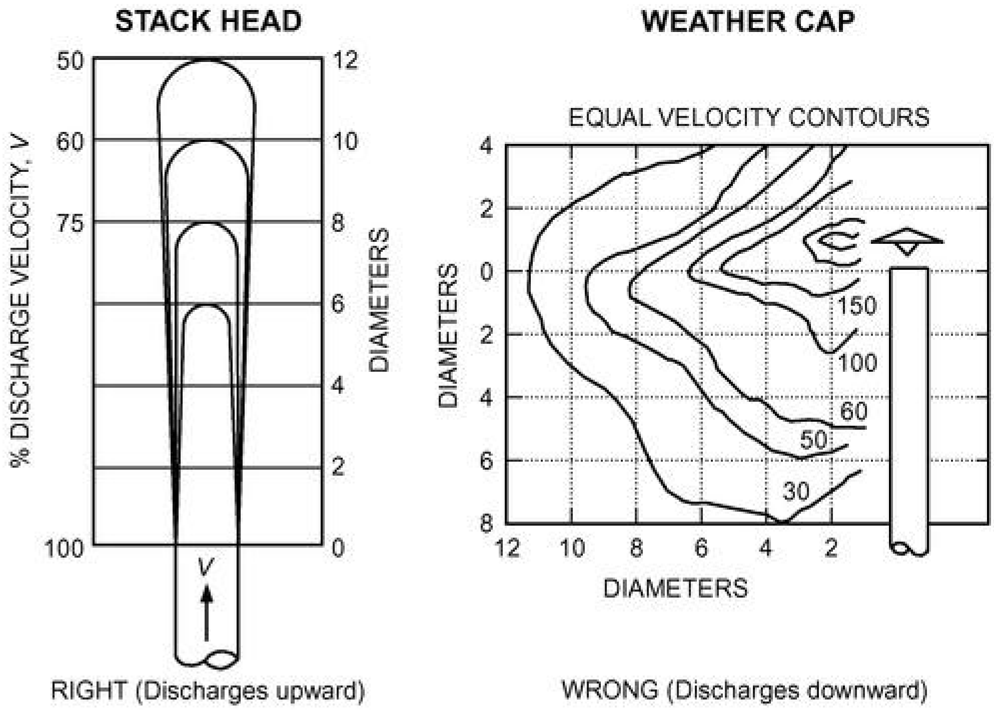

Figure 12. Comparison of Flow Pattern for Stack Heads and Weather Caps

4. OPERATION

System Testing and Balancing

After installation, an exhaust system should be tested and balanced to ensure that it operates properly, with the required flow rates through each hood. If actual flow rates are different from design values, they should be corrected before the system is used. Testing is also necessary to obtain and document baseline data to determine (1) compliance with federal, state, and local codes; (2) by periodic inspections or real-time monitoring, whether maintenance on the system is needed to ensure design operation; (3) whether a system has sufficient capacity for additional airflow; (4) whether system leakage is acceptable; and (5) compliance with testing, adjusting, and balancing (TAB) standards. AMCA (1990) and Chapter 5 of ACGIH (2007) contain detailed information on preferred methods for testing systems.

Operation and Maintenance

Periodic inspection and maintenance are required for proper operation of exhaust systems. System designers should keep this requirement in mind and account for it through the installation of clean-out/inspection doors and through strategic placement of equipment that ensures access for maintenance activities. Systems are often changed or damaged after installation, resulting in low duct velocities and/or incorrect volumetric flow rates. Low duct velocities can cause contaminants to settle and plug the duct, reducing flow rates at affected hoods. Adding hoods to an existing system can change volumetric flow at the original hoods. In both cases, changed hood volumes can increase worker exposure and health risks. The maintenance program should include (1) inspecting ductwork for particulate accumulation and damage by erosion or physical abuse, (2) checking exhaust hoods for proper volumetric flow rates and physical condition, (3) checking fan drives, (4) maintaining air-cleaning equipment according to manufacturers' guidelines, and (5) confirming that the system continues to meet compliance with worker exposure and environmental pollution requirements. These and other details are also discussed in ACGIH (2007).

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The preparation of this chapter is assigned to TC 5.8, Industrial Ventilation Systems.