HVAC FUNDAMENTALS

The initial chapters of this book deal with heating, ventilating, and air-conditioning (HVAC) systems. HVAC systems use and convert energy and move fluids to make buildings provide thermal comfort and healthy air quality. Fig. 2.1 illustrates that air and water are conducted through ducts and pipes to accomplish the task. A basic understanding of fluid flow, energy forms, and conversion factors is essential to the study of HVAC systems along with other mechanical and electrical (M/E) systems.

2.1 BASICS OF ENERGY AND POWER

M/E systems use and convert energy and move fluids to make buildings habitable and functional. Energy forms applicable to building systems include thermal energy, electricity, mechanical energy, and chemically stored energy (fuels).

Thermal energy is measured in British thermal units (Btu). A Btu is the amount of heat required to raise 1 lb of water 1°F. Stated another way, if we heat 1 lb of water (about 1 pint) 1°F, the water will have absorbed 1 Btu. If we heat a pound of water 2°F, we will need 2 Btu. Pound for pound, water will absorb much more heat than most other materials for a given temperature rise. Only 0.156 Btu will be necessary to raise 1 lb of concrete 1°F. If we normalize the heat-absorbing capacity of water at 1.0, the heat capacity (C) of concrete will be 0.156. These relationships can be combined into the following equation:

$$q = M \times C \times \Delta T \tag{2.1}$$

where

q = heat absorbed (or released) (Btu)
M = mass (lb)
C = heat capacity (often called "specific heat") (Btu lb °F)
ΔT = temperature increase or decrease, °F

The quantity C, heat capacity or specific heat, is listed for many common materials in Table 2.1.

Example 2.1 A 10'-by-10' concrete floor is 8" thick. If the floor is warmed by the sun to 80°F during the day and cools to 70°F overnight, how much heat is stored and released by the floor on a daily basis?

Solution: The specific heat of concrete is 0.21 Btu per lb °F. The density of concrete is approximately 144 lb/ft^3. Heat storage is calculated as follows:

$$\begin{aligned} Q &= M \times C \times \Delta T \\ &= 144 \times (10 \times 10 \times 8/12) \times 0.21 \times (80 - 70) \\ &= 20{,}200 \text{ Btu} \end{aligned}$$

The words "energy" and "power" are often used interchangeably, but there is an important distinction between the two. Energy is a quantity, such as heat; power is the rate at which the quantity is transferred or used. Table 2.2 shows the forms of energy and power, their units of measure, and conversion factors.

The unit of *energy* for heat is the Btu. The unit of *power* for heat will be Btu per hour, abbreviated Btuh. This unit is used in quantifying the amount of heating gained or lost by a structure (load) and the amount of heating or cooling capacity required by equipment to offset the heat or load.

For all forms of energy the following equation will apply, but units will depend on energy form:

$$\text{Power} = \text{Energy}/\text{time}$$

or

$$\text{Energy} = \text{Power} \times \text{time} \tag{2.2}$$

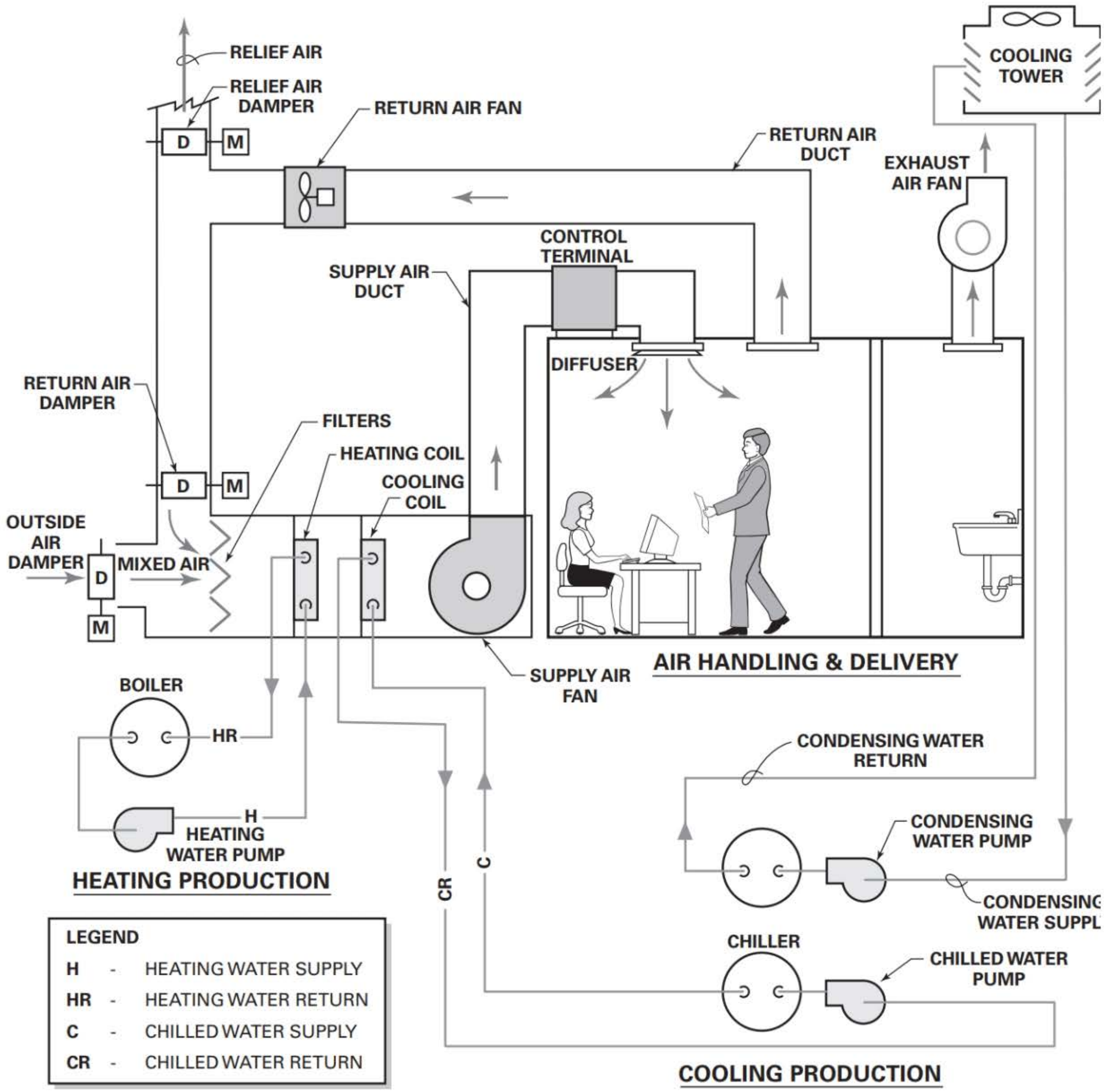


FIGURE 2.1. Components of a large HVAC system (based on hot–chilled water system).

TABLE 2.1 Heat Capacities of Common Materials

Material	Density lb/ft^3	Heat Capacity Btu/°F lb
Water	62.4	1.0
Wood	45	0.57
Foam insulation	2.5	0.34
Air	0.075	0.24
Concrete	144	0.21
Steel	489	0.12

TABLE 2.2 Forms and Units of Energy and Power

	Unit of Measure		
Energy Form	Energy	Power	Conversion to Btu
Heat	British thermal unit (Btu)	British thermal unit per hour (Btuh)	1.00
Electric	Watt-hour (Wh)	Watt (W)	3.41
	Kilowatt-hour (kWh)	Kilowatt (kW)	3,412
Mechanical	Horsepower-hour (hp-hr)	Horsepower (hp)	2,545

Example 2.2 In the previous example, the heat was released from the concrete slab during a night setback period from 10:00 p.m. to 6:00 a.m. What was the average capacity of the slab over this period to assist in heating the building?

Solution: The amount of heat is 15,000 Btu. It was released over an 8-hour period; therefore, the average capacity was

$$\begin{aligned} \text{Power} &= \text{Energy/time} \\ &= 20{,}200 \text{ Btu}/8\,\text{hr} = 2500 \text{ Btuh} \end{aligned}$$

Electric power is measured in watts (W) or kilowatts (1000 W). These are power units. If power is applied over time, energy is the product:

$$\begin{aligned} &\text{Electric energy (kilowatt-hours, or kWh)} \\ &\quad = \text{Electric power (kilowatts, or kW)} \\ &\quad\quad \times \text{ time (hours)} \end{aligned} \tag{2.3}$$

Example 2.3 A 100-W light is on for 10 hours per day. How much energy will the light use in a year's time?

Solution:

$$\begin{aligned} \text{Energy} &= \text{power} \times \text{time} \\ \text{Energy(kWh)} &= 100 \text{ Watts} \times 10 \text{ hr/day} \\ &\qquad \times 365 \text{ days per year} \\ &= 365{,}000 \text{ watt-hours, or } 365 \text{ kWh} \end{aligned}$$

Electrical energy can be converted to mechanical energy in a motor, to light in a lamp, or to heat in a resistance heater. All of the electrical energy used in a heater becomes heat. In a motor, the majority of the electrical energy becomes mechanical power, measured in horsepower. A small portion of the electrical energy is lost as heat. Eventually, even the mechanical energy degrades into heat. In a lamp, a portion of the electrical energy becomes light, and a portion becomes heat. Eventually, virtually all the light is absorbed by room surfaces and becomes heat.

Example 2.4 An electric motor running a large copier draws 1.6 kW. How much heat is produced in the space as a result of the copier's operation?

Solution: From Table 2.2 we find the conversion factor from electric to heat energy or power:

$$\begin{aligned} \text{Heat power (Btuh)} &= \text{Electric power (kW)} \times 3412 \text{ Btuh/kWh} \\ &= 1.6 \times 3412 = 5460\,\text{Btuh} \end{aligned}$$

2.2 FUELS

2.2.1 Energy Content

Fuels are burned to produce thermal energy, which can be used to heat buildings or run engines to produce mechanical energy. The mechanical energy can be used to operate machinery, vehicles, or to produce electricity in a generator. Fuels commonly associated with building systems include natural gas (primarily methane), propane (LP), oil (various grades), and coal (for very large applications). The thermal energy produced by burning various fuels is shown in Table 2.3.

2.2.2 Relative Cost of Fuels

The relative cost of fuels is an important consideration in selection of the energy source for heating buildings. Based on approximate average 2016 U.S. costs for various fuels, Table 2.4 shows the cost per million Btu of net heating energy, considering typical equipment efficiencies. Energy costs can vary greatly between locations, and due to market fluctuations, so current, local analysis should be performed for actual projects. The analysis should consider not only current prices but also projected future trends based on best available opinions.

TABLE 2.3 Heating Values of Various Fuels

Fuel	Unit of Measure[a]	Nominal Heating Value/Unit, Btu (kJ)
Natural gas	cu ft	1,000 (1,055)
LP (propane gas)	gal	93,000 (98,000)
No. 1 oil (diesel)	gal	138,000 (146,000)
No. 5 oil (heavy)	gal	145,000 (153,000)
No. 6 oil (bunker C)	gal	153,000 (161,000)
Soft coal (bituminous)	lb	13,000 (14,000)
		13,700 (14,800)
Hard coal (anthracite)	lb	12,500 (13,500)
		13,200 (14,300)
Electrical resistance[b]	kWh	3,412 (3,600)
Electric heat pump[c]	kWh	10,200 (10,800)

[a]1 gallon = 3.78 liters; 1 cubic foot = 28.32 liters; 1 pound = 0.454 kilogram.

[b]Electrical to heat energy conversion efficiency.

[c]Heat available with coefficient of performance (COP) of 3. COP for heat pump is the ratio of useful heat output divided by energy input.

Example 2.5 A 75% efficient boiler is required to produce 800,000 Btuh to offset a heating load. If the boiler uses natural gas, what will the input rate be in cubic feet per hour?

Solution: From Table 2.3, each cubic foot of gas has a heating value of 1000 Btu. At 75% efficiency, each cubic foot will produce a net heating value of 0.75×1000, or 750 Btu. To produce 800,000 Btuh, we will need 800,000 Btuh/750 Btu/ft^3, or 1067 ft^3 per hour.

Electric Rates Determining electric rates is not a simple issue due to complexity in rate structure. Cost per kWh from most utilities is generally lower in winter, so the cost used for a heating energy comparison should be lower than the average annual cost per kWh. For instance, a Midwest utility might have an average summer cost of $0.12 per kWh, and an average winter cost of $0.08. The lower cost is due to supply and demand factors. More power is demanded in summer due to air conditioning, and the electric utility has more available capacity in winter, so more efficient power plants can be base loaded.

An additional complexity results from rate "steps," which could be considered as a volume discount. The lowest "block" of usage has a higher unit cost per kWh than subsequent blocks. Accordingly, a large residence will pay a lower average cost for electricity than a small residence because the former has more usage in the higher blocks.

The stepped rate structure also promotes electric heating. A homeowner, for instance, might pay $0.09 per kWh for blocks representing the kWh quantity that is typically used for general power usage (lights and appliances). The block above general power usage could be priced at $0.06, which the electric company might statistically assume is used for heating.

A very large building may have a rate structure that includes a demand charge for the peak monthly power requirement (kW) as well as an energy charge (kWh). In many areas demand charges can be half or more of the total electric bill in the summer months. The application of demand charge is shown in Example 2.6.

Example 2.6 The summer rate structure for a large building is $0.04 per kWh and $15.00 per kW of peak monthly demand. If a large building under this rate uses 300,000 kWh in July and the peak July demand is 1,200 kW, what is the July electric bill? What is the average cost per kWH? (Ignore basic charges and taxes for simplicity.)

Solution:

Usage charge 300,000 kWh × $0.04/kWh = $12,000

Demand charge 1,200 kW × $15.00/kW = $18,000

Total July bill (exclusive of basic charges and taxes) $30,000 (Avg. $0.10 per kWh)

TABLE 2.4 Range of Cost for Various Fuels

Energy Source for Heating a Building	Billing Unit	Energy (Btu) per Unit	Typical Efficiency (%)	Range of Unit Cost $/Unit		Range of Cost $/ Million Btu	
				Low	High	Low	High
Natural gas	Therm	100,000	80	0.30	0.95	3.75	12.88
LP (propane)	Gallon	93,000	80	2.00	4.75	13.44	63.84
No. 1 oil (diesel)	Gallon	138,000	80	2.50	2.75	13.59	24.91
Electric resistance	kWh	3,412	100	0.04	0.08	10.26	23.45
Heat pump	kWh	3,412	300	0.04	0.08	3.42	7.82

For large buildings, most utility companies measure demand in two periods: peak and off-peak. The time period between 10:00 a.m. and 10:00 p.m. weekdays is commonly considered as peak period. Demand during the off-peak period may be allowed to exceed peak period demand by a factor of 2 times before being used as a basis for the demand charge. Since most heating occurs at night and during the early morning hours, the cost per unit for most of the kWh used for electric heat could be very low since this power doesn't contribute to the demand charge. *Usage* charges (exclusive of demand) between $0.035 and $0.06 per kWh are not uncommon for large buildings in the Midwest. Much higher values could apply in other parts of the United States.

Heat Pumps For heat pumps the coefficient of performance (COP) is defined as the heating energy output divided by the electric energy input. If a heat pump has a COP of 3, then 3 units of heat are produced by 1 unit of electric input. Stated another way, 1 kWh input transports 2 kWh of heat from outdoor air (air source heat pump) or from the earth (ground source heat pump) for a total of 3 kWh of heat. COP varies greatly by system and location, so a COP of 3 is used in Tables 2.3 and 2.4 to give a general comparison of electric heat pumps with other heating energy sources.

Natural Gas Cost of gas is similarly complicated by rates and contracts. In 2016 the average cost of gas for residential customers was about $0.95 per therm according to the U.S. Energy Information Administration. Commercial customers paid, on average, about $0.65 per therm. These values vary by location and size of building and are similar to electric rates. Very large facilities may have much lower gas prices if they directly procure from producers and pay the local utilities only for distribution overhead. Gas costs as low as $0.30 are not uncommon for this practice, but it's only used for very large facilities such as college campuses and industrial complexes.

LP and Oil During the same general time frame referenced for electric and gas, LP (propane) cost varied from about $2.00 per gallon to $4.75 per gallon. Heating oil cost varied from $2.50 per gallon to $2.75 per gallon, with a national average of about $2.10 per gallon. Heavy oils and coal are not commonly used as a primary heating energy for buildings, so they are excluded from Table 2.4.

Example 2.7 A proposed building has an estimated annual heating energy load of 3000 mmBtu per year. The owner wishes to consider using a heat pump concept (air source or ground source) instead of natural gas, which is the most commonly used fuel in his town, despite the fact that the town's gas rates are on the high side. Before spending a lot of time in design, he'd like to get a ballpark estimate of potential savings. His engineer suggests that electric to run the heat pumps during the winter would cost about $0.06 per kWh. How much might he expect to save using the heat pump concept?

Solution: From Table 2.4, natural gas would likely cost about $12 per mmBtu, and cost of heat pumps would lie between $3.42 and $7.82, or about $5.50 per mmBtu. This results in an estimate of 3000 mmBtu × $12.00 per mmBtu = $36,000 for gas and 3000 mmBtu × $5.50 = $16,500 for heat pump. Savings would likely be in the range of $20,000 per year.

2.3 PROPERTIES OF AIR–WATER MIXTURES

The design of environmental control systems relies on an understanding of the properties of air, including temperature and humidity. These properties affect loads on buildings, and HVAC systems are used to alter the properties of air and produce comfort.

2.3.1 Psychrometry

Psychrometry is the study of properties of air–water mixtures. A psychrometric chart is a convenient source for data on the properties of such mixtures. Fig. 2.2 shows how important properties are presented on a psychrometric chart. Fig. 2.3 is a complete chart that can be used in analysis of processes associated with HVAC.

2.3.2 Absolute and Relative Humidity

Two basic properties of air–water mixtures are temperature and humidity. The humidity of the air can be expressed in two ways: absolute and relative. *Absolute humidity*, also known as the *humidity ratio* (*W*), is the amount of water in the air and is measured in grains or pounds of water per pound of dry air. A grain is equivalent to 1/7000 of a pound. This unit is preferred owing to the very small amount of water present in air. *Relative humidity* (RH) is the ratio of the actual water content to the maximum possible moisture content at a given temperature, expressed as a percent. If the air is currently holding all the moisture possible, the relative humidity is 100 percent, and the air is termed *saturated.*

2.3.3 Effect of Temperature on Humidity

The moisture-holding capacity of the air depends on the air temperature. Warm air can hold more moisture than cold air. For this reason, the same absolute humidity results in different relative humidities at different temperatures. The psychrometric chart illustrates the relationship of temperature, absolute humidity, and RH.

2.3.4 Wet-Bulb Temperature

If a wet sock is placed over the bulb of a conventional thermometer, a lower temperature will be recorded owing to evaporative cooling. The drier the air, the more effective will be the evaporative cooling, and the lower will be the temperature measured. If the air is saturated, then there will be no evaporation and the wet-bulb thermometer will measure the same temperature as a dry-bulb thermometer. The temperature and humidity of the air can be determined by measuring both dry-bulb and wet-bulb temperatures. A combination of wet- and dry-bulb temperature represents a discrete point on the psychrometric chart.

2.3.5 Sensible, Latent, and Total Heat

Air contains thermal energy in two forms: sensible heat and latent heat. Water vapor, or humidity, in the air contains the water's latent heat of vaporization (approximately 1000 Btu/lb of water). Temperature is a measure of sensible heat, while water vapor content is a measure of latent heat. Total heat—the sum of sensible and latent heat—is *enthalpy*, symbolized by the Greek letter eta, or by *H*. Enthalpy is expressed in units of Btu/lb of dry air. High temperature or high humidity constitutes high energy.

On the psychrometric chart, horizontal movement is associated with sensible heat change (no change in absolute humidity), and vertical movement is associated with latent heat change (no change in temperature). Moving upward or to the right indicates a higher energy level; moving downward or to the left indicates a lower energy level. Lines of

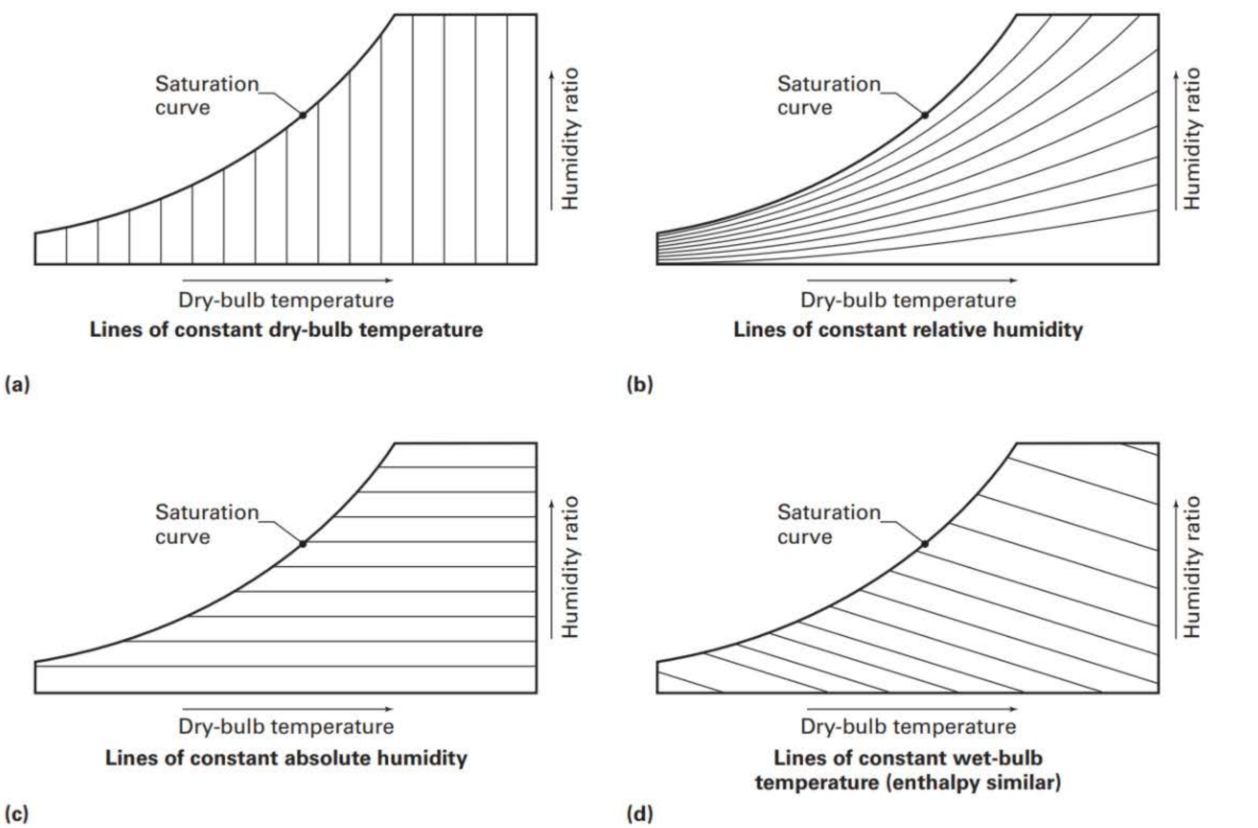


FIGURE 2.2. Lines representing major properties of air–water mixture on the ASHRAE psychrometric chart. (a) Vertical lines: constant dry-bulb (DB) temperature. (b) Curved lines: constant relative humidity (RH). (c) Horizontal lines: constant humidity ratio (*W*), also commonly referred to as *absolute humidity.* (d) Sloped lines: constant wet-bulb (WB) temperature; lines with same slope: constant enthalpy (*H*).

constant enthalpy slope upward and to the left at approximately the same slope as lines of constant wet-bulb temperature. This is no coincidence, for wet-bulb temperature is a good measure of total energy.

Often, changes in air conditions result in changes in both humidity and temperature as shown in Fig. 2.4. The net change in energy level, or enthalpy, can be determined by plotting the initial and final conditions on the psychrometric chart.

2.3.6 Sensible Heating and Cooling

Sensible heating (cooling) occurs when the temperature of an air–water mixture is raised (lowered) but the absolute moisture content remains the same. Sensible heating or cooling occurs as air in spaces is warmed or cooled by building loads that do not change the moisture content of the air. Sensible heating or cooling is also performed by systems to compensate for loads. For instance, room air may be cooled by an outside wall during cold winter weather. To compensate, a heater at the base of the wall may warm the air. Sensible heating or cooling is represented by a horizontal movement along the psychrometric chart.

2.3.7 Processes Involving Latent Heat

Heating and cooling represent a change of sensible heat; humidification and dehumidification represent a change of latent heat. The amount of moisture liberated or absorbed by air is measured by its initial and final absolute humidities.

Air can be humidified either by adding dry steam to it or by evaporating moisture into it. If dry steam is added, the air will have a higher energy level, taking on the latent heat of the steam. (There will also be a slight increase in temperature owing to the sensible heat of the steam, but the effect is small and generally ignored in practice.) On the psychrometric chart, this process is represented by a vertical movement.

If water is evaporated into air, the air will cool, but the final energy level of the air does not change. The heat required to vaporize the water cools the air. The sensible heat loss equals the latent heat gain, resulting in constant enthalpy. This process is called *adiabatic saturation.* (No energy is added or removed.) Evaporative humidification is accompanied by evaporative cooling and is represented on the psychrometric chart by an upward movement along a line of constant enthalpy (approximately parallel to a line of constant wet-bulb temperature).

Cooling is a method for dehumidifying air. If moist air is cooled to the saturation curve, further cooling will not only reduce temperature but also remove moisture. The temperature at which moisture begins to condense is termed the *dew point.* Liquid moisture removed from the air by this process is termed *condensate.* The air that results from the process is both cooler and less humid than it was initially.

Air also can be dehumidified by absorption. Some substances are *hygroscopic*, meaning that they absorb moisture. Hygroscopic substances, or desiccants, such as silica gel and lithium bromide are used in certain applications to absorb moisture from the air. As moisture condenses in the desiccant its latent heat is liberated, heating the desiccant and the air. Absorption is represented by a movement on the psychrometric chart approximately opposite in direction to evaporative cooling.

2.3.8 Examples to Understand the Psychrometric Chart

1. Air at 70°F DB and 75% RH is heated to 84°F. What is the RH of the air at this higher temperature?

Solution: In Fig. 2.3, locate the air at the initial condition (70°F DB and 75% RH) and follow the horizontal line to the right until it meets the 84°F DB line (vertical). The heated air is now at 47% RH.

2. Air at 90°F DB and 70% RH is cooled to 75°F. What is the relative humidity?

Solution: In Fig. 2.3, from the intersecting point of 90°F DB and 70% RH, draw a line to the left. This line meets the saturation curve at 79°F, which is the dew point temperature of the air. The air is then cooled further, following the saturation curve until it stops at 75°F. Between 79°F and 75°F, the air is saturated, and moisture condenses out of it. The RH of the air is now 100%.

3. Outside air at 95°F DB and 78°F WB is mixed with air returning from a room at 75°F / 50% RH. The mix is 20% OA / 80% return. What is the condition of the mix?

Solution: The dry-bulb temperature of the mixed air can be determined as follows:

$$\text{Mixed air temp} = 20\% \times \text{OA temp} + 80\% \times \text{RA temp}$$
$$= 0.2 \times 95 + 0.8 \times 75 = 79°\text{F}$$

The humidity ratio of the mixed air can be determined by a similar equation. From the psychrometric chart, the humidity ratio of air at 95°F DB and 78°F WB is 0.0168 lbs/lb, and the humidity ratio of air at 75°F DB and 50% RH is 0.0093 lbs/lb. The mix is 0/0108 lbs/lb.

4. Air at 95°F DB and 78°F WB is cooled to 55°F. What is the change in humidity ratio?

Solution: In Fig. 2.3, from the intersecting point of 95°F DB and 78°F WB, draw a line to the right to the vertical axis, and read the humidity ratio, which is 0.0168 lbs/lb. Then draw a line from the initial condition to the left. This line meets the saturation curve at 72°F, which is the dew point temperature of the air. The air is then cooled further, following the saturation curve until it stops at 55°F. Between 72°F and 55°F, the air is saturated, and moisture condenses out of it. Humidity ratio at 55°F saturated is determined by drawing a line to the right to the vertical axis, and read the humidity ratio, which is 0.0092 lbs / lb. The change is humidity ratio is 0.0168 minus 0.0092, or 0.0076 lbs / lb.

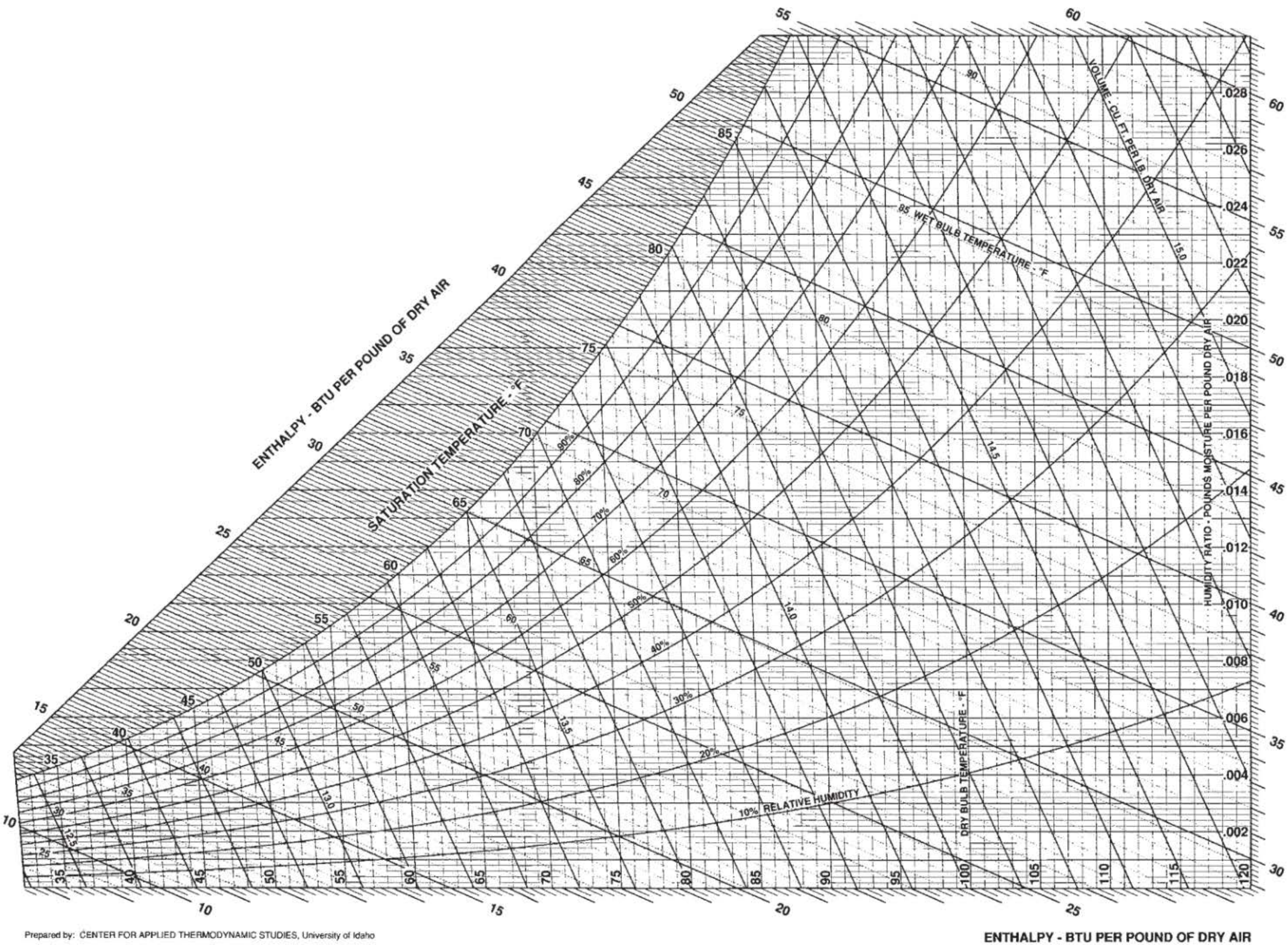
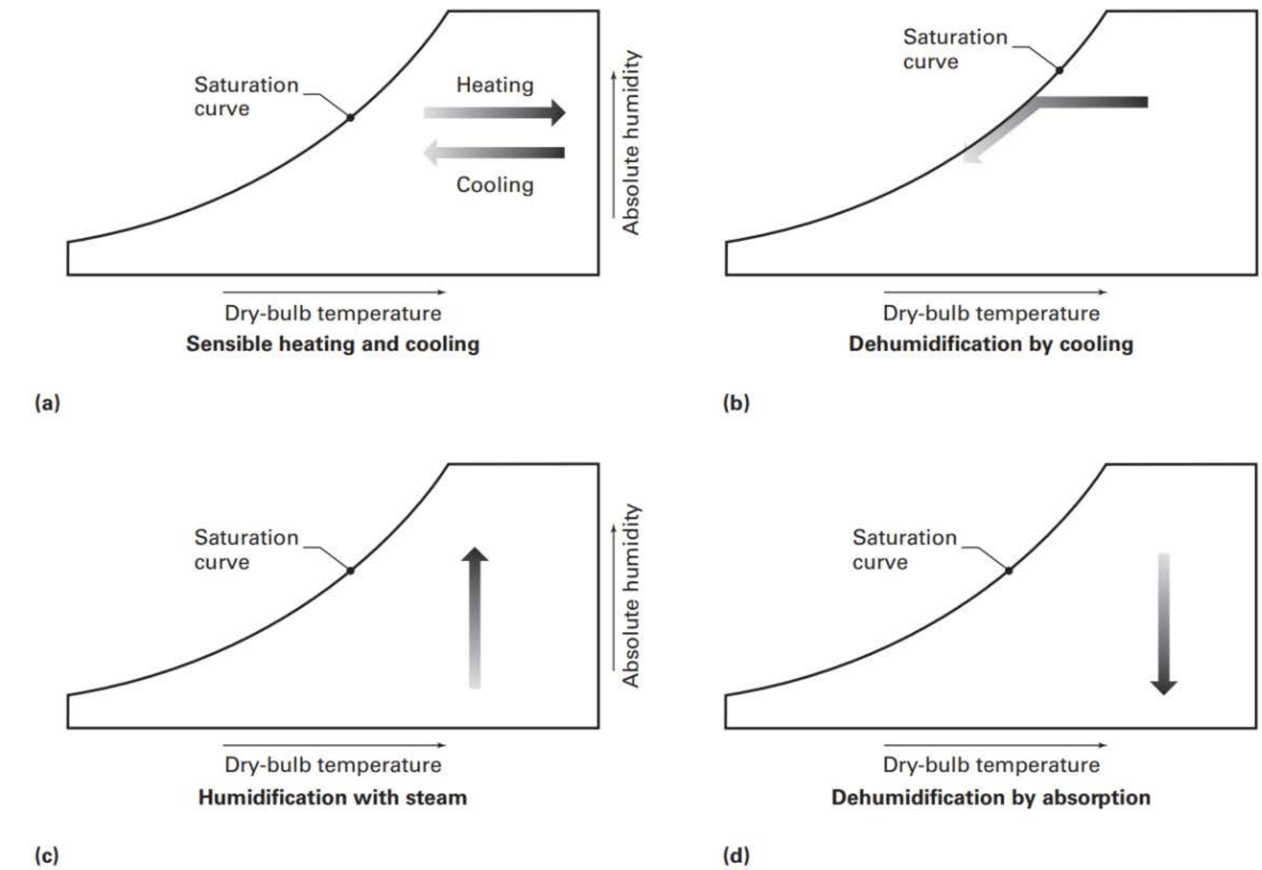


FIGURE 2.3. Psychrometric chart.

(©ASHRAE, www.ashrae.org. (2017) ASHRAE Handbook—(IP version page 1.15, their Fig.1 ASHRAE Psychrometric Chart No. 1.). Used with permission.)



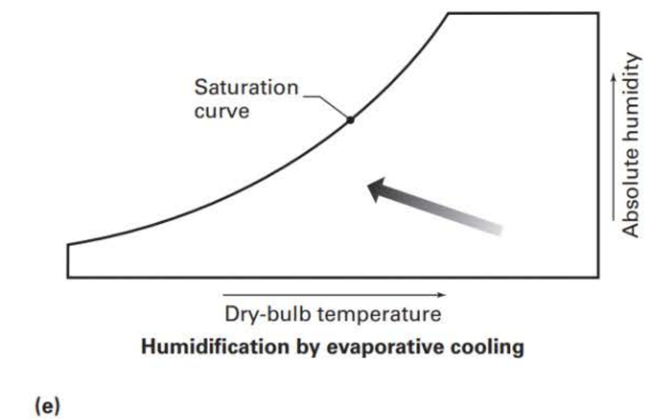


FIGURE 2.4. Basic psychrometric process. (a) Sensible heating and cooling—horizontally. (b) Dehumidification by cooling—follows saturation curve. (c) Humidification with steam—essentially up vertically with slight heating. (d) Dehumidification by absorption—essentially down vertically with slight heating. (e) Humidification by evaporative cooling—approximately follows the wet-bulb line.

2.4 FLUID FLOW AND PRESSURE IN MECHANICAL SYSTEMS

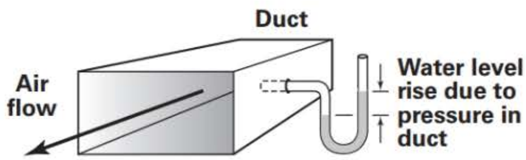
Mechanical systems use the flow of air, water, and steam to transfer energy. Airflow is measured in cubic feet per minute, abbreviated CFM. Air pressures in heating and air-conditioning systems are very low, and measuring in the familiar unit of psi (pound per sq in) would result in numbers too small to be used conveniently. Pressure is measured in "inches of water column" as explained in Fig. 2.5.

Water flow is measured in gallons per minute, abbreviated GPM. Pressures are measured in two units: psig and "ft of head." Head, measured in feet, is equal to the pressure at the bottom of a column of water. For instance, a dam that has a headwall holding water 100 ft in depth has a pressure of 100 ft of head at the bottom. A pressure measurement of 100 ft of head at a particular point in a piping system would be the same as water pressure at 100 ft depth. One psig is equal to 2.31 ft of head.

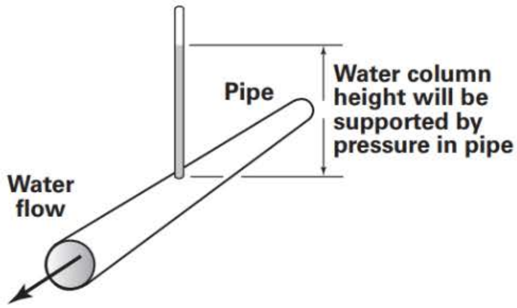
Steam is measured in pounds (lbs), and flow is measured in lbs per hour. Pressure is measured in psig.

2.5 ENERGY TRANSPORT IN HVAC SYSTEMS

Fig. 2.1 shows that HVAC systems use fluids to transport heat and cold to satisfy loads and maintain comfort. Such fluids include air, water, steam, and refrigerant. Equations



Air pressure measured in "inches of water column."



Water pressure measured in "feet of head."

FIGURE 2.5. Measuring pressure of air and water in HVAC systems.

are developed in this section that can be used to determine heat transport based on the flow rate and the initial and final conditions of the fluid. These equations can also be used in equipment design to specify flow rates or conditions, based on requirements for heat transport. The rate of heat flow is measured in Btus per hour, or Btuh. Fluids are used to transport heat in HVAC systems.

2.5.1 Heat Transport in Air

Sensible Heat Transfer in Air The natural property of a fluid that affects heat transfer is called *specific heat*; this is the amount of energy (Btu) required to raise the temperature of 1 lb of a substance 1°F. The specific heat of water is 2.0 and that of air is 0.24. The heat liberated from a quantity of fluid is equal to the specific heat of the fluid multiplied by the number of pounds of the fluid and the temperature change between the initial and final states of the fluid; that is,

$$q = m \times C \times \Delta T \qquad \textbf{(2.4)}$$

where q = heat energy (Btu)
m = mass (lb)
C = specific heat (Btu / (lb·°F))
ΔT = temperature difference, °F (final temperature minus initial temperature)

HVAC equipment loads, equipment capacity, and output are expressed as quantities per unit time, or *rates*:

$$Q = M \times C \times \Delta T \qquad \textbf{(2.5)}$$

where Q = heat flow (Btu / hr, or Btuh)
M = mass flow (lbm / hr)
C = specific heat (Btu / (lb·°F))
ΔT = temperature difference, °F

Mass flow is quantified in units of cubic feet per minute, or CFM. An equation for sensible heat transfer in air can be derived given that the density of air at standard pressure is 0.075 lb / ft^3 and that the specific heat of air is 0.24 Btu / lb·°F:

$$\begin{aligned} Q_{\text{sensible}} &= 0.076 \text{ lbs/ft}^3 \times .024 \text{ Btu/lb} \cdot {}^\circ\text{F} \\ &\quad \times 60 \text{ min/hr} = 1.1 \times \text{CFM} \times \Delta T \end{aligned} \qquad \textbf{(2.6)}$$

where CFM = airflow (ft^3 / min)

Latent Heat Transfer in Air Mass flow is quantified in units of cubic feet per minute, or CFM. An equation for latent heat transfer in air can be derived given that the density of air at standard pressure is 0.075 lb / ft^3 and that the latent heat of vaporization of water is 1076 Btu / lb. The difference in humidity ratio WD can be expressed in lbs of H_2O / lb of dry air or in grains H_2O / lb of dry air:

$$\begin{aligned} Q_{\text{latent}} &= 0.075 \text{ lbs/ft}^3 \times 1076 \text{ Btu/lb} \\ &\quad \times 60 \text{ min/hr} = 4840 \times \text{CFM} \times \Delta W \end{aligned} \qquad \textbf{(2.7)}$$

where CFM = airflow (ft^3 / min)
ΔW = difference in humidity ratios (lbs of H_2O / lb of dry air)

Or, if difference in humidity ratio WD is expressed in grains of H_2O per lb of dry air:

$$\begin{aligned} Q_{\text{latent}} &= (0.075 \text{ lbs/ft}^3 \times 1760 \text{ Btu/lb} \times 60\text{/min/hr})/ \\ &\quad 7000 \text{ grains/lb} = 0.68 \times \text{CFM} \times \Delta W \end{aligned} \qquad \textbf{(2.7a)}$$

where CFM = airflow (ft^3 / min)
ΔW = difference humidity ratios (grains of H_2O / lb of dry air)

Total Heat Transfer in Air Total heat, termed *enthalpy (H)*, is the sum of sensible and latent heat. The total heat of air at various conditions of temperature and humidity can be taken from a psychrometric chart or tables, and the following equation can be used to determine energy flow:

$$Q = 4.5 \times \text{CFM} \times \Delta H \qquad \textbf{(2.8)}$$

where ΔH = change in enthalpy (Btu / lb) Δ

2.5.2 Heat Transport in Water

Mass flow is quantified in units of gallons per minute (GPM). Knowing that 1 gal of water has a mass of 8.35 lb and that there are 60 minutes in 1 hour, the following equation can be derived:

$$\begin{aligned} Q &= 1 \text{ Btu/lb} \cdot {}^\circ\text{F} \times 8.35 \text{ lbs/gal} \\ &\quad \times 60 \text{ min/hr} \times \text{flow (gal/hr)} \\ &\quad \times \text{temp. difference (°F)} \\ &= 500 \times \text{GPM} \times \Delta T \end{aligned} \qquad \textbf{(2.9)}$$

where Q = Heat flow (Btu / hr, or Btuh)
GPM = water flow (gal / min)
ΔT = temperature difference, °F

2.5.3 Heat Transport by Fluid Phase Change

Heat Transfer in Steam Heat is liberated from steam by a change of phase from vapor to liquid. One pound of steam liberates approximately 1000 Btu as it condenses. Conversely, a boiler must produce 1000 Btu to boil 1 lb of water. For steam, heat flow is approximated by the equation

$$Q = 1000\ \text{Btu/lb} \times \text{lb/hr} = 1000 \times \text{SFR} \quad \textbf{(2.10)}$$

where SFR = steam flow rate (lb / hr)

Heat Transfer in Refrigerants Refrigerants absorb heat by changing phase from liquid to gas. The heat absorbed is equal to the latent heat of vaporization, measured in Btu per pound, times the refrigerant flow rate, measured in pounds per hour. There are many types of refrigerants, and each has its own distinct latent heat of vaporization.

2.5.4 Selecting Fluid Flow Rates for HVAC Systems

HVAC systems and subsystems are designed to satisfy heat loads by using heat transport fluids. Fans, pumps, boilers, and distribution elements are sized according to flow requirements, which must be determined by the HVAC designer. The first step is to estimate building heat loads. Methods for estimating loads are presented later in this chapter. Once they are estimated, the HVAC designer must decide on the proper combination of flow and conditions for fluids used to transfer heat and thereby compensate for loads. Initial and final conditions are generally selected on the basis of accepted general practice found to achieve satisfactory results. Equations (2.1) through (2.5) can be used to calculate flow, given the heat transfer requirement and the initial and final conditions of the fluid.

Water Flow For devices using hot water for heating, a supply temperature of 160°F might be chosen and the load equipment selected to allow a 20°F drop in water temperature, resulting in a 140° return temperature. Once this decision is made, the required water flow rate can be calculated using Equation 2.11.

$$\text{GPM} = Q/(500 \times \Delta T) \quad \textbf{(2.11)}$$

Similarly, chilled water can be used for cooling. Chilled-water supply temperatures between 40°F and 50°F are common for building HVAC applications, and systems are designed for water temperature rises ranging from 10°F to 15°F. The same equation applies for determining the required chilled-water flow rate.

Airflow For systems using warm air for heating, supply temperatures between 105°F and 140°F will be appropriate to maintain a space at, say, 75°F. Given a space temperature and a selected supply temperature, the required airflow rate can be calculated using Equation 2.12.

$$\text{CFM} = Q/(1.1 \times \Delta T) \quad \textbf{(2.12)}$$

Systems using chilled air for cooling generally have supply air temperatures between 50°F and 60°F. Equation 2.12 can also be used to determine the airflow rate required to satisfy the sensible portion of cooling loads. Once the airflow rate is determined, the humidity can be determined from a psychrometric chart.

Steam Flow The rate of steam flow required to satisfy a given heating load is determined by using Equation 2.13.

$$\text{SFR} = Q/1000 \quad \textbf{(2.13)}$$

where SFR = steam flow rate (lb / hr)
Q = heat flow (Btuh)
1000 = heat (Btu) liberated by condensation of 1 lb of steam

Refrigerant Flow The rate of refrigerant flow for cooling is determined by dividing the cooling load by the latent heat of vaporization.

The foregoing concepts and equations are used to estimate theoretical fluid flow rates required to meet a given load. The resulting estimates are the basis for sizing the piping and duct systems, along with the pumps and fans required to transport heating and cooling.

2.5.5 Examples for Understanding Heat Transfer by Fluid Flow

1. A room has a sensible cooling load of 55,000 Btuh. How many CFM at 55°F will be required to keep the room at 75°F?

   Solution: Using Equation 2.12, the required airflow will be as follows:

   $$\text{CFM} = Q/(1.1 \times \Delta T) = 55{,}000/(1.1 \times (75 - 55)) = 2500\ \text{CFM}$$

2. The air in the preceding example is cooled and dehumidified in a cooling coil. The coil inlet condition is 79°F, 0.0108 lbs of H_2O/lb of dry air, and the coil outlet condition is 55°F, 0.0092 lbs of H_2O/lb of dry air.

   What is the sensible heat removal at the coil?

   Solution: Using Equation 2.6, the sensible heat removal will be as follows:

   $$Q_{\text{sensible}} = 1.1 \times \text{CFM} \times \Delta T = 1.1 \times 2500 \times (79 - 55) = 66{,}000\ \text{Btuh}$$

   What is the latent heat removal at the coil?

   Solution: Using Equation 2.7, the latent heat removal will be as follows:

   $$Q_{\text{latent}} = 4840 \times \text{CFM} \times \Delta W = 4840 \times 2500 \times (0.0108 - 0.0092) = 19{,}400\ \text{Btuh}$$

   What is the total heat removal at the coil?

   Solution: From the psychrometric chart we determine that the entering air enthalpy (H) is approximately 30.7 Btu / lb and the enthalpy of the leaving air is approximately 23.2 Btu / lb. Using Equation 2.8, the total heat removal will be as follows:

$$Q_{total} = 4.5 \times CFM \times \Delta H = 4.5 \times 2500 \times (30.8 - 23.2) = 85{,}500 \text{ Btuh}$$

3. The coil receives 45°F chilled water, and is selected based on a 15°F temperature rise to 60°F. What chilled water flow rate is required to remove the 85,500 Btuh?

   Solution: Using Equation 2.11, the required chilled water flow will be as follows:

$$GPM = Q/500 \times \Delta T = 85{,}500/500 \times (60 - 45) = 11.4 \text{ GPM}$$

4. A building has a heating load (heat loss) of 6000 mBh. The heating system uses hot water and is designed for a 40°F ΔT at full load conditions. What is the required hot water flow?

   Solution: Using Equation 2.11, the required hot water flow will be as follows:

$$GPM = Q/500 \times \Delta T = 6{,}000{,}000/500 \times (40) = 300 \text{ GPM}$$

5. If the building in the preceding example were heated by steam, what steam flow would be required?
6. Solution: Using Equation 2.13, the steam flow will be as follows:

$$SFR = Q/1000 = 6{,}000{,}000/1000 = 6000 \text{ lbs/hr}$$

2.6 ENVIRONMENTAL COMFORT

2.6.1 Comfort for Occupants

The temperature of a space is not the only factor affecting a person's comfort. Even if the temperature is within an acceptable range, the space may seem warm if the humidity is too high, the airflow is too low, or there are warm surfaces radiating heat to occupants. Conversely, a space may seem cool if the humidity is low, the space is drafty, or there are cold surfaces absorbing heat radiated from occupants. Comfort for building occupants is affected by a number of environmental variables, including the following:

- Temperature
- Airflow
- Humidity
- Radiation

Indoor air quality is another aspect of comfort. In air of good quality, sufficient oxygen is present and objectionable impurities such as dust, pollen, odors, and hazardous materials are absent.

Different conditions may be deemed comfortable, depending on the type of activity that goes on in a space. Appropriate conditions for an office would be too warm for a gymnasium and too dry and cool for a natatorium. Expectations must also be considered: Saunas are hot on purpose, and a wide variety of conditions are commonly tolerated without complaint in factories. The physical condition of the occupants, including their age and health, also affects their comfort. Even the seasons affect comfort: Warmer environments are tolerated during the summer and cooler environments in winter, because of clothing and acclimatization.

Economics and concerns about energy conservation are also considered in defining comfort. People might be satisfied with less comfort when they know the purpose is energy conservation or to save money.

2.6.2 Temperature and Humidity

Both temperature and humidity affect our sense of comfort. An ASHRAE graph shows the acceptable range of each for persons wearing typical summer and winter clothing involved in sedentary activities. The lower comfort limit in cold weather is 68°F at about 30 percent RH. More recent versions of the ASHRAE graph have eliminated the lower limit on humidity, recognizing that most commercial buildings do not use humidifiers during the heating season, due primarily to cost and high maintenance. The upper limit in hot weather is 79°F at about 55 percent RH. HVAC systems are generally designed to maintain temperature and RH within a tighter range during the cooling season, and to maintain temperatures, but not humidity in a tighter range during the heating season.

An interior design temperature of about 75°F is considered comfortable by most people in general-use spaces. During the summer, a slightly higher temperature may be appropriate because of light clothing and acclimatization to warm weather; this should be considered in designing air-conditioning systems. Conversely, slightly cooler temperatures are acceptable and can be considered in the design of heating systems. Most air-conditioning systems are designed to maintain a summer temperature of 72–78°F. During winter, heavier clothing and acclimatization to cold weather result in a recommended design temperature of 68–72°F for heating systems. These interior design temperatures will be appropriate for the majority of buildings.

Humidity in excess of 60 percent is considered high in general-use spaces. High humidity not only is uncomfortable but also can result in indoor air-quality problems due to mold growth. Humidity lower than 25–30 percent can result in discomfort due to drying of breathing passages and also cause problems with electronic equipment due to static electricity.

2.6.3 Airflow

Systems must be designed for adequate airflow to prevent complaints of "stuffiness" or drafts. The measure of airflow is velocity. Space air velocities less than 10 feet per minute will be stuffy; those more than 50 feet per minute may seem drafty.

2.6.4 Air Quality

Systems must provide sufficient amounts of clean air to keep oxygen at an acceptable level and to dilute contaminants generated within occupied spaces. Air should be reasonably free of dust, and spaces free of odors or other pollutants that may be hazardous or objectionable. These conditions are generally achieved through the use of filters and by the introduction of outside air into the system at rates specified in ASHRAE Standard 62, "Ventilation for Acceptable Indoor Air Quality."

Ventilation rates for indoor air quality have been subject to change based on social context. They decreased during the energy crisis of the 1970s and subsequently increased with reports of "sick-building syndrome" shortly thereafter. There is current research available which might increase ventilation rates further based on reported health and productivity benefits. Accordingly, there are LEED Credits associated with using ventilation rates higher than ASHRAE Standard 62.

2.6.5 Radiant Effects

Even if the temperature, humidity, and airflow in a space are acceptable, the space may be uncomfortable owing to radiant effects from cold windows or walls. Systems must therefore compensate for these effects with radiant heat or higher temperatures. Similarly, cooler temperatures or higher air velocities will be needed to offset the effects of warm surfaces. Downdrafts from cold surfaces are also uncomfortable and can be offset by proper placement of heating devices, generally below windows.

2.6.6 Special Considerations

Buildings such as museums, computer centers, and laboratories have special requirements for temperature, humidity, airflow, and air quality. In some instances these requirements are consistent with the comfort of the occupants, but in others they are at odds with comfort.

Interior environmental criteria are often based on specifications for equipment used within an occupied space. Computer rooms, for example, are often drafty and cold in the aisles where air is supplied to rack fronts and hot in the aisles where the racks discharge their heat. This will be an uncomfortable environment for staff in the computer room, and special provisions may necessary for comfort certain areas of the room. Similarly, materials stored in a warehouse may tolerate cold or hot temperature, but the warehouse employees need a refuge of human comfort.

Economics and expectations of comfort also affect design criteria. Energy conservation is a component of sustainable design, and occupants might accept less comfortable conditions to save energy. However, as noted in Chapter 1, comfort should not be sacrificed at the expense of productivity.

QUESTIONS

2.1 If the lighting load for a 10,000-ft^2 building is estimated at 1 W/ft^2, what will be the resulting heat generated by lighting in units of MBtu for 3000 hours of lights on?

2.2 If the lighting load were increased, what would be the effect on other building systems in a Midwestern U.S. climate? Would you increase the capacity of the heating system? The cooling system? What would the energy impact of higher lighting loads be on gas for heating, electric for cooling, and overall electric usage?

2.3 How much heat (Btus) will be stored in a 100-ft^2 concrete wall 1 ft thick if it is warmed from 65°F to 85°F by exposure to sunlight?

2.4 What is the equivalent value of the heat in Question 2.3 compared with gas at $0.65 per therm burned in a boiler at 85% efficiency? What equivalent value compare with electric at $0.06 per kWh?

2.5 Compare the annual cost of heating by propane at $2.00/gallon in a 85% efficient furnace versus electric heat pump with a COP of 3 using electric at $0.06 per kWh. The building is 3000 ft^2, and the engineer assumes an annual heating requirement of 30,000 Btu/ft^2/yr.

2.6 What is the difference between absolute humidity, often called *humidity ratio*, and relative humidity? What are the units used to express each of these quantities?

2.7 If the dry-bulb temperature is 95°F and the wet-bulb temperature is also 78°F, what is the relative humidity? What is the dew point? What is the humidity ratio? What is the enthalpy?

2.8 If the dry-bulb temperature is 55°F and the wet-bulb temperature is also 55°F, what is the relative humidity? What is the dew point? What is the humidity ratio? What is the enthalpy?

2.9 If 20,000 CFM of air at the condition in Question 2.7 is cooled to the condition in Question 2.8, what is the rate of sensible heat removal (Btuh)? What is the rate of latent heat removal (Btuh)? What is the rate of total heat removal (Btuh)?

2.10 If 2000 CFM of air at 5°F is mixed with 8000 CFM of air at 75°F, what is the temperature of the mixed air?

2.11 If the humidity ratio of the 5°F air in Question 2.10 is 0.002 lbs of H_2O / lb of dry air, and the humidity ratio of the 75°F air is 0.0093, what is the humidity ratio of the mixed air? How much moisture in lbs/hour would be needed to raise the mixed air humidity to 0.0093 lbs of H_2O /lb of dry air?

2.12 A space has a heat gain of 40,000 Btuh sensible. How much 55°F air needs to be supplied to the space to maintain the space temperature at 75°F? How much would be needed if the supply air were 50°F?

2.13 If the 55°F air in Question 2.12 is being discharged in a saturated (100% RH) condition from a chilled water coil, and the inlet air to the coil is 100% outside air at 95°F DB and 78°F WB, what is the sensible load on the coil (Btuh)? Latent load? Total load?

2.14 If the chilled water is being supplied at 45°F, and the coil is selected so that the chilled water temperature rise is 10°F, what is the required chilled water flow through the coil in GPM?

2.15 A space has a 60,000 Btuh heat loss in winter. It is heated by a furnace discharging 110°F air. How much air will be needed to keep the space at 72°F?

2.16 If the space in Question 2.15 were heated with air from a hot water coil discharging air at 110°F, what hot water flow would be required through the coil if the hot water supply temperature is 140°F, and the hot water return temperature is 120°F?

2.17 If a steam coil were used in Question 2.16, what would be the required steam flow in lbs/hr?

2.18 Discuss the effects of humidity on interior comfort. What would you recommend for upper and lower limits during summer and winter? How does temperature influence your answer?

2.19 What are the effects of excessively high and excessively low air velocities in occupied spaces? What range of values might be appropriate for design?

2.20 In general, nonnumerical terms, how would you define good air quality?

2.21 How might you compensate for discomfort from a cold window?

2.22 Historically, what factors have caused variations in standards for ventilation of buildings in the United States? What is the authoritative source of these values?