4.6 DEFINITION OF HEAT

The thermodynamic definition of heat is somewhat different from the everyday understanding of the word. It is essential to understand clearly the definition of heat given here, because it plays a part in many thermodynamic problems.

If a block of hot copper is placed in a beaker of cold water, we know from experience that the block of copper cools down and the water warms up until the copper and water reach the same temperature. What causes this decrease in the temperature of the copper and the increase in the temperature of the water? We say that it is the result of the transfer of energy from the copper block to the water. It is from such a transfer of energy that we arrive at a definition of heat.

Heat is defined as the form of energy that is transferred across the boundary of a system at a given temperature to another system (or the surroundings) at a lower temperature by virtue of the temperature difference between the two systems. That is, heat is transferred from the system at the higher temperature to the system at the lower temperature, and the heat transfer occurs solely because of the temperature difference between the two systems. Another aspect of this definition of heat is that a body never contains heat. Rather, heat can be identified only as it crosses the boundary. Thus, heat is a transient phenomenon. If we consider the hot block of copper as one system and the cold water in the beaker as another system, we recognize that originally neither system contains any heat (they do contain energy, of course). When the copper block is placed in the water and the two are in thermal communication, heat is transferred from the copper to the water until equilibrium of temperature is established. At this point we no longer have heat transfer, because there is no temperature difference. Neither system contains heat at the conclusion of the process. It also follows that heat is identified at the boundary of the system, for heat is defined as energy transferred across the system boundary.

Heat, like work, is a form of energy transfer to or from a system. Therefore, the units for heat, and for any other form of energy as well, are the same as the units for work, or at least are directly proportional to them. In the International System the unit for heat (energy) is the joule. In the English System, the foot pound force is an appropriate unit for heat. However, another unit came to be used naturally over the years, the result of an association with the process of heating water, such as that used in connection with defining heat in the previous section. Consider as a system 1 lbm of water at 59.5 F. Let a block of hot copper of appropriate mass and temperature be placed in the water so that when thermal equilibrium is established, the temperature of the water is 60.5 F. This unit amount of heat transferred from the copper to the water in this process is called the British thermal unit (Btu). More specifically, it is called the *60-degree Btu*, defined as the amount of heat required to raise 1 lbm of water from 59.5 F to 60.5 F. (The Btu as used today is actually defined in terms of the standard SI units.) It is worth noting here that a unit of heat in metric units, the calorie, originated naturally in a manner similar to the origin of the Btu in the English System. The calorie is defined as the amount of heat required to raise 1 g of water from 14.5°C to 15.5°C.

Heat transferred *to* a system is considered positive, and heat transferred *from* a system is considered negative. Thus, positive heat represents energy transferred to a system, and negative heat represents energy transferred from a system. The symbol Q represents heat. A process in which there is no heat transfer ($Q = 0$) is called an adiabatic process.

From a mathematical perspective, heat, like work, is a path function and is recognized as an inexact differential. That is, the amount of heat transferred when a system undergoes a change from state 1 to state 2 depends on the path that the system follows during the change of state. Since heat is an inexact differential, the differential is written as δQ. On integrating, we write

$$\int_1^2 \delta Q = {}_1Q_2$$

In words, ${}_1Q_2$ is the heat transferred during the given process between states 1 and 2.

The rate at which heat is transferred to a system is designated by the symbol $\dot{Q}$:

$$\dot{Q} \equiv \frac{\delta Q}{dt}$$

It is also convenient to speak of the heat transfer per unit mass of the system, q, often termed *specific heat transfer*, which is defined as

$$q \equiv \frac{Q}{m}$$

4.7 HEAT TRANSFER MODES

Heat transfer is the transport of energy due to a temperature difference between different amounts of matter. We know that an ice cube taken out of the freezer will melt when it is placed in a warmer environment such as a glass of liquid water or on a plate with room air around it. From the discussion about energy in Section 2.6, we realize that molecules of matter have translational (kinetic), rotational, and vibrational energy. Energy in these modes can be transmitted to the nearby molecules by interactions (collisions) or by exchange of molecules such that energy is emitted by molecules that have more on average (higher temperature) to those that have less on average (lower temperature). This energy exchange between molecules is heat transfer by conduction, and it increases with the temperature difference and the ability of the substance to make the transfer. This is expressed in Fourier's law of conduction,

$$\dot{Q} = -kA\frac{dT}{dx} \tag{4.18}$$

giving the rate of heat transfer as proportional to the conductivity, k, the total area, A, and the temperature gradient. The minus sign indicates the direction of the heat transfer from a higher-temperature to a lower-temperature region. Often the gradient is evaluated as a temperature difference divided by a distance when an estimate has to be made if a mathematical or numerical solution is not available.

Values of conductivity, k, are on the order of 100 W/m K for metals, 1 to 10 for nonmetallic solids as glass, ice, and rock, 0.1 to 10 for liquids, around 0.1 for insulation materials, and 0.1 down to less than 0.01 for gases.

A different mode of heat transfer takes place when a medium is flowing, called convective heat transfer. In this mode the bulk motion of a substance moves matter with a certain energy level over or near a surface with a different temperature. Now the heat transfer by conduction is dominated by the manner in which the bulk motion brings the two substances in contact or close proximity. Examples are the wind blowing over a building or flow through heat exchangers, which can be air flowing over/through a radiator with water flowing inside the radiator piping. The overall heat transfer is typically correlated with Newton's law of cooling as

$$\dot{Q} = Ah\,\Delta T \tag{4.19}$$

where the transfer properties are lumped into the heat transfer coefficient, h, which then becomes a function of the media properties, the flow and geometry. A more detailed study of fluid mechanics and heat transfer aspects of the overall process is necessary to evaluate the heat transfer coefficient for a given situation.

Typical values for the convection coefficient (all in W/m^2 K) are:

Natural convection	$h = 5–25$, gas	$h = 50–1000$, liquid
Forced convection	$h = 25–250$, gas	$h = 50–20\,000$, liquid
Boiling phase change	$h = 2500–100\,000$	

The final mode of heat transfer is radiation, which transmits energy as electromagnetic waves in space. The transfer can happen in empty space and does not require any matter, but the emission (generation) of the radiation and the absorption do require a substance to be present. Surface emission is usually written as a fraction, emissivity ε, of a perfect black body emission as

$$\dot{Q} = \varepsilon \sigma A T_s^4 \tag{4.20}$$

with the surface temperature, T_s, and the Stefan-Boltzmann constant, σ. Typical values of emissivity range from 0.92 for nonmetallic surfaces to 0.6 to 0.9 for nonpolished metallic surfaces to less than 0.1 for highly polished metallic surfaces. Radiation is distributed over a range of wavelengths and it is emitted and absorbed differently for different surfaces, but such a description is beyond the scope of this book.

EXAMPLE 4.7

Consider the constant transfer of energy from a warm room at 20°C inside a house to the colder ambient temperature of -10°C through a single-pane window, as shown in Fig. 4.19. The temperature variation with distance from the outside glass surface is shown by an outside convection heat transfer layer, but no such layer is inside the room (as a simplification). The glass pane has a thickness of 5 mm (0.005 m) with a conductivity of 1.4 W/m K and a total surface area of 0.5 m^2. The outside wind is blowing, so the convective heat transfer coefficient is 100 W/m^2 K. With an outer glass surface temperature of 12.1°C, we would like to know the rate of heat transfer in the glass and the convective layer.

For the conduction through the glass we have

$$\dot{Q} = -kA\frac{dT}{dx} = -kA\frac{\Delta T}{\Delta x} = -1.4\frac{\text{W}}{\text{m K}} \times 0.5\ \text{m}^2\,\frac{20 - 12.1}{0.005}\,\frac{\text{K}}{\text{m}} = -1106\ \text{W}$$

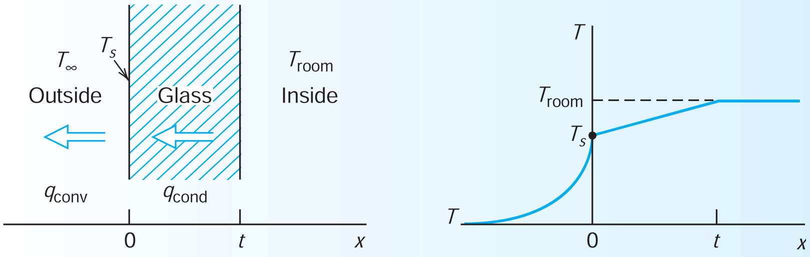


FIGURE 4.19 Conduction and convection heat transfer through a window pane.

and the negative sign shows that energy is leaving the room. For the outside convection layer we have

$$\dot{Q} = hA\,\Delta T = 100\frac{\text{W}}{\text{m}^2\ \text{K}} \times 0.5\ \text{m}^2[12.1 - (-10)]\ \text{K} = 1105\ \text{W}$$

with a direction from the higher to the lower temperature, that is, toward the outside.

4.8 COMPARISON OF HEAT AND WORK

At this point it is evident that there are many similarities between heat and work.

1. Heat and work are both transient phenomena. Systems never possess heat or work, but either or both cross the system boundary when a system undergoes a change of state.
2. Both heat and work are boundary phenomena. Both are observed only at the boundary of the system, and both represent energy crossing the boundary.
3. Both heat and work are path functions and inexact differentials.

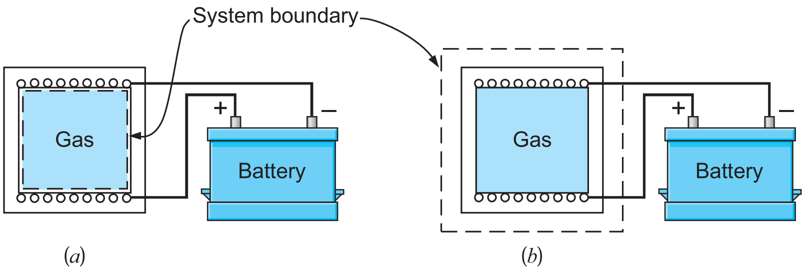
It should also be noted that in our sign convention, $+Q$ represents heat transferred *to* the system and thus is energy added to the system, and $+W$ represents work done *by* the system and thus is energy leaving the system.

Another illustration may help explain the difference between heat and work. Figure 4.20 shows a gas contained in a rigid vessel. Resistance coils are wound around the outside of the vessel. When current flows through the resistance coils, the temperature of the gas increases. Which crosses the boundary of the system, heat or work?

In Fig. 4.20*a* we consider only the gas as the system. The energy crosses the boundary of the system because the temperature of the walls is higher than the temperature of the gas. Therefore, we recognize that heat crosses the boundary of the system.

In Fig. 4.20*b* the system includes the vessel and the resistance heater. Electricity crosses the boundary of the system and, as indicated earlier, this is work.

Consider a gas in a cylinder fitted with a movable piston, as shown in Fig. 4.21. There is a positive heat transfer to the gas, which tends to increase the temperature. It also tends to increase the gas pressure. However, the pressure is dictated by the external force acting on its movable boundary, as discussed in Section 2.8. If this remains constant, then the volume increases instead. There is also the opposite tendency for a negative heat transfer, that is,



(*a*) (*b*)

FIGURE 4.20 An example of the difference between heat and work.

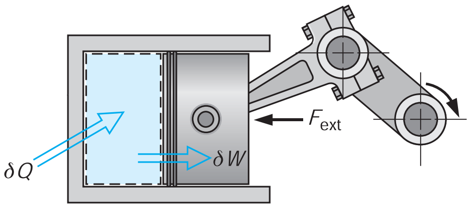


FIGURE 4.21 The effects of heat addition to a control volume that also can give out work.

one out of the gas. Consider again the positive heat transfer, except that in this case the external force simultaneously decreases. This causes the gas pressure to decrease so that the temperature tends to go down. In this case, there is a simultaneous tendency toward temperature change in the opposite direction, which effectively decouples the directions of heat transfer and temperature change.

Often when we want to evaluate a finite amount of energy transferred as either work or heat, we must integrate the instantaneous rate over time:

$$ {}_1W_2 = \int_1^2 \dot{W}\,dt, \qquad {}_1Q_2 = \int_1^2 \dot{Q}\,dt $$

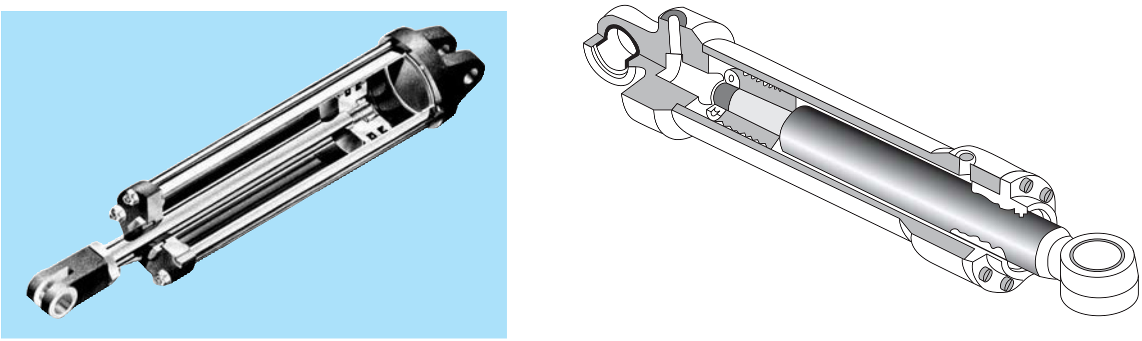
In order to perform the integration, we must know how the rate varies with time. For time periods when the rate does not change significantly, a simple average may be sufficiently accurate to allow us to write

$$ {}_1W_2 = \int_1^2 \dot{W}\,dt = \dot{W}_{\text{avg}}\,\Delta t \tag{4.21} $$

which is similar to the information given on your electric utility bill in kW-hours.

4.9 ENGINEERING APPLICATIONS

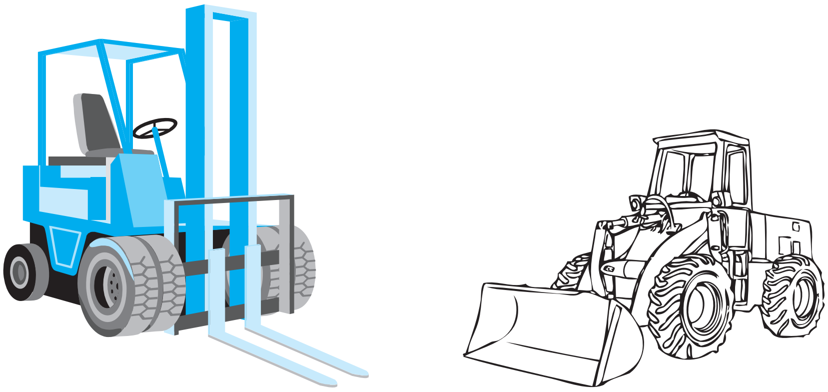
When work needs to be transferred from one body to another, a moving part is required, which can be a piston/cylinder combination. Examples are shown in Fig. 4.22. If the



(*a*) Hydraulic cylinder

(*b*) Hydraulic or pneumatic cylinder

FIGURE 4.22 Basic hydraulic or pneumatic cylinders.


(*a*) Forklift

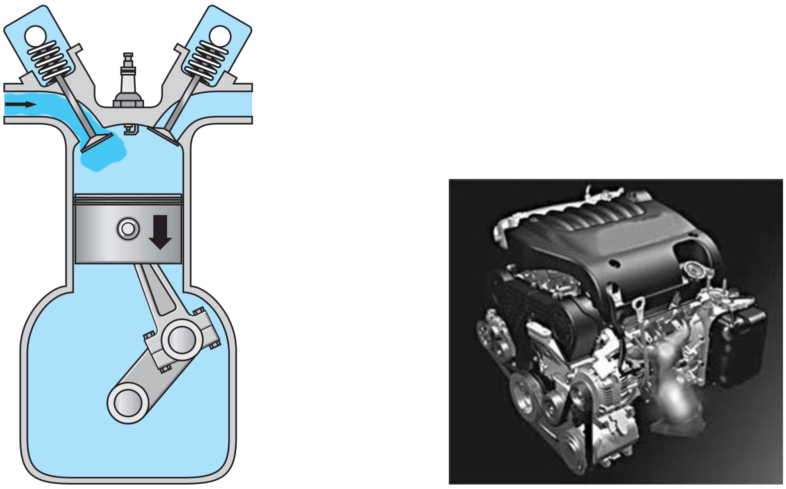
(*b*) Construction frontloader

FIGURE 4.23 Heavy-duty equipment using hydraulic cylinders.

substance that generates the motion is a gas, it is a pneumatic system, and if the substance is a liquid, it is a hydraulic system. The gas or vapor is typically used when the motion has to be fast or the volume change large and the pressures moderate. For high-pressure (large-force) displacements a hydraulic cylinder is used (examples include a bulldozer, forklift, frontloader, and backhoe. Also, see Example 2.7). Two of these large pieces of equipment are shown in Fig. 4.23.

We also consider cases where the substance inside the piston/cylinder undergoes a combustion process, as in gasoline and diesel engines. A schematic of an engine cylinder and a photo of a modern V6 automotive engine are shown in Fig. 4.24. This subject is discussed in detail in Chapter 12.

Many other transfers of work involve rotating shafts, such as the transmission and drive shaft in a car or a chain and rotating gears in a bicycle or motorcycle (Fig. 4.25).


(*a*) Schematic of engine cylinder

(*b*) V6 automotive engine

FIGURE 4.24 Schematic and photo of an automotive engine.

FIGURE 4.25 Bicycle chain drive.

FIGURE 4.26 Electrical power transmission tower and line.

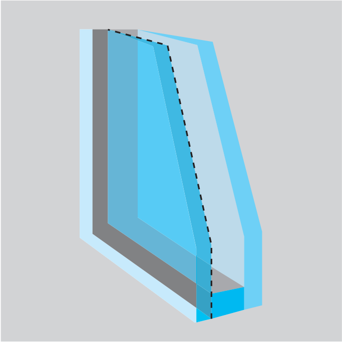


FIGURE 4.27 Thermopane window.

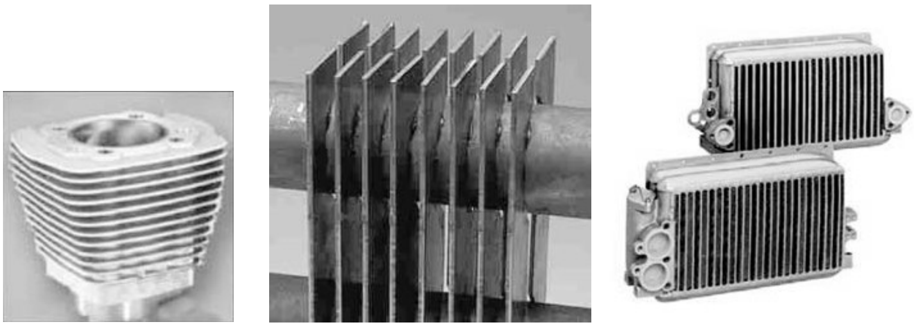


FIGURE 4.28 Examples of fin-enhanced heat transfer.

(*a*) Motorcycle engine cylinder

(*b*) Inside of a baseboard heater

(*c*) Air cooled heavy-equipment oil coolers

For transmission of power over long distances, the most convenient and efficient form is electricity. A transmission tower and line are shown in Fig. 4.26.

Heat transfer occurs between domains at different temperatures, as in a building with different inside and outside temperatures. The double set of window panes shown in Fig. 4.27 is used to reduce the rate of heat transfer through the window. In situations where an increased rate of heat transfer is desirable, fins are often used to increase the surface area for heat transfer to occur. Examples are shown in Fig. 4.28.

SUMMARY

Work and heat are energy transfers between a control volume and its surroundings. Work is energy that can be transferred mechanically (or electrically or chemically) from one system to another and must cross the control surface either as a transient phenomenon or as a steady rate of work, which is power. Work is a function of the process path as well as the beginning state and end state. The displacement work is equal to the area below the process curve drawn in a P–V diagram in an equilibrium process. A number of ordinary processes can be expressed as polytropic processes having a particular simple mathematical form for the P–V relation. Work involving the action of surface tension, single-point forces, or electrical systems should be recognized and treated separately. Any nonequilibrium processes (say, dynamic forces, which are important due to accelerations) should be identified so that only equilibrium force or pressure is used to evaluate the work term.

Heat transfer is energy transferred due to a temperature difference, and the conduction, convection, and radiation modes are discussed.

You should have learned a number of skills and acquired abilities from studying this chapter that will allow you to

- Recognize force and displacement in a system.
- Understand power as the rate of work (force × velocity, torque × angular velocity).
- Know that work is a function of the end states and the path followed in a process.
- Calculate the work term knowing the P–V or F–x relationship.
- Evaluate the work involved in a polytropic process between two states.
- Know that work is the area under the process curve in a P–V diagram.

- Apply a force balance on a mass and determine work in a process from it.
- Distinguish between an equilibrium process and a nonequilibrium process.
- Recognize the three modes of heat transfer: conduction, convection, and radiation.
- Be familiar with Fourier's law of conduction and its use in simple applications.
- Know the simple models for convection and radiation heat transfer.
- Understand the difference between the rates ($\dot{W}$, $\dot{Q}$) and the amounts (${}_1W_2$, ${}_1Q_2$) of work.

KEY CONCEPTS AND FORMULAS

Work	Energy in transfer: mechanical, electrical, and chemical
Heat	Energy in transfer caused by ΔT
Displacement work	$W = \int_1^2 F\,dx = \int_1^2 P\,dV = \int_1^2 \mathcal{S}\,dA = \int_1^2 T\,d\theta$
Specific work	$w = W/m$ (work per unit mass)
Power, rate of work	$\dot{W} = F\mathbf{V} = P\dot{V} = T\omega$ ($\dot{V}$ displacement rate) Velocity $\mathbf{V} = r\omega$, torque $T = Fr$, angular velocity $= \omega$
Polytropic process	$PV^n =$ constant or $Pv^n =$ constant
Polytropic process work	${}_1W_2 = \frac{1}{1-n}(P_2V_2 - P_1V_1)$ (if $n \neq 1$) ${}_1W_2 = P_1V_1 \ln\frac{V_2}{V_1}$ (if $n = 1$)
Conduction heat transfer	$\dot{Q} = -kA\frac{dT}{dx}$
Conductivity	k (W/m K)
Convection heat transfer	$\dot{Q} = -hA\,\Delta T$
Convection coefficient	h (W/m^2 K)
Radiation heat transfer (net to ambient)	$\dot{Q} = \varepsilon\sigma A(T_s^4 - T_{\text{amb}}^4)$ ($\sigma = 5.67 \times 10^{-8}$ W/m^2 K^4)
Rate integration	${}_1Q_2 = \int \dot{Q}\,dt \approx \dot{Q}_{\text{avg}}\,\Delta t$

CONCEPT-STUDY GUIDE PROBLEMS

4.1 A car engine is rated at 160 hp. What is the power in SI units?

4.2 Two engines provide the same amount of work to lift a hoist. One engine can provide 3 F in a cable and the other 1 F. What can you say about the motion of the point where the force F acts in the two engines?

4.3 Two hydraulic piston/cylinders are connected through a hydraulic line so that they have roughly the same pressure. If they have diameters D_1 and $D_2 = 2D_1$, respectively, what can you say about the piston forces F_1 and F_2?

4.4 Normally pistons have a flat head, but in diesel engines pistons can contain bowls and protruding ridges. Does this geometry influence the work term?

4.5 CV A is the mass inside a piston/cylinder. CV B is that mass plus the mass of the piston, outside which is the standard atmosphere. Write the process equation and the work term for the two CVs.