Section 3.5 Thermal Comfort and Heat Stress

Table 3.6 Metabolic rate as a function of physical activity for a 70 kg adult man (abstracted from ASHRAE, 1997).

activity	metabolic rate (W)	metabolic rate (kcal/hr)
sleeping	72	62
seated, quiet	108	93
standing, relaxed	126	108
walking about the office	180	155
seated, heavy limb movement	234	201
flying a combat aircraft	252	217
walking on level surface at 1.2 m/s	270	232
housecleaning	284	244
driving a heavy vehicle	333	286
calisthenics/exercise	369	317
heavy machine work	423	364
handling 50-kg bags	423	364
playing tennis	432	372
playing basketball	657	565
heavy exercise	900	774

Thermodynamic analysis of the human body:

The first law of thermodynamics for a stationary system is

$$\frac{dU}{dt} = \dot{Q} - \dot{W}$$

(3-36)

where U is the internal energy of the system, $\dot{Q}$ is the rate of heat transfer *into* the system, and $\dot{W}$ is the rate of work being done *by* the system, following the standard convention in thermodynamics.

Since the body's temperature does not change, the body's internal energy decreases at a rate equal to $\dot{M}$ ($dU/dt = -\dot{M}$), and this same rate of change of energy must be transferred from the body in the form of heat transfer to the environment. Thus, the first law of thermodynamics for this system simplifies to

$$\dot{M} + \dot{Q} = 0$$

(3-37)

which states that all of the energy associated with metabolism is rejected ultimately into the ambient environment as heat. Note that since $\dot{M}$ is positive, $\dot{Q}$ must be negative in order to satisfy Eq. (3-37). Note also that under conditions in which the person is doing thermodynamic work, $\dot{M}$ in Eq. (3-37) is replaced by $\dot{M} - \dot{W}$.

Five types of heat transfer into the body are considered: conduction, convection, respiration, radiation, and evaporation, which are denoted as $\dot{Q}_{cond}$, $\dot{Q}_{conv}$, $\dot{Q}_{res}$, $\dot{Q}_{rad}$, and $\dot{Q}_{evap}$ respectively. Eq. (3-37) thus becomes

$$\dot{M} + \dot{Q}_{cond} + \dot{Q}_{conv} + \dot{Q}_{res} + \dot{Q}_{rad} + \dot{Q}_{evap} = 0$$

(3-38)

All terms in Eq. (3-38) have dimensions of energy per unit time, i.e. power. Each of these heat transfer terms is considered separately below.

Conduction: Conduction heat transfer is by direct contact with solid surfaces, such as chairs, the floor, etc. Since the surface area in such contact is small, and since the materials are generally good insulators, with clothing between the body and the material providing further insulation, conduction heat transfer is negligible in the present analysis.

$$\dot{Q}_{cond} \approx 0$$

(3-39)

Convection: Energy transferred into the body by convection depends on the velocity of air passing over the body and the temperature difference between skin and air. Wadden and Scheff (1987) suggest an expression of the following form, for $\dot{Q}_{conv}$ expressed now in units of kcal/min:

$$\dot{Q}_{conv} = KA_s \left(0.0325 + 0.1066 U_a^{0.67} \right) \left(T_a - T_s \right)$$

(3-40)

where

- K   = fraction of skin exposed to atmosphere
- U_a = ambient air velocity (m/s)
- T_a, T_s = ambient and skin temperatures; for a first approximation, $T_s = 35.0$ °C (308.15 K)

Respiration: The process of breathing in and out involves mass transfer as well as heat transfer, and technically should not be considered as part of thermodynamic closed system analysis. Nevertheless, one can approximate the net rate of heat transfer due to respiration as a steady-state heat transfer term. The chapter on "Thermal Comfort" in the ASHRAE Fundamentals Handbook (1997) provides a

simple expression for the heat transfer rate, which takes into account both sensible and latent heat transfer due to respiration,

$$\dot{Q}_{res} = -\dot{M}\left[0.0014\left(307.15 - T_a\right) + 0.0173\left(5.87 - \Phi_a P_v(\text{at } T_a)\right)\right]$$

(3-41)

where

- $\dot{M}$ = metabolic rate in watts or kcal/min ($\dot{Q}_{res}$ has the same units as $\dot{M}$)
- T_a = ambient air temperature in Kelvin
- Φ_a = relative humidity of ambient air expressed as a fraction, not a percentage
- $P_v(\text{at } T_a)$ = vapor (saturation) pressure of water at the ambient air temperature in kPa

Radiation: Energy transferred into the body by radiation depends on the skin and radiating surface temperatures, the *emissivity* of the radiating surfaces, and various shape factors (Incropera and DeWitt, 1990). In most industrial situations, the identity, location, and temperature of the radiating surfaces are difficult to ascertain. A useful parameter to account for these factors is *globe temperature* (T_G), defined as the air temperature inside an enclosure subjected to both convection with ambient air, and radiation from nearby hot or cold surfaces. Figure 3.34 shows a commercial instrument used to measure globe temperature. In the presence of hot radiating surfaces, globe temperature is larger than ambient temperature. Globe temperature depends on the location of the radiating surfaces; thus globe temperature is a physical measurement that must be made where the workers perform their duties. Globe temperature integrates surrounding radiating wall temperatures into a mean effective radiation temperature. To simplify the computation, the conventional difference between temperatures raised to the fourth power is replaced by a first-order difference between a "wall temperature" and skin temperature. Wadden and Scheff (1987) report that the following expression can be used to relate *wall temperature* (T_W) and the measured globe and ambient temperatures:

$$T_w = \left[T_G{}^4 + \left(0.248 \times 10^9 U_a{}^{0.5}\right)\left(T_G - T_a\right)\right]^{0.25}$$

(3-42)

where the temperatures must be in Kelvin, and U_a is the characteristic air speed which must be in m/s. In lieu of experimental measurement, the observations in Table 3.7 can be used to estimate the speed of moving indoor air. Wadden and Scheff (1987) report that the rate of energy transferred to the body by radiation ($\dot{Q}_{rad}$) in units of kcal/min can be expressed in the following form:

$$\dot{Q}_{rad} = 0.0728 A_s K \left(T_w - T_s\right)$$

(3-43)

Evaporation: It is much more difficult to estimate the rate of heat transfer to the body by evaporation. The *required* value of heat transfer by evaporation ($\dot{Q}_{evap,req}$) can instead be found from Eq. (3-38), since all the other terms are now known.

$$\dot{Q}_{evap,req} = -\dot{M} - \dot{Q}_{conv} - \dot{Q}_{res} - \dot{Q}_{rad}$$

(3-44)

Table 3.7 Estimates of the characteristic speed of moving indoor air (to two significant digits).

physiological response or observation	air speed ft/min (m/s)
observable settling velocity of skin particles	3.0 (0.015)
random indoor air movement, air at lower speed is considered "stale"	20. (0.10)
exposed neck and ankles begin to sense air movement, upper limit of "comfort" at acceptable room temperatures	50. (0.25)
skin on hands begins to sense air movement, moisture on skin increases sensitivity	100 (0.51)
typical walking speed, eddy velocity of a person walking at a brisk speed	250 (1.3)
8-hr, upper comfort level of blown air for cooling, average outdoor air speed	700 (3.6)
30-min, upper comfort level of blown air for cooling, typical fan exit speed for free-standing fans	1,800 (9.1)
10-min, upper comfort level of blown air for cooling	3,500 (18.)

3.5.3 Heat Stress Index

There are several ways to quantify heat stress so that designers can anticipate hazardous conditions and take steps to reduce risk. The chapter on "Thermal Comfort" in the ASHRAE Fundamentals Handbook (1997) gives the historical development of this technology and presents several methods to quantify heat stress of varying sophistication. What follows is a description of one of these methods, the ***heat stress index*** (HSI), developed by Belding and Hatch (1955). While an old concept and perhaps lacking the detail found in more current technologies, HSI describes the basic physical elements that constitute heat stress, and does so with sufficient accuracy to be a useful design tool for practicing engineers. Belding and Hatch (1955) define HSI as

$$\boxed{HSI = \frac{\dot{Q}_{evap,req}}{\dot{Q}_{evap,max}} \times 100\%}$$ (3-45)

where $\dot{Q}_{evap,max}$ is the maximum amount of evaporation the body can achieve assuming the entire surface of exposed skin is covered with sweat. Wadden and Scheff (1987) report that $\dot{Q}_{evap,max}$ (in units of kcal/min) can be computed from

$$\boxed{\dot{Q}_{evap,max} = 0.198 K A_s U_a^{0.63} \left[\Phi_a P_v (at\ T_a) - P_v (at\ T_s) \right]}$$ (3-46)

where Φ_a is the relative humidity of the ambient air expressed as a number rather than as a percentage ($0 < \Phi_a < 1.0$), P_v(at T_a) is the vapor pressure (in mm Hg) of water based on ambient air temperature T_a, and P_v(at T_s) is the vapor pressure (in mm Hg) of water based on skin temperature T_s. Since skin temperature is generally higher than ambient air temperature, and the relative humidity of the ambient air is generally less than unity, Eq. (3-46) yields a negative value of $\dot{Q}_{evap,max}$ which, coupled with the negative value of $\dot{Q}_{evap,req}$, results in a positive value of HSI. It is mathematically possible for $\dot{Q}_{evap,max}$ to be positive under extremely hot and humid conditions, but Eq. (3-46) cannot be used in such cases since the body cannot *absorb* heat due to evaporation. (Perspiration can only cool the body, not heat the body.) In such cases, Eq. (3-45) cannot be used. The ratio of required to maximum evaporative cooling reflects whether the body is capable of maintaining equilibrium by evaporation, and thus is capable of preventing energy from accumulating within the body. Shown in Table 3.8 are the physiological implications of different values of the heat stress index that enable engineers to anticipate hazardous conditions for 8-hour exposures. Values of HSI above 100% are possible, and indicate that the body is unable to cool itself adequately; hyperthermia results. Note that negative values of HSI are also possible; this indicates that the body cannot maintain its constant temperature in cold ambient air, and hypothermia results.

Table 3.8 Heat stress index (adapted from ASHRAE, 1997).

HSI (%)	consequence of 8-hr exposure
< 0	Indicates varying degrees of stress due to hypothermia.
0	No thermal strain.
10-30	<u>Mild to moderate</u> heat stress. Manual dexterity and mental alertness may suffer but there is little impairment to perform heavy work.
40-60	<u>Severe</u> heat stress. Health may be threatened unless physically fit. This condition should be avoided by people with cardiovascular or respiratory impairment or chronic dermatitis.
70-90	<u>Very severe</u> heat stress. Only specially selected people are capable of sustaining these conditions for 8 hrs. Special care must be taken to replace water and salt.
100	<u>Maximum</u> heat stress. Only acclimated, physically fit young people can withstand this for 8-hrs.
>100	Indicates varying degrees of stress due to hyperthermia.

Example 3.6 - **Heat Stress Index in a Restaurant Kitchen**

Given: The air in the workspace of a restaurant kitchen has a characteristic air speed (U_a) of 0.75 or 1.5 m/s, depending on the fan speed setting. The wet bulb temperature (T_{wb}) is 25. °C and the dry bulb temperature (T_{db}) is 30. °C, which corresponds to a relative humidity of 68.%. Note that the dry bulb temperature is the same as the ambient temperature, i.e. $T_{db} = T_a$. The globe temperature (T_G) is measured and found to be 35. °C. It is estimated that the tasks the workers perform require a net metabolic rate that may be as low as 1.5 kcal/min or as high as 5.0 kcal/min. Assume the worker is clothed, with 60.% of his skin area available for heat transfer.

To do: Estimate the heat stress index (HSI) for workers in the restaurant kitchen under various possible conditions.

Solution: The least dangerous situation is examined first, i.e. the case with the lowest metabolic rate and the highest air speed in the kitchen. The rate of convection heat transfer can be found from Eq. (3-40),

$$\dot{Q}_{conv} = 0.6(1.8)\left(0.0325 + 0.1066(1.5)^{0.67}\right)(303.15 - 308.15) = -0.931\frac{kcal}{min}$$

$\dot{Q}_{conv}$ is negative since the ambient air, although warm, is cooler than the worker's skin temperature. The rate of heat transfer due to respiration is found from Eq. (3-41),

$$\dot{Q}_{res} = -1.5\frac{kcal}{min}\left[0.0014(307.15 - 303.15) + 0.0173(5.87 - 0.68(4.246))\right] = -0.0858\frac{kcal}{min}$$

The wall temperature can be found from Eq. (3-42). Being careful to use absolute temperatures in the calculations,

$$T_w = \left[308.15^4 + \left(0.248 \times 10^9 \left(1.5^{0.5}\right)\right)(308.15. - 303.15.)\right]^{0.25} = 320.4 \text{ K} \cong 320. \text{ K}$$

Note that this is very high (47. °C) but not unusual in a small kitchen containing grills, ovens, and gas ranges. The radiation heat transfer rate can be found from Eq. (3-43),

$$\dot{Q}_{rad} = 0.0728(1.8)(0.6)(320.4 - 308.15) = 0.961\frac{kcal}{min}$$

$\dot{Q}_{rad}$ is positive, indicating radiation heat transfer *into* the worker's body, as expected. The required evaporative heat transfer can be found from Eq. (3-44). At the lower extreme of the metabolic rate ($\dot{M}$ = 1.5 kcal/min),

$$\dot{Q}_{evap,req} = -\dot{M} - \dot{Q}_{conv} - \dot{Q}_{res} - \dot{Q}_{rad} = -1.5 - (-0.931) - (-0.0858) - 0.961 = -1.44\frac{kcal}{min}$$

In this particular case, the effects of radiation and convection heat transfer nearly cancel each other out, the respiratory heat loss is small compared to the other terms, and the required rate of evaporative cooling is nearly equal to the metabolic rate. The maximum amount of evaporative cooling can be found from Eq. (3-46),

$$\dot{Q}_{evap,max} = 0.198(0.60)(1.8)(1.5)^{0.63}\left[(0.68)31.84 - 42.21\right] = -5.67\frac{kcal}{min}$$

where the water vapor pressures are obtained from thermodynamic tables or Appendix A.17. The heat stress index is thus found from Eq. (3-45),

$$HSI = \frac{\dot{Q}_{evap,req}}{\dot{Q}_{evap,max}} \times 100\% = \frac{-1.44}{-5.67} \times 100\% = 25.\%$$

The heat stress values that can be expected for three metabolic rates and two air speeds are shown below (to two significant digits). It is assumed that K = 0.60 for all cases.

metabolic rate	HSI (%) for $U_a = 0.75$ m/s	HSI (%) for $U_a = 1.5$ m/s
1.5 kcal/min	40.	25.
3.0 kcal/min	78.	50.
5.0 kcal/min	130	84.

Discussion: It is clear that if $U_a = 0.75$ m/s, workers should not work strenuously for 8 hours. If the air speed can be increased to 1.5 m/s (difficult to achieve in a kitchen), stressful conditions can be reduced substantially. Alternatively, if the work is strenuous, the work schedule should be divided by periods of rest, worker assignments should be rotated, or steps should be taken to reduce the room temperature (e.g. air conditioning) to reduce the risks of heat stress. The workers should also be advised to drink plenty of water. An Excel spreadsheet which was used to generate the above table is available on the book's web site.