Related Commercial Resources

CHAPTER 32. VENTILATION OF THE INDUSTRIAL ENVIRONMENT

INDUSTRIAL environments require ventilation to reduce exposure to excess heat and contaminants that are generated in the workplace; in some situations, cooling may also be required. Ventilation is primarily used to control excess heat, odors, and hazardous particulate and chemical contaminants. These could affect workers' health and safety or, in some cases, become combustible or flammable when allowed to accumulate above their minimum explosive concentration (MEC) or lower flammable limit (LFL) [also called the lower explosive limit (LEL)] (Cashdollar 2000). Excess heat and contaminants can best be controlled by using local exhaust systems whenever possible. Local exhaust systems capture heated air and contaminants at their source and may require lower airflows than general (dilution) ventilation. See Chapter 32 for more information on the selection and design of industrial local exhaust systems.

General ventilation can be provided by mechanical (fan) systems, by natural draft, or by a combination of the two. Combination systems could include mechanically driven (fan-driven) supply air with air pressure relief through louvers or other types of vents, and mechanical exhaust with air replacement inlet louvers and/or doors.

Mechanical (fan-driven) supply systems provide the best control and the most comfortable and uniform environment, especially when there are extremes in local climatic conditions. The systems typically consist of an inlet section, filtration section, heating and/or cooling equipment, fans, ductwork, and air diffusers for distributing air in the workplace. When toxic gases or vapors are not present and there are no aerosol contaminants associated with adverse health effects, air cleaned in the general exhaust system or in packaged air filtration units can be recirculated via a return duct. When applied appropriately, air recirculation can be a major contributor to a sustainable industrial ventilation design and may reduce heating and cooling costs.

In addition, regardless of the method selected, any positive ventilation into an industrial space should be from a source that is essentially free of any contaminants under both normal and abnormal conditions in the surrounding atmosphere. In many cases, this may require a sealed intake stack or ductwork, as opposed to a perimeter wall hood or other air intake device, wherein the source of intake should be from a point well above or beyond the veil of the hazardous space that may surround a ventilated space. Where this cannot be achieved, additional action should be undertaken (e.g., providing particulate or carbon filtration).

A general exhaust system, which removes air contaminated by gases, vapors, or particulates not captured by local exhausts, usually consists of one or more fans, plus inlets, ductwork, and air cleaners or filters. After air passes through the filters, it is either discharged outdoors, or partially recirculated within the building. The air filtration system's cleaning efficiency should conform to environmental regulations and depends on factors such as building location, background contaminant concentrations, type and toxicity of contaminants, and height and velocity of building exhaust discharge.

Many industrial ventilation systems must handle simultaneous exposures to temperature extremes and hazardous substances. In these cases, the required ventilation can be provided by a combination of local exhaust, general ventilation air supply, and general exhaust systems. The ventilation engineer must carefully analyze supply and exhaust air requirements to determine the worst case. For example, air supply makeup for hood exhaust may be insufficient to control heat exposure. It is also important to consider seasonal climatic effects on ventilation system performance, especially for natural ventilation systems. Duct material and its compatibility with the exhaust airstream is also important to consider when ventilating hazardous, abrasive, or corrosive substances.

Most importantly, if the hazardous substances are ignitable gases or dusts, all electrical components of the ventilation system should be rated for the proper electrical classification in the absence of any ventilation, regardless of their locations in the ventilation system.

In specifying acceptable chemical contaminant and heat exposure levels, the industrial hygienist or industrial hygiene engineer must consult the appropriate occupational exposure limits that apply as well as any governing standards and guidelines. The legislated limits for the maximum airborne concentration of chemical substances to which a worker may be exposed are listed as (1) maximum average exposures to which a worker may be exposed over a given work day (generally assumes an 8 to 10 h work day and a traditional 40 h work week); (2) short-term exposure limits, which are the maximum average airborne concentration to which a worker may be exposed over any 15 min period; and (3) ceiling limits, which are the maximum airborne concentration to which a worker may be exposed at any time. However, occupational exposure limits for cold, heat, and contaminants are not lines of demarcation between safe and unsafe exposures. Rather, they represent conditions to which it is believed nearly all workers may be exposed day after day without adverse and/or long-term effects. Because a small percentage of workers may be affected by occupational exposure below the regulated limits, it is prudent to design for control to the most conservative occupational exposure limits (OELs) available.

In the case of exposure to hazardous chemicals, the number of contaminant sources, their generation rates, and the effectiveness of exhaust hoods may not be known. Consequently, the ventilation engineer must rely on industrial hygiene engineering practices when designing toxic and/or hazardous chemical controls. Close cooperation among the industrial hygienist, process engineer, and ventilation engineer is required.

In the case of exposure to flammable or ignitable chemicals, the specific gravity of the contaminant source(s), their concentration, and the rating of all electrical devices in the space, along with any source or point of excessive heat, must be carefully considered to prevent possible loss of life or severe injury. As with all hazardous chemicals, cooperation of knowledgeable experts, including electrical engineers, is required.

This chapter describes principles of ventilation practice and includes other information on industrial hygiene in the industrial environment. Publications from the American Industrial Hygiene Association (AIHA 2011), British Occupational Hygiene Society (BOHS 2002), U.S. Department of Health and Human Services (DHHS 1986), National Safety Council (2012), and U.S. National Institute for Occupational Safety and Health (NIOSH 1986) provide further information on industrial hygiene principles and their application.

1. VENTILATION DESIGN PRINCIPLES

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), the Occupational Safety and Health Administration (OSHA), and the 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.

General Ventilation

General ventilation supplies and/or exhausts air to provide heat relief, dilute contaminants to an acceptable level, and replace exhaust air. Ventilation can be provided by natural or mechanical supply and/or exhaust systems. Industrial areas must comply with ASHRAE *Standard* 62.1-2013 and other standards as required (e.g., by NFPA). Outdoor air is unacceptable for ventilation if it is known to contain any contaminant at a concentration above that given in ASHRAE *Standard* 62.1. If air is thought to contain any contaminant not listed in the standard, consult relevant federal, state, provincial, or local jurisdictions for acceptable exposure levels. In addition to their role in controlling industrial contaminants, general ventilation rates must be sufficient to dilute the carbon dioxide produced by occupants to a level acceptable under ASHRAE *Standard* 62.2.

For complex industrial ventilation problems, experimental scale models and computational fluid dynamics (CFD) models are often used in addition to field testing.

Makeup Air

When large volumes of air are exhausted to provide acceptable comfort and safety for personnel and acceptable conditions for process operations, this air must be replaced, either through intentional design strategy or through paths of least resistance. A safe and effective ventilation design should be strategic about the mechanism, locations, and physical parameters by which makeup air enters the occupied space. Makeup air, consistently provided by good air distribution, allows more effective cooling in the summer and more efficient and effective heating in the winter. When makeup air design is not incorporated into the ventilation design scheme, it may lead to inefficient operation of local exhaust systems and/or combustion equipment and cross-drafts that affect occupant comfort and environmental control settings. Relying on windows or other air inlets that cannot function in year-round weather conditions is discouraged. Some factors to consider in designs for makeup air include

- Makeup air must be sufficient to replace air being exhausted or consumed by combustion processes, local and general exhaust systems (see Chapter 32), or process equipment. (Large air compressors can consume a large amount of air and should be considered if air is drawn from within the building.)
- Makeup air systems should be designed to eliminate uncomfortable cross-drafts by properly arranging supply air outlets, and to prevent infiltration (through doors, windows, and similar openings) that may make hoods unsafe or ineffective, defeat environmental control, bring in or stir up dust, or adversely affect processes by producing temperature or airflow disturbances. The design engineer needs to consider side drafts and other sources of air movement close to the capture area of a local exhaust hood. In industrial applications, it is common to see large fans blowing air onto workers positioned in front of the hood. This can render the local exhaust hood ineffective to the point that no protection is provided for the worker: Ahn et al. (2008), Caplan and Knutson (1977, 1978), and Tseng et al. (2010) found that air movement in front of laboratory hoods can cause contaminants to escape from the hood and into the operator's breathing zone. Hoods should be located safe distances from doors and openable windows, supply air diffusers, and areas of high personnel traffic (AIHA *Standard* Z9.5; NFPA *Standard* 45).

- Makeup air should be obtained from a clean source with no more than trace amounts of any airborne contaminants or hazardous, ignitable substances. Supply air can be filtered, but infiltration air cannot. For transfer air use, see ASHRAE *Standard* 62.1.
- Makeup air for spaces contaminated by toxic, ignitable, or combustible chemicals may have to be acquired through carefully sealed ductwork from an area known to be free of contamination and be supplied at sufficient rates, pressures, and mixing efficiencies to (1) remove all contamination, and (2) prevent infiltration of similar contaminants from surrounding areas or adjacent spaces.
- Makeup air should be used to control building pressure and airflow from space to space to (1) avoid positive or negative pressures that make it difficult or unsafe to open doors, (2) minimize drafts, and (3) prevent infiltration.
- Makeup air should be used to reduce contaminant concentration, to control temperature and humidity, and minimize undesirable air movement.
- Makeup air systems should be designed to recover heat and conserve energy (see the section on Energy Conservation, Recovery, and Sustainability).

For more information on potential adverse conditions caused by specific negative pressure levels in buildings, see ACGIH (2013) and Chapter 28 in the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*.

2. GENERAL COMFORT AND DILUTION VENTILATION

Effective air diffusion in ventilated rooms and the proper quantity of conditioned air are essential for creating an acceptable working environment, removing contaminants, and reducing installation and operating costs of a ventilation system. Ventilation systems must supply air at the proper velocity and temperature, with resulting contaminant concentrations within permissible occupational exposure limits (OELs). For the industrial environment, the most common objective is to provide tolerable (acceptable) working conditions rather than comfort (optimal) conditions.

General ventilation system design is based on the assumption that local exhaust ventilation, radiation shielding, and equipment insulation and encapsulation have been selected to minimize both heat load and contamination in the workplace (see the section on Heat Control). When work operations are generally restricted, such as with equipment operating stations or control booths, spot conditioning of the work environment with clean conditioned air (see the section on Makeup Air) may further reduce the reliance on general ventilation for conditioning or contaminant dilution. In cold climates, infiltration and heat loss through the building envelope may need to be minimized by pressurizing buildings.

For more information on dilution ventilation, see ACGIH (2013).

Quantity of Supplied Air

Sufficient air must be supplied to replace air exhausted by process ventilation and local exhausts, dilute contaminants (gases, vapors, or airborne particles) not captured by local exhausts, prevent the entry of contaminants or hazardous (ignitable) substances from any surrounding atmosphere during ingress or egress, and provide the required thermal environment. The amount of supplied air should be the largest of the amounts needed for temperature control, dilution, and replacement.

Air Supply Methods

Air supply to industrial spaces can be by natural or mechanical ventilation systems. Although natural ventilation systems driven by gravity forces and/or wind effect are still widely used in industrial spaces (especially in hot premises in cold and moderate climates), they are inefficient in large buildings, may cause drafts, and may not sufficiently solve air contamination problems, because the prerequisite environmental conditions may not be available during all required periods of need or there is no practical filtration method available. Thus, most ventilation systems in industrial spaces are either mechanical (fan-driven) or a combination of mechanical supply with natural exhaust, using louvers or doors for air pressure relief (or for air replacement in exhaust systems).

The most common methods of air supply to industrial spaces are mixing, displacement, and localized.

Mixing Air Distribution. In mixing systems, air is normally supplied at velocities much greater than those acceptable in the occupied zone. Supply air temperature can be above, below, or equal to the air temperature in the occupied zone, depending on the heating/cooling load. The supply air diffuser jet mixes with room air by entrainment, which reduces air velocities and equalizes the air temperature. The occupied zone is ventilated either directly by the air jet or by reverse flow created by the jet. Properly selected and designed mixing air distribution creates relatively uniform air velocity, temperature, humidity, and air quality conditions in the occupied zone and over the room height. Note that supply systems should introduce air into the workspace in such a way as to not interfere with contaminant control systems such as ventilation hoods. If possible, ventilation hoods (e.g., fume hoods) should have quiescent air conditions (~0.5 m/s) at their face.

Displacement Ventilation Systems. Conditioned air that is slightly cooler than the desired room air temperature in the occupied zone is supplied from air outlets at low air velocities (~0.5 m/s or less). Because of buoyancy, the cooler air spreads along the floor and floods the room's lower zone. Air close to the heat source is heated and rises upward as a convective air stream; in the upper zone, this stream spreads along the ceiling. The height of the lower zone depends on the air volume and temperature supplied to the occupied zone and on the amount of convective heat discharged by the sources.

Typically, outlets are located at or near the floor, and supply air is introduced directly into the occupied zone. In some applications (e.g., in computer rooms or hot industrial buildings), air may be supplied to the occupied zone through a raised floor. Exhaust or air returns are located at or close to the ceiling or roof.

Displacement ventilation is common in European countries. It is an option when contaminants are released in combination with surplus heat, and contaminated air is warmer (more buoyant) than the surrounding air. It is not a good choice when air turbulence can interfere with convective conveyance of heat and contaminants. Further information on displacement air distribution systems can be found in Chen and Glicksman (2003) and Goodfellow and Tahti (2001).

Localized Ventilation. Air is supplied locally for occupied regions or a few permanent work areas (Figure 1). Conditioned air is supplied toward the occupants' breathing zone to create comfortable conditions and/or to reduce the concentration of pollutants. These zones may have air that is cleaner than the surrounding air, and should generally be compliant with ASHRAE *Standard* 62.1. In localized ventilation systems, air is supplied through one of the following devices:

- Nozzles or grilles (e.g., for spot cooling), specially designed low-velocity/low-turbulence devices
- Perforated panels suspended on vertical duct drops and positioned close to the workstation

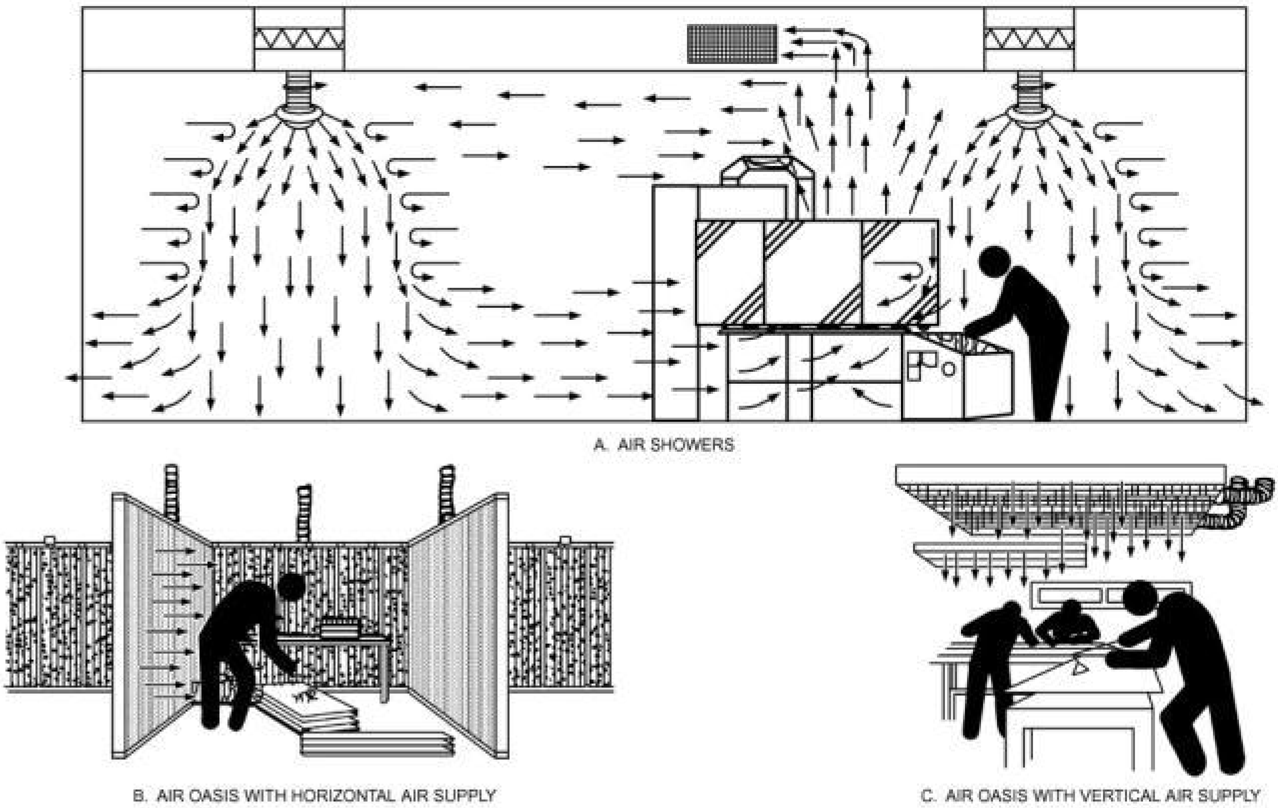

Figure 1. Localized Ventilation Systems

Local Area and Spot Cooling

In hot workplaces that have few work areas, it is likely impractical to maintain a comfortable environment in the entire space. However, environmentally controlled cabins, individual cooling, and spot cooling and extraction can improve working conditions in occupied areas. Certain applications require minimum distances from supplied air (and natural ventilation points) to ensure airflow in ventilated hoods and cabinets is not affected.

Environmentally controlled cabins (e.g., operating cabs, pulpits, control rooms, enclosures) can provide thermal comfort, and, when pressurized with a dedicated clean-air supply (either dedicated source or through effective filtration), can improve air quality in occupational environments. There usually are significant economic benefits to properly designing, installing, and maintaining worker-protective environmental enclosures.

Spot cooling, probably the most popular method of improving the thermal environment, can be provided by radiation (changing mean radiant temperature), convection (changing air velocity and/or air supply temperatures), or both. Spot-cooling equipment is fixed at the workstation, whereas in **individual cooling**, the worker wears the equipment.

Local exhaust ventilation (spot extraction) is another method to remove excess heat from a process or source of high temperature, and should be the first step considered for energy saving over spot cooling.

Locker Room, Toilet, and Shower Space Ventilation

Ventilation of locker rooms, toilets, and shower spaces is important in industrial facilities to remove odor and reduce humidity. In some industries, control of workroom contamination requires prevention of both ingestion and inhalation routes of exposure, so adequate hygienic facilities, including appropriate ventilation, may be required in locker rooms, changing rooms, showers, lunchrooms, and break rooms. State, provincial, and local regulations should be consulted early in design.

Supply air may be introduced through doors or wall grilles. In some cases, workplace air may be so contaminated that filtration or a dedicated source of clean supply air is required. When control of workroom contaminants is inadequate or not feasible, reduce employee exposure by positively pressurizing locker rooms, lunchrooms, and break rooms to minimize the level of contamination in those areas. Treated supply air may be ineffective in some applications because it can introduce drafts and outdoor contamination or result in excessive condensation in a humid indoor environment.

When mechanical ventilation of supply air is used, the supply system should have adequate ducting and air distribution devices, such as diffusers or grilles, to distribute air throughout the area.

In locker rooms, take exhaust primarily from the toilet and shower spaces as needed and secondarily from the lockers. Exhausting from the room's open ceiling areas should be a last option. ASHRAE *Standard* 62.1 and many local mechanical codes provide requirements for these areas.

Roof Ventilators

Roof ventilators are heat escape ports located high in a building and should be properly enclosed for weathertightness (Goodfellow 1985). Stack effect and some wind induction are the motive forces for gravity- (buoyancy-) driven operation of continuous and round ventilators. Round ventilators can be equipped with a fan barrel and motor, allowing gravity or forced ventilation operation.

Many ventilator designs are available, including the **low ventilator**, which consists of a stack fan with a rain hood, and a **ventilator with a split butterfly closure** that floats open to discharge air and closes by a counterweight. Both use minimum enclosures and have little or no gravity capacity. Split butterfly dampers tend to increase fan airflow noise and are subject to damage from slamming during strong winds. Because noise is frequently a problem in powered roof ventilators, the manufacturer's sound rating should be reviewed. Sound attenuators should be installed where required to meet the design sound ratings.

Continuous ventilation monitors remove substantial, concentrated heat loads most effectively. One type, the **streamlined continuous ventilator**, is efficient, weathertight, and designed to prevent backdraft; it usually has dampers that may be closed in winter to conserve building heat. Its capacity is limited only by the available roof area and the proper location and sizing of low-level air inlets. Continuous ventilation to achieve a slight pressure above the surrounding atmosphere (referred to as **pressurization** by NFPA) also can be used to reduce or declassify the electrical classification of enclosed spaces. Typically, reductions from class I, zone 1 or division 1 to class I, zone 2 or division 2 can be achieved by following the recommendations of NFPA *Standard* 496. This allows using general-purpose electrical devices instead of zone 2 or division 2 devices, or using zone 2 or division 2 electrical devices instead of zone 1 or division 1 devices, which (1) greatly reduces the cost of electrical equipment and (2) provides a sound alternative when particular devices are not available for the higher (more volatile) electrical area classifications.

Gravity ventilators, also highly effective, have low operating costs, do not generate noise, and are self-regulating (i.e., higher heat release increases airflow through the ventilators). Gravity ventilators can be affected by environmental conditions and thus should only be used for heat control rather than for the control of gaseous or aerosol contaminants. Care must be taken to ensure positive pressure at the ventilators, particularly during the heating season. Otherwise, outside air will enter the ventilators.

Next in order of heat removal capacity are (1) round gravity or wind-band ventilators, (2) round gravity ventilators with fan and motor added, (3) low-hood powered ventilators, and (4) vertical upblast powered ventilators. The shroud for the vertical upblast design has a peripheral baffle to deflect air upward instead of downward. Vertical discharge is highly desirable to reduce roof damage caused by hot air if it contains condensable oil or solvent vapor. Ventilators with direct-connected motors are desirable to avoid belt maintenance. Round gravity ventilators are applicable for warehouses with light heat loads and for manufacturing areas with high roofs and light loads.

Streamlined continuous ventilators must operate effectively without mechanical power. To ensure ventilator performance, sufficient low-level openings must be provided for incoming air; insufficient inlet area and significant space air currents are the most common reasons gravity roof ventilators malfunction. A positive supply of air around hot equipment may be necessary in large buildings where external wall inlets are remote from the equipment. Chapter 16 of the 2021 *ASHRAE Handbook—Fundamentals* has additional information on ventilation and infiltration.

The cost of electrical power for mechanical ventilation over that of roof ventilators can be offset by the advantage of constant airflow. Mechanical ventilation can also create the pressure differential necessary for good airflow, even with small inlets. Inlets should be sized correctly to avoid infiltration and other problems caused by high negative pressure in the building. Often, a mechanical system is justified to supply enough makeup air to maintain the work area under positive pressure.

Roof ventilators can comprise either mechanically operated openings or fan-powered mechanical exhaust. Operator-assisted openings or dampers are usually used in shops with high ceilings, and must be installed when natural ventilation is used to provide air to the space.

3. HEAT CONTROL

Ventilation control alone may frequently be inadequate for meeting heat stress standards for industrial work areas. Optimum solutions may involve additional controls such as spot cooling, changes in work/rest patterns, and radiation shielding.

Ventilation for Heat Relief

Many industrial processes release large amounts of heat and moisture to the environment. In such environments, it may not be economically feasible to maintain comfort conditions (ASHRAE *Standard* 55), particularly during summer. Comfortable conditions are not physiologically necessary: the body must be in thermal balance with the environment, but this can occur at temperature and humidity conditions well above the normal comfort zone. In areas where heat and moisture generated by a process are low to moderate, comfort conditions may not have to be provided if personnel exposures are infrequent and brief. In such cases, ventilation may be the only control necessary to prevent excessive physiological heat stress.

The engineer must distinguish between control needs for hot/dry industrial areas and warm/moist conditions. In hot/dry areas, a process gives off only sensible (primarily convective and radiant) heat without adding moisture to the air. This increases the heat load on exposed workers, but the rate of cooling by evaporation of perspiration may not be significantly reduced. Body heat equilibrium may be maintained, but could cause excessive perspiration. Hot/dry work situations occur around furnaces, forges, metal-extruding and rolling mills, glass-forming machines, etc.

In warm/moist conditions, a wet process may generate a significant latent heat load. The rise in sensible heat load on workers may be insignificant, but the increased moisture content of the air can seriously reduce cooling by evaporation of perspiration, making warm/moist conditions potentially more hazardous than hot/dry. Typical warm/moist operations are found in textile mills, laundries, dye houses, and deep mines, where water is used extensively for dust control.

Industrial heat load is also affected by local climate. Solar heat gain and elevated outdoor temperatures increase the heat load at the workplace, but may be insignificant compared to process heat generated locally. The moisture content of outdoor air is an important factor that can affect hot/dry work situations by restricting an individual's evaporative cooling. For warm/moist working environments, solar heat gain and elevated outdoor temperatures are even more important because moisture contributed by outdoor air is insignificant compared to that released by the process.

Both ASHRAE *Standard* 55 and International Organization for Standardization (ISO) *Standard* 7730 specify thermal comfort conditions.

Methods for evaluating the general thermal state of the body both in comfort conditions and under heat and cold stress are based on analysis of the heat balance for the human body, as discussed in Chapter 9 of the 2021 *ASHRAE Handbook—Fundamentals*. A person may find the thermal environment unacceptable or intolerable because of local effects on the body caused by asymmetric radiation, air velocity, vertical air temperature differences, or contact with hot or cold surfaces (floors, machinery, tools, etc.).

Heat Stress—Thermal Standards

Another heat stress indicator for evaluating an environment's heat stress potential is the **wet-bulb globe temperature** (WBGT), defined as follows:

Outdoors with solar load

$$\mathrm{WBGT} = 0.7t_{nwb} + 0.2t_g + 0.1t_{db} \tag{1}$$

Indoors, or outdoors with no solar load

$$\mathrm{WBGT} = 0.7t_{nwb} + 0.3t_g \tag{2}$$

where

t_{nwb} = naturally ventilated wet-bulb temperature (no defined range of air velocity; different from saturation temperature or psychrometric wet-bulb temperature), °C

t_g = globe temperature (Vernon bulb thermometer, 150 mm diameter), °C

t_{db} = dry-bulb temperature (sensor shaded from solar radiation), °C

Coefficients in Equations (1) and (2) represent the fractional contributions of the component temperatures.

Exposure limits for heat stress for different levels of physical activity are shown in Figure 2 (NIOSH 1986), which depicts the allowable work regime (in terms of rest periods and work periods each hour) for different levels of work over a range of WBGT. When applying Figure 2, assume that the rest area has the same WBGT as the work area. The curves are valid for workers acclimatized to heat. ASHRAE *Standard* 62.1 provides some metabolic rates for different activities that can be used with Figure 2. Refer to NIOSH (1986) for recommended WBGT limits for nonacclimatized workers.

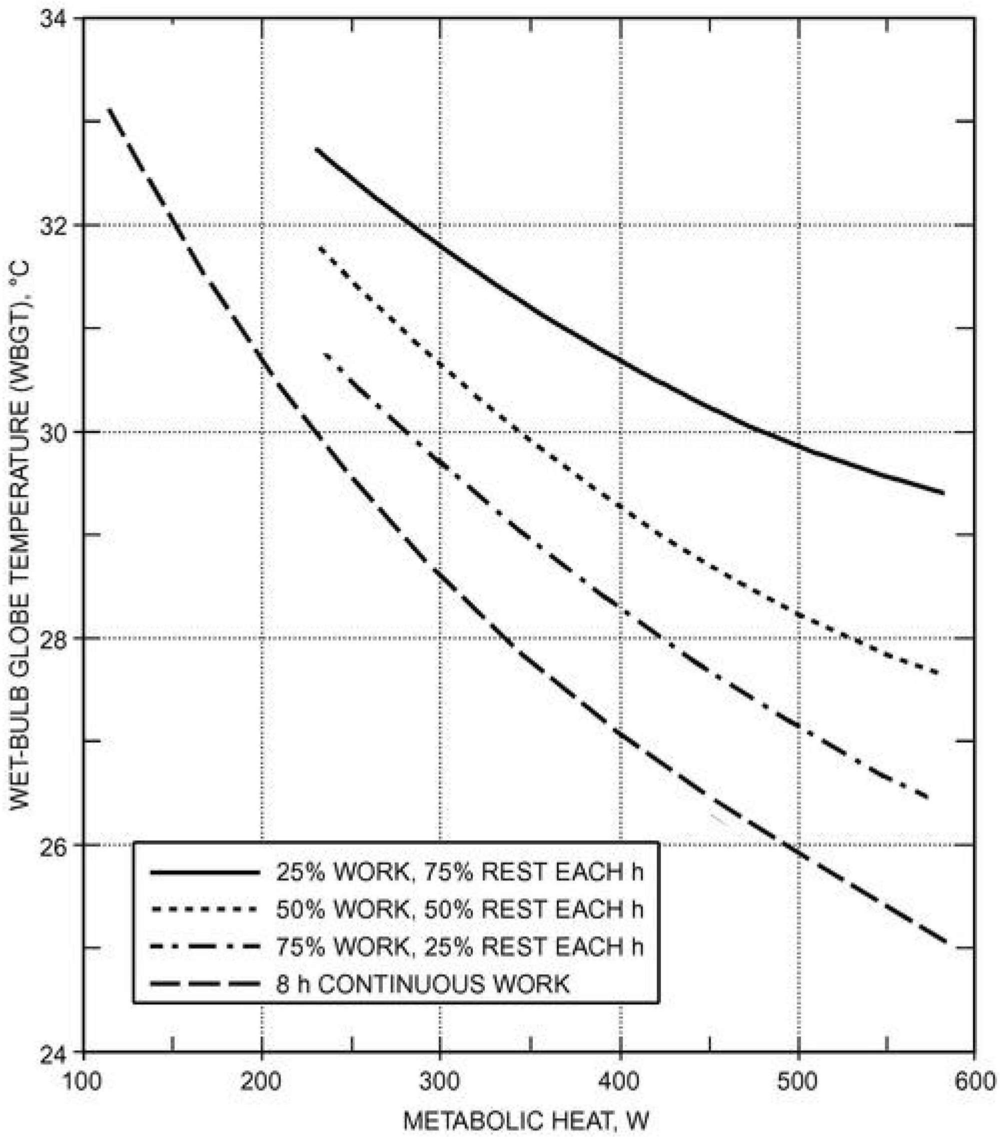

Figure 2. Recommended Heat Stress Exposure Limits for Heat-Acclimatized Workers (Adapted from NIOSH [1986])

The **WBGT index** is an international standard (ISO *Standards* 7243, 7730, and 7933) for evaluating hot environments. The WBGT index and activity levels should be evaluated on 1 h mean values; that is, WBGT and activity are measured and estimated as time-weighted averages on a 1 h basis for continuous work, or on a 2 h basis when exposure is intermittent. Although recommended by NIOSH, the WBGT has not been accepted as the sole legal standard by the Occupational Safety and Health Administration (OSHA), and it may not apply for non-U.S. jurisdictions. The WBGT is generally used in conjunction with other methods to determine heat stress.

Although Figure 2 is useful for evaluating heat stress exposure limits, it is of limited use for control purposes or for evaluation of comfort. Air velocity and psychrometric wet-bulb measurements are usually needed to specify proper controls, and are only measured indirectly in WBGT determinations. Information on other useful tools, including the heat stress index (HSI), can be found in Chapter 9 of the 2021 *ASHRAE Handbook—Fundamentals* and in ISO *Standards* 7243, 7730, and 7933.

The thermal relationship between humans and their environment is determined by four independent environmental variables:

- Air temperature

- Radiant temperatures
- Moisture content of the air
- Air velocity

Together with the rate of internal heat production (metabolic rate) and clothing variables, these factors may combine in various ways to create different degrees of heat stress. The HSI is defined as the percent of the skin that is wetted by perspiration:

$$\mathrm{HSI} = E_{sk}/E_{max} \times 100 \qquad (3)$$

where

E_{sk} = evaporative heat loss from the skin, W/m^2

E_{max} = maximum possible evaporative heat loss from the skin, W/m^2

and incorporates relative contributions of metabolism, radiant heat gain (or loss), convective heat gain (or loss), and evaporative (perspiration) heat gain (or loss). For supplemental information on evaluation and control of heat stress using methods such as reduction of radiation, changes in work/rest pattern, spot cooling, and cooling vests and suits, refer to ACGIH (2013), Brief et al. (1983), Caplan (1980), NIOSH (1986), and Ontario MOL (2009).

Heat Exposure Control

Control at Source. Heat exposure can be reduced by providing sufficient insulation to hot equipment or locating it outdoors or in zones with general or local exhaust ventilation, covering steaming water tanks, providing covered drains for direct removal of hot water, and maintaining tight joints and valves where steam may escape.

Local Exhaust Ventilation. Local exhaust ventilation removes heated air generated by a hot process and/or gases emitted by process equipment, while removing a minimum of air from the surrounding space. Local exhaust systems, including heat exposure control using overhead canopy hoods, are discussed in detail in Chapter 32 and McKernan et al. (2014).

Radiation Shielding. In some industries, the major environmental heat load is radiant heat from hot objects and surfaces, such as furnaces, ovens, furnace flues and stacks, boilers, molten metal, hot ingots, castings, and forgings. Because air temperature has no significant effect on radiant heat flow, ventilation is of little help in controlling such exposure. The only effective control is to reduce the amount of radiant heat impinging on the workers by insulating or placing radiation shields around the source.

Radiation shields are effective in the following forms:

- **Reflective shielding**. Sheets of reflective material or insulating board are temporarily attached to the hot equipment or arranged in a semiportable floor stand.
- **Absorptive shielding (water-cooled)**. These shields absorb and remove heat from hot equipment.
- **Transparent shields**. Heat-reflective tempered plate glass, reflective metal chain curtains, and close-mesh wire screens moderate radiation without obstructing the view of hot equipment.
- **Flexible shielding**. Aluminum-treated fabrics give a high degree of radiation shielding.
- **Protective clothing**. Reflective garments such as aprons, gauntlet gloves, and face shields provide moderate radiation shielding. For extreme radiation exposures, complete suits with vortex tube cooling may be required.

If the shield is a good reflector, it remains relatively cool in severe radiant heat. Bright or highly polished tinplate, stainless steel, and ordinary flat or corrugated aluminum sheets are efficient and durable. Foil-faced plasterboard, although less durable, reflects well on one side. To be efficient, however, the reflective shield must remain bright. Radiation shields are much more efficient when used in multiple layers; they should reflect the radiant heat back to the primary source, where the resulting hot gases can be removed by local exhaust. However, unless the shield completely surrounds the primary source, some infrared energy is reflected into the cooler surroundings and possibly into an occupied area. The direction of reflected heat should be studied to ensure proper shielding installation.

Spot Cooling. If the workplace is located near a source of radiant heat that cannot be entirely controlled by radiation shielding, spot cooling can be used. See Chapter 20 in the 2021 *ASHRAE Handbook—Fundamentals* and data from spot-cooling diffuser manufacturers for further information.

4. ENERGY CONSERVATION, RECOVERY, AND SUSTAINABILITY

Because of the large air volumes required to ventilate industrial plants, energy conservation and recovery should be practiced, and can provide substantial savings if this practice does not compromise overriding life safety concerns. Therefore, after all critical life safety issues have been adequately addressed, energy recovery should be incorporated into preliminary planning for an industrial plant wherever and whenever it is both safe and practical to deploy. When selecting energy recovery equipment, ensure that materials are compatible with all contaminants and hazardous substances that may be exhausted. Verify the acceptability of the energy recovery method with local codes.

In some cases, it is possible to provide unheated or partially heated makeup air to the building. Although most energy conservation and recovery methods in this section apply to heating, the savings possible with cooling systems are similar. The following are some methods of energy conservation and recovery:

- In the original design phase, process and equipment insulation and heat shields should be provided to minimize heat loads. Vaporproofing and reducing the glass area may be required. Exhaust requirements for hoods and processes should be reviewed and kept to a practical, safe minimum; for more on local exhaust systems, see Chapter 32.
- Design the supply and exhaust general ventilation systems for optimal operation throughout the year. Provide air as close to the occupied zone as possible without affecting exhaust operation. Clean, recirculated air can be used in winter makeup if it does not increase the levels of contamination in the space (see the following bullet points for more details and restrictions) (ACGIH 2013). Supply and exhaust systems may be interlocked together to avoid overpressurization of the space by the supply unit if intermittent extracts are used.
- Supply air can be passed through air-to-air, liquid-to-air, or hot-gas-to-air heat exchangers to recover building or process heat. Rotary, regenerative, coil energy recovery (runaround), and air-to-air heat exchangers are discussed extensively in Chapters 25 and 26 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*. Energy recovery is also discussed in Chapters 5 and 11 of ACGIH (2013).
- Operate the system for economy if this does not compromise life safety. Although CO_2-based demand control ventilation (DCV) is unsuitable for industrial spaces where human activity is not the main reason for ventilating the space (DOE 2004), industrial spaces may offer their own kind of demand control ventilation for providing makeup air to offset process and exhaust hood exhaust volumes. If the space does not contain a potential source of toxic contaminants or hazardous (ignitable) substances, shut such systems down at night, on weekends, or whenever possible, and operate makeup air in balance with the needs of process equipment and exhaust hoods. Keep heating supply air temperatures at the minimum, and cooling supply temperatures at the maximum, consistent with process needs and employee comfort. Keep the building in pressure balance so that uncomfortable drafts do not necessitate excessive heating. Increase the deadband/control limits
- If the exhaust air has contaminants that do not pose an unacceptable health risk, and does not contain a potential source of hazardous (ignitable) substances, then recirculation can be considered. However, even then, contaminant concentrations in recirculated air must be determined so that allowable limits in the space are not exceeded. As recirculated air returns to the space, the concentration of contaminants in the partially filtered return air adds to the contaminant levels already existing in the space. It must be determined whether the concentration increases beyond the allowable time-weighted average (TWA) exposure limit during the period for which the worker is exposed. This period is usually assumed to be 8 h for an 8 h work shift, but could be any period of exposure. Once installed, real-time or periodic monitoring is likely required to support this determination. Depending on the contaminant's toxicity, the monitoring system may be required to perform some form of corrective action or shut down once a target level (a percentage of the safe exposure limit) concentration is attained. Predicted energy cost savings from recirculation should be weighed against the necessary costs of air cleaning and monitoring requirements (to include calibration and maintenance of monitoring equipment).

Assuming equilibrium has been established, the predicted TWA concentration at the workers' breathing zone can be calculated (ACGIH 2013):

$$C_B = \frac{Q_B}{Q_A}(C_G - C_M)(1-f) + (C_O - C_M)f + K_B C_R + (1-K_B)C_M \quad (4)$$

where

C_B	=	TWA worker breathing zone contaminant concentration during recirculation, ppm
Q_B	=	total ventilation airflow without considering recirculation, m^3/s
Q_A	=	total ventilation airflow including recirculation, m^3/s
C_G	=	average space concentration if no recirculation, ppm
f	=	fraction of time worker spends at workstation
C_O	=	TWA contaminant concentration at breathing zone of workstation if no recirculation, ppm
K_B	=	fraction of worker breathing zone air that consists of recirculated air, 0 to 1.0
C_R	=	recirculated air (after air cleaner) discharge concentration, ppm, or

$$C_R = \frac{(1-\eta)(C_E - K_R C_M)}{1-(1-\eta)K_R} \quad (5)$$

η	=	fractional air cleaner efficiency for contaminant
C_E	=	(local) exhaust concentration without recirculation, ppm
K_R	=	fraction of exhaust air that is recirculated air, 0 to 1.0
C_M	=	replacement air contaminant concentration, ppm

Other recirculation system examples are given in Chapter 8 of Goodfellow and Tahti (2001).

Example 1. An industrial space uses 4.7 m^3/s for ventilation, of which 2.35 m^3/s is general exhaust and 2.35 m^3/s local exhaust (ACGIH 2013). Local exhaust is recirculated through an air cleaner with an efficiency of 0.75. Recirculated air is directed toward the worker spaces, such that K_B = 0.5 and K_R = 0.8 (more of the recirculated air is locally exhausted than enters the worker's breathing zone). The worker is at the workstation 100% of the time (f = 1). The makeup air has a concentration of 5 ppm (C_M), the local exhaust has a concentration of 500 ppm (C_E), the space has an average concentration of 20 ppm (C_G), and without recirculation the worker's breathing zone is 35 ppm (C_O).

Solution: The concentration C_B at the breathing zone with recirculation is determined from

$$C_R = \frac{(1-0.75)[500-0.8(5)]}{1-(1-0.75)(0.8)} = 155 \text{ ppm}$$

and

$$C_B = \frac{4.7}{2.35}(20-5)(1-1) + (35-5)(1) + 0.5(155) + (1-0.5)5 = 110 \text{ ppm}$$

which may or may not exceed the allowable TWA exposure limit of the worker space, depending on the specific contaminant.

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