CHAPTER 29

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 that could affect the health and safety of industrial workers. Control of excess heat and contaminants can best be accomplished by using local exhaust systems whenever possible. Local exhaust systems exhaust heated air and contaminants at the source of the heat and contaminants and may require lower airflows than general (dilution) ventilation. Chapter 30, Industrial Local Exhaust Systems, supplements this chapter.

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 supply systems (fan-driven 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, a filter, heating and/or cooling equipment, fans, ductwork, and air diffusers for distributing air within the workplace. When toxic gases or vapors are not present, air cleaned in the general exhaust system or in free-hanging filter units can be recirculated via a return duct. Air recirculation can reduce heating and cooling costs.

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 an air cleaner or filters. After air passes through the filters, the cleaned air is either discharged outside or partially recirculated to the building workplace. The cleaning efficiency of an air filter system should conform to environmental regulations and depends on factors such as building location, background contaminant concentrations in the atmosphere, nature of the contaminants, and height and velocity of the building exhaust discharge.

Many industrial ventilation systems must handle simultaneous exposures to heat 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.

In specifying acceptable chemical contaminant and heat exposure levels, the industrial hygienist or industrial hygiene engineer must consult the appropriate governing standards and guidelines. The standard levels for most chemical and heat exposures are time-weighted averages that allow excursions above the limit as long as they are balanced by equivalent excursions below the limit during the workday. However, exposure level standards for 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 effects (ACGIH 2001a). Because a small percentage of workers may be overly stressed at exposure levels below the standards, it is prudent to design for exposure levels below the limits.

In the case of exposure to toxic 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 common ventilation industrial hygiene practice when designing toxic chemical controls. Close cooperation among the industrial hygienist, process engineer, and ventilation engineer is required.

This chapter describes principles of ventilation practice and includes other information on hygiene in the industrial environment. Publications from the U.S. National Institute for Occupational Safety and Health (NIOSH 1986), the British Occupational Hygiene Society (1987), the National Safety Council (1988), and the U.S. Department of Health and Human Services (1986) provide further information on industrial hygiene principles and their application.

VENTILATION DESIGN PRINCIPLES

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. Outdoor air is unacceptable for ventilation if it is known to contain any contaminant at a concentration above that given in ASHRAE *Standard* 62. If air is thought to contain any contaminant not listed in the standard, guidance on acceptable exposure levels should be obtained from OSHA Standards (ACGIH 2001a). General ventilation rates must be high enough to dilute the carbon dioxide produced by occupants.

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

Need for Makeup Air

For safe, effective operation, most industrial plants require makeup air to replace the large volumes of air exhausted to provide acceptable comfort and safety for personnel and acceptable conditions for process operations. Makeup air, consistently provided by good air distribution, allows more effective cooling in the summer and more efficient and effective heating in the winter. Installing windows or other inlets that cannot function in stormy weather is discouraged. Some factors to consider in makeup air design include the following:

- Makeup air must be sufficient to replace air being exhausted through combustion processes and local and general exhaust systems (see Chapter 30).

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

- Makeup air systems should be designed to eliminate uncomfortable crossdrafts 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 cooling or disturbances.
- Makeup air should be obtained from the cleanest source. Supply air can be filtered, but infiltration air cannot.
- 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) to minimize drafts, and (3) to prevent infiltration.
- Makeup air should be used to confine contaminants and reduce their concentration and to control temperature, humidity, and air movement.
- Makeup air systems should be designed to recover heat and conserve energy (see the section on Energy Conservation and Recovery).

ACGIH (2001b) provides information on adverse conditions that may result from specific negative pressure levels in buildings.

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, for removing contaminants, and for reducing the initial and operating costs of a ventilation system. Ventilation systems must supply air at the proper speed and temperature, with contaminant concentrations within permissible limits. In most cases, the 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 in Industrial Work Areas). In cold climates, infiltration and heat loss through the building envelope may need to be minimized.

For more information on dilution ventilation, see ACGIH (2001b).

Quantity of Supplied Air

Sufficient air must be supplied to replace air exhausted by process ventilation and local exhausts, to dilute contaminants (gases, vapors, or airborne particles) not captured by local exhausts, and to 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 solve air pollution problems. Thus, most ventilation systems in industrial spaces are either mechanical or a combination of mechanical supply with natural exhaust. 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 to the space 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.

Displacement Ventilation Systems. Conditioned air 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 lower zone of the room. 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 false floor. Exhaust or air returns are located at or close to the ceiling or roof.

Displacement ventilation has become common in Scandinavia and is becoming popular in other European countries. Displacement ventilation is an option when contaminants are released in combination with surplus heat, and contaminated air is warmer (more buoyant) than the surrounding air. Further information on displacement air distribution systems can be found in 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 breathing zone of the occupants to create comfortable conditions and/or to reduce the concentration of pollutants. These zones may have air 5 to 10 times cleaner than the surrounding air. 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

Local Area and Spot Cooling

In hot workplaces that have only few work areas, it is likely impractical and energy-inefficient to maintain a comfortable environment in the entire space. However, air-conditioned cabins, individual cooling, and spot cooling can improve working conditions in occupied areas.

Air-conditioned cabins can provide thermal comfort. Control rooms for monitoring production and manufacturing processes can use this technology.

Spot cooling, probably the most popular method of improving the thermal environment, can be provided by radiation (changing the mean radiant temperature), by convection (changing the 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.

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, adequate control of workroom contamination requires prevention of both ingestion and inhalation, so adequate hygienic facilities, including appropriate ventilation, may be required in locker rooms, changing rooms, showers, lunchrooms, and break rooms. State and local regulations should be consulted early in design.

Supply air may be introduced through doors or wall grilles. In some cases, plant air may be so contaminated that filtration or (preferably) mechanical ventilation may be required. When control of workroom contaminants is inadequate or not feasible, minimizing the level of contamination in the locker rooms, lunchrooms, and

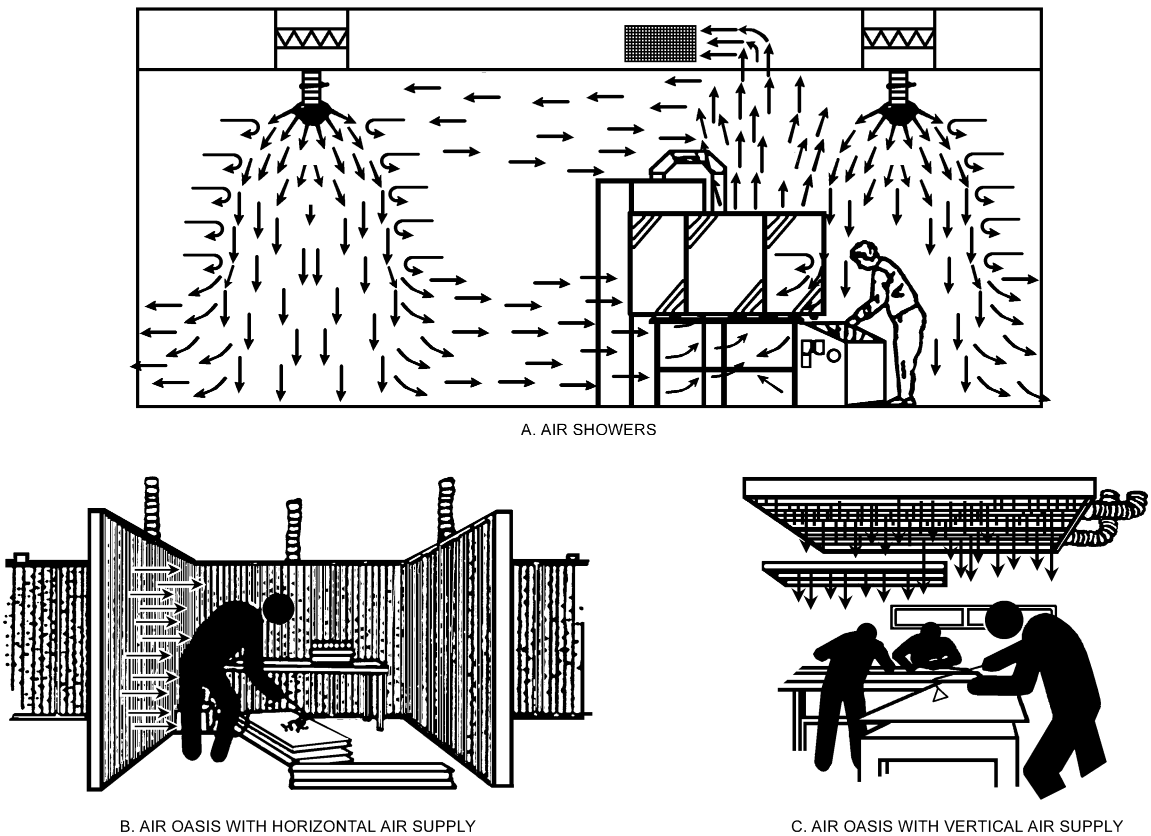

Fig. 1 Localized Ventilation Systems

Table 1 Ventilation for Locker Rooms, Toilets, and Shower Spaces

Description of Space	Ventilation
Locker Rooms	
Coat hanging or clean changing room for nonlaboring shift employees with clean work clothes	5 L/(s·m^2)
Changing room for laboring employees with wet or sweaty clothes	10 L/(s·m^2); 3 L/s exhausted from each locker
Changing room for laborers or workers assigned to heavy work; clothes will be wet or pick up odors	15 L/(s·m^2); 5 L/s exhausted from each locker
Toilet Spaces	10 L/(s·m^2); at least 12 L/s per toilet facility; 95 L/s minimum
Shower Spaces	10 L/(s·m^2); at least 24 L/s per shower head; 95 L/s minimum

Note: The source of this table is unknown. Nevertheless, the information has been used with apparent success for many years (*ASHRAE Guide and Data Book* 1970). Also refer to Article 16 of the BOCA *National Building Code* and ASHRAE *Standard* 62.

break rooms by pressurizing these areas with excess supply air can reduce employee exposure.

When mechanical ventilation 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, exhaust should be taken primarily from the toilet and shower spaces as needed, and the remainder from the lockers and the room ceiling. In the absence of specific codes, Table 1 provides a guide for ventilation of these spaces. ASHRAE *Standard* 62-2001, Ventilation for Acceptable Indoor Air Quality, provides additional guidance in this area.

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, permitting 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 wind conditions. Because noise is frequently a problem in powered roof ventilators, the manufacturer's sound rating should be reviewed.

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. **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). Care must be taken to ensure that positive pressure exists at the ventilators. Otherwise, outside air will enter the ventilators. This is of particular importance during the heating season.

Next according to their heat removal capacity are (1) round gravity or windband 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 the 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 on units in difficult locations. 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 26 of the 2001 *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.

HEAT CONTROL IN INDUSTRIAL WORK AREAS

Ventilation control alone may frequently be inadequate for meeting heat stress standards. 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 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 possibly at the expense of 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 the 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 the 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 conditions, solar heat gain and elevated outdoor temperatures are 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 for humans.

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 8 of the 2001 *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 diam.), °C

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

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. Table 1 provides some metabolic rates for different activities (2001 *ASHRAE Handbook—Fundamentals*) that can be used with Figure 2. Refer to NIOSH (1986) for recommended WBGT limits for non-acclimatized workers.

The **WBGT index** is an international standard (ISO *Standards* 7730 and 7243) 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 a legal standard by the Occupational Safety and Health Administration (OSHA). It 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 8 of the 2001 *ASHRAE Handbook—Fundamentals* and in ISO *Standards* 7730, 7243, and 7933.

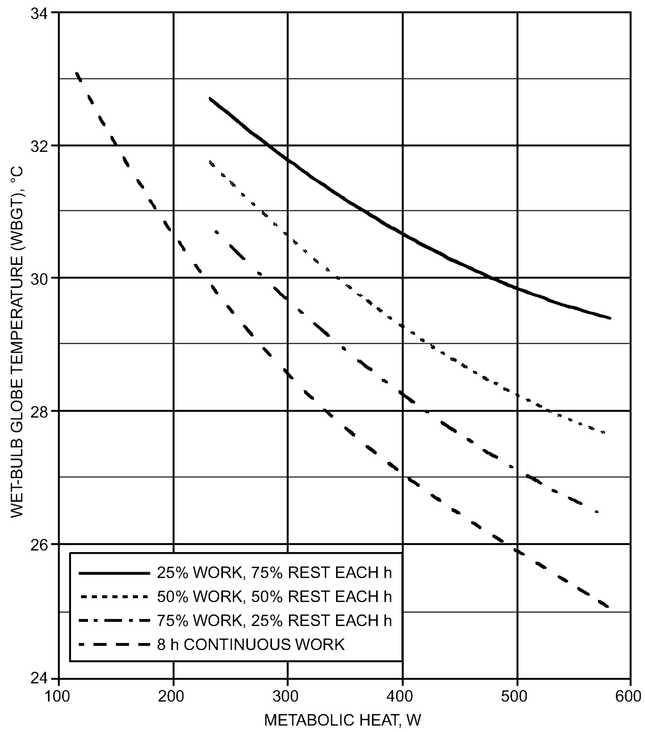

Fig. 2 Recommended Heat Stress Exposure Limits for Heat-Acclimatized Workers
[Adapted from NIOSH (1986)]

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

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

Together with the rate of internal heat production (metabolic rate), 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:

$$\text{HSI} = E_{sk}/E_{max} \times 100 \tag{3}$$

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 such methods as reduction of radiation, changes in work/rest pattern, spot cooling, and cooling vests and suits, refer to ACGIH (2001b), Brief et al. (1983), Caplan (1980), and NIOSH (1986).

Heat Exposure Control

Control at Source. Heat exposure can be reduced by insulating hot equipment or locating it in zones with good general ventilation or outdoors, 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 nonbuoyant gases emitted by process equipment, while removing a minimum of air from the surrounding space. Local exhaust systems are discussed in detail in Chapter 30.

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. Radiant heat exposure can be reduced 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 will remain 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 it can be removed by local exhaust. However, unless the shield completely surrounds the primary source, some of the infrared energy will be reflected into the cooler surroundings and possibly into an occupied area. The direction of the reflected heat should be studied to ensure proper installation of the shielding.

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 32 in the 2001 *ASHRAE Handbook—Fundamentals* and data from spot-cooling diffuser manufacturers for further information.

ENERGY CONSERVATION AND RECOVERY

Because of the large air volumes required to ventilate industrial plants, energy conservation and recovery should be practiced and will provide substantial savings; it should be incorporated into preliminary planning for an industrial plant.

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 30.
- Design the supply and exhaust general ventilation systems for optimal operation throughout the year. Air should be supplied as close to the occupied zone as possible. Recirculated air should be

used in winter makeup, and unheated or partially heated air should be brought to hoods and processes (ACGIH 2001b).

- 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 Chapter 44 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment*. Energy recovery is also discussed in Chapter 7 of the ACGIH (2001b) *Industrial Ventilation* handbook.

Operate the system for economy. Shut systems down at night or on weekends whenever possible, and operate makeup air in balance with the needs of process equipment and 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.

Contaminant concentrations in any 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) 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.

The TWA at the workers breathing zone is (ACGIH 2001b)

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

where

C_B = TWA worker breathing zone contaminant concentration with recirculation, ppm
Q_B = total ventilation airflow without recirculation, m^3/s
Q_A = total ventilation airflow with recirculation, m^3/s
C_G = average space concentration without recirculation, ppm
f = fraction of time worker spends at workstation
C_O = TWA contaminant concentration at breathing zone of workstation without recirculation, ppm
K_B = fraction of worker breathing zone that consists of recirculated air, 0 to 1.0
C_R = recirculated air (after air cleaner) discharge concentration, ppm, or

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

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

Other recirculation systems 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 2001b). The local exhaust is recirculated through an air cleaner with an efficiency of 0.8. The 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 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 (C_G), and without recirculation the worker's breathing zone is 35 ppm (C_O).

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

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

and

$$C_B = \frac{10{,}000}{5000}(20-5)(1-1) + (35-5)(1) + 0.5(155) + (1-0.5)5 = 110 \text{ ppm}$$

which may or may not exceed the TWA or threshold limit value (TLV) of the worker space, depending on the specific contaminant.

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