Fundamentals of Renewable Energy

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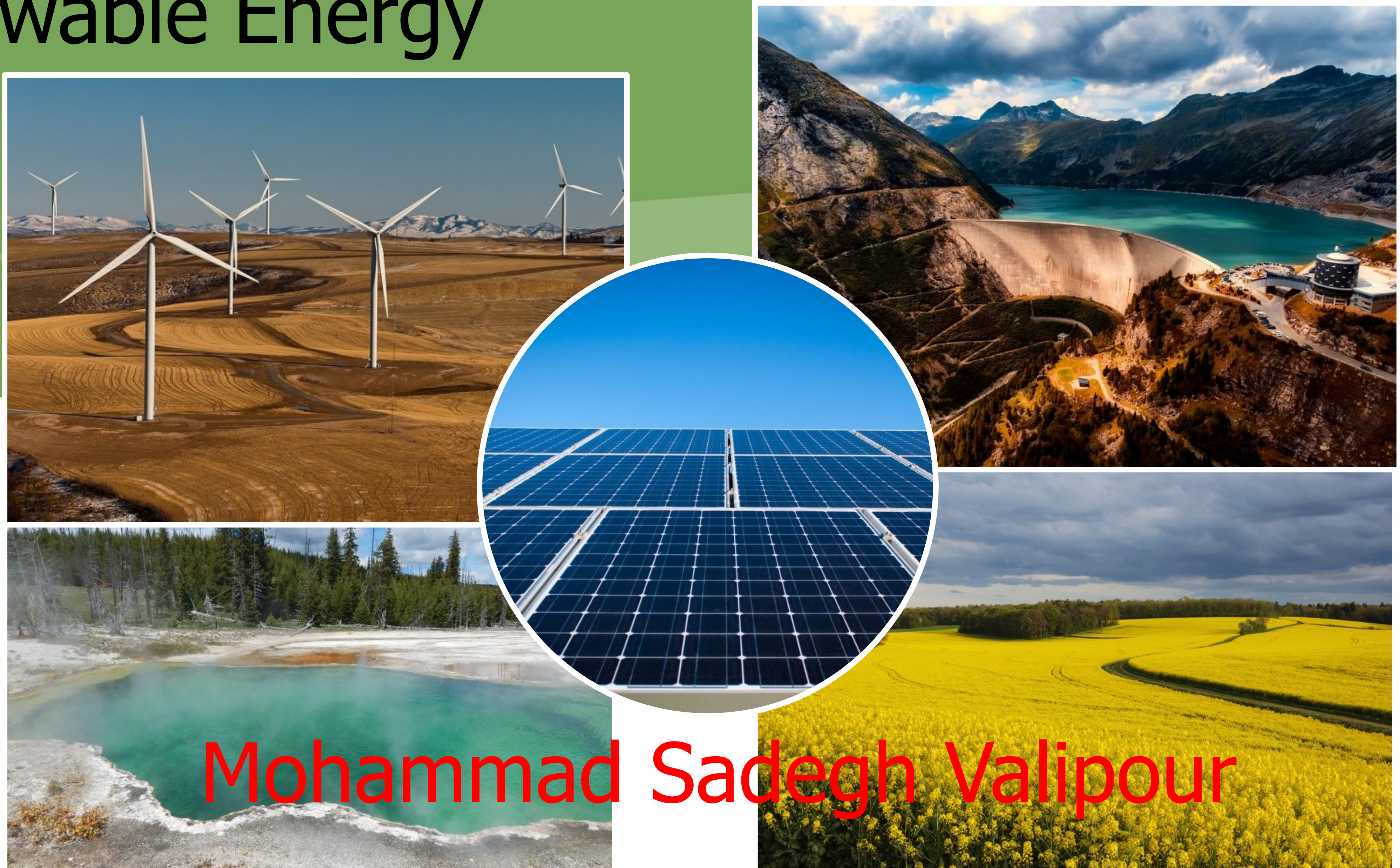

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CHAPTER 2

A Review of Thermal Sciences

THERMAL SCIENCES

The analysis of renewable energy systems requires a solid understanding of energy conversion processes, transformation between various forms of energy, and ways of defining efficiencies of energy producing and consuming systems. In this chapter, we review fundamental concepts of thermodynamics, heat transfer, fluid mechanics, thermochemistry, power plants, and refrigeration systems to form a solid and useful foundation for the renewable energy systems to be covered in the upcoming chapters.

THERMAL SCIENCES

The physical sciences that deal with energy and the transfer, transport, and conversion of energy are usually referred to as thermal-fluid sciences or just thermal sciences.

THERMAL SCIENCES

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The design and analysis of most thermal systems involve all categories of thermal sciences. For example, designing a solar collector involves the determination of the amount of energy transfer from a knowledge of thermodynamics, the determination of the size of the heat exchanger using heat transfer, and the determination of the size and type of the pump using fluid mechanics.

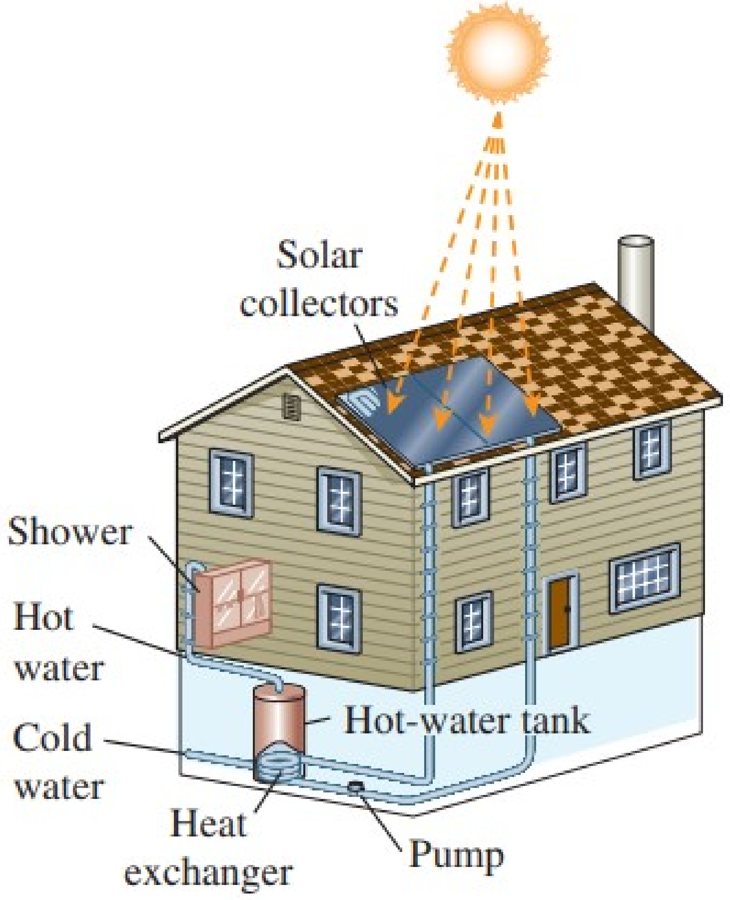

Figure 2-1
The design and analysis of renewable energy systems, such as this solar hot water system, involves thermal sciences.

THERMODYNAMICS

Thermodynamics can be defined as the science of energy. The name thermodynamics stems from the Greek words therme (heat) and dynamics (power), which is most descriptive of the early efforts to convert heat into power.

conservation of energy principle

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It simply states that during an interaction, energy can change from one form to another but the total amount of energy remains constant. That is, energy cannot be created or destroyed.

The change in the energy content of a body or any other system is equal to the difference between the energy input and the energy output, and the energy balance is expressed as:

$$E_{in} - E_{out} = \Delta E_{system}$$

THERMODYNAMICS

The first law of thermodynamics is simply an expression of the conservation of energy principle, and it asserts that energy is a thermodynamic property.

The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy.

Heat and Other Forms of Energy

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear, and their sum constitutes the total energy E (or e on a unit mass basis) of a system. The sum of all microscopic forms of energy is called the internal energy of a system, and is denoted by U (or u on a unit mass basis).

Heat and Other Forms of Energy

Internal energy may be viewed as the sum of the kinetic and potential energies of the molecules. The portion of the internal energy of a system associated with the kinetic energy of the molecules is called sensible energy or sensible heat. At higher temperatures the molecules possess higher kinetic energy, and as a result, the system has a higher internal energy.

The internal energy is also associated with the intermolecular forces between the molecules of a system.

If sufficient energy is added to the molecules of a solid or liquid, they will overcome these molecular forces and simply break away, turning the system to a gas.

Heat and Other Forms of Energy

We perefer the term enthalpy for convenience. That is, h = u + Pv, where the term Pv represents the flow energy of the fluid (also called the flow work), which is the energy needed to push a fluid and to maintain flow. In the energy analysis of flowing fluids, it is convenient to treat the flow energy as part of the energy of the fluid and to represent the microscopic energy of a fluid stream by enthalpy h.

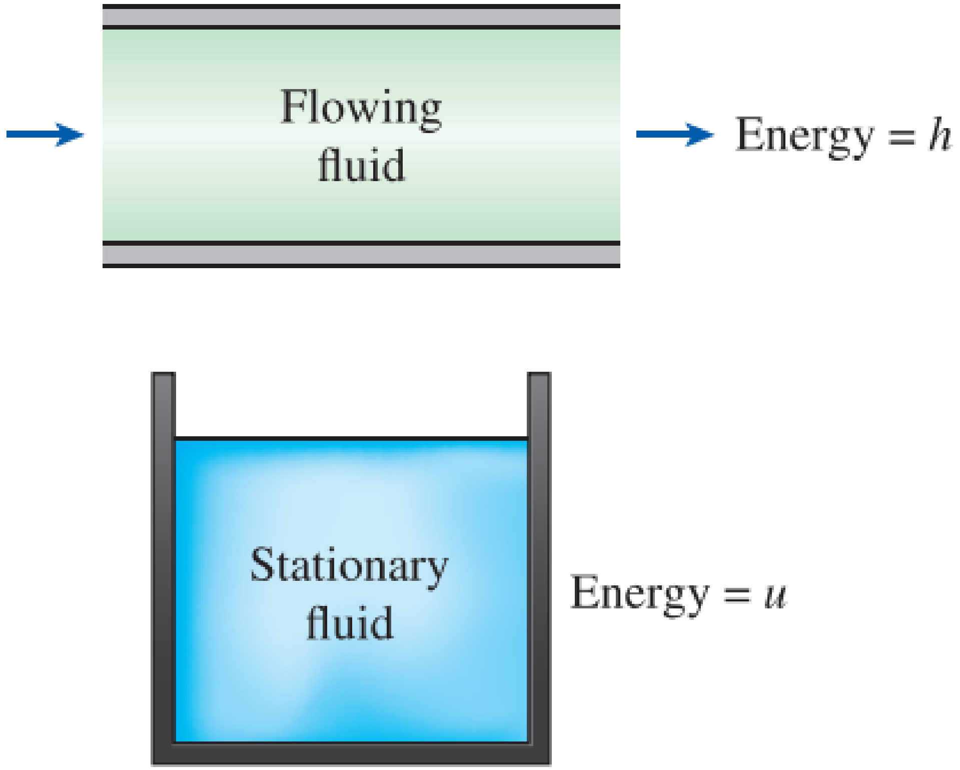

Figure 2-2
The internal energy u represents the microscopic energy of a nonflowing fluid, whereas enthalpy h represents the microscopic energy of a flowing fluid.

Specific Heats of Gases, Liquids, and Solids

An ideal gas is defined as a gas that obeys the relation

$$Pv = RT \quad or\ P = \rho RT$$

Specific Heats of Gases, Liquids, and Solids

Specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree.

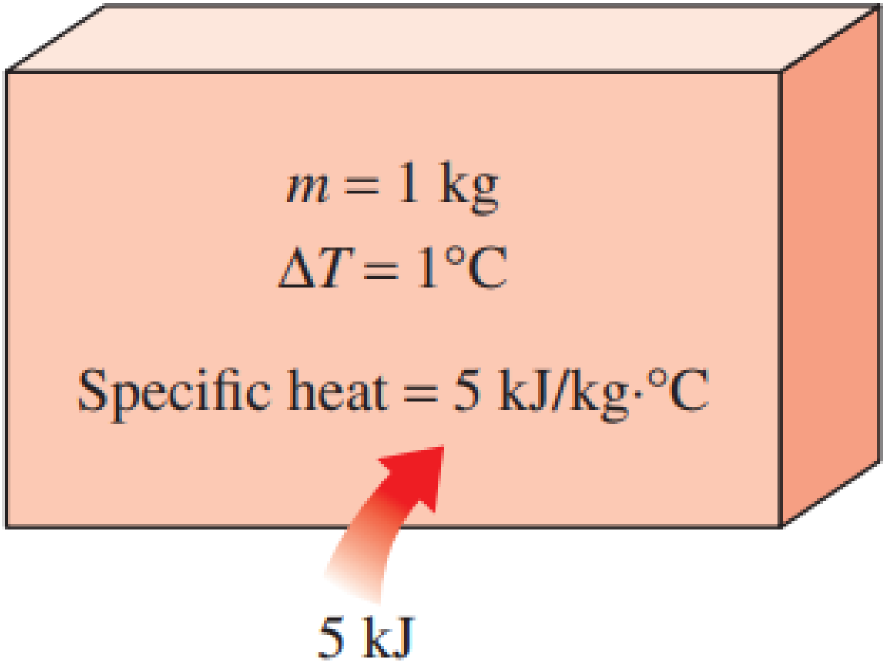

Figure 2-3
Specific heat is the energy required toraise the temperature of a unit mass of a substance by one degree in a specified way.

Specific Heats of Gases, Liquids, and Solids

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The specific heat of a substance, in general, depend on two independent properties such as temperature and pressure. For an ideal gas, however, they depend on temperature only (Fig. 2-4). At low pressures all real gases approach ideal gas behavior, and therefore their specific heats depend on temperature only.

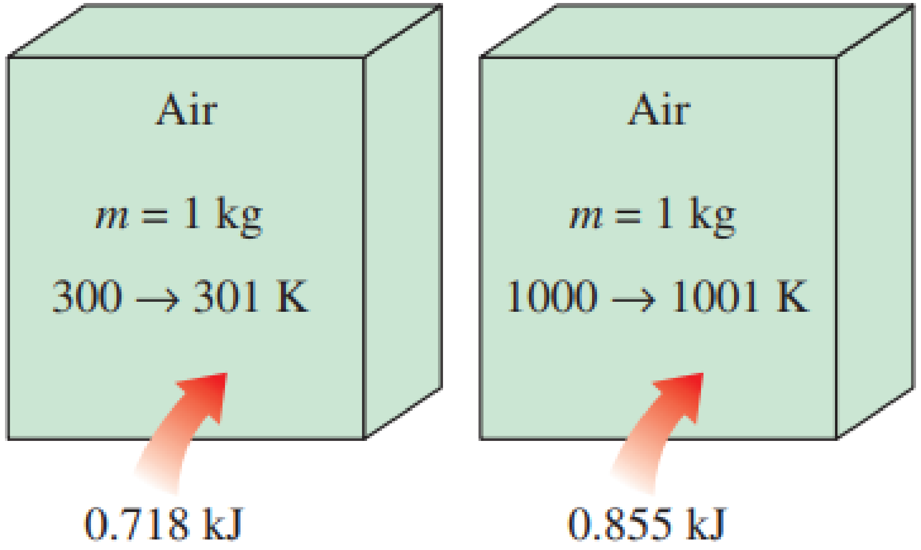

Figure 2-4
The specific heat of a substance changes with temperature.

Specific Heats of Gases, Liquids, and Solids

The differential changes in the internal energy u and enthalpy h of an ideal gas can be expressed in terms of the specific heats as

$$du = c_v dT \ and \ dh = c_p dT$$

The finite changes in the internal energy and enthalpy of an ideal gas during a process can be expressed approximately by using specific heat values at the average temperature as

$$\Delta u = c_{v.ave} \Delta T \ and \ \Delta h = c_{p.ave} \Delta T$$

$$\Delta U = m c_{v,ave} \Delta T \ and \ \Delta H = m c_{p,ave} \Delta T$$

Specific Heats of Gases, Liquids, and Solids

A substance whose specific volume (or density) does not change with temperature or pressure is called an incompressible substance.

The constant-volume and constant-pressure specific heats are identical for incompressible substances. Therefore, for solids and liquids the subscripts on cv and cp can be dropped and both specific heats can be represented by a single symbol, c. That is, cp =cv = c.

Specific Heats of Gases, Liquids, and Solids

The specific heats of incompressible substances depend on temperature only. Therefore, the change in the internal energy of solids and liquids can be expressed as

$$\Delta U = mc_{avg}\Delta T$$

The First Law of Thermodynamics

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The first law of thermodynamics, also known as the conservation of energy principle, states that energy can neither be created nor be destroyed during a process; it can only change forms.

$$E_{in} - E_{out} = \Delta E_{system}$$

Noting that energy can be transferred to or from a system by heat, work, and mass flow, and that the total energy of a simple compressible system consists of internal, kinetic, and potential energies, the energy balance for any system undergoing any process can be expressed as

The First Law of Thermodynamics

In the absence of significant electric, magnetic, motion, gravity, and surface tension effects (i.e., for stationary simple compressible systems), the change in the total energy of a system during a process is simply the change in its internal energy. That is, DEsystem = DUsystem. Energy balance can be written in the rate form, as

$$\dot{E}_{in} - \dot{E}_{out} = dE_{system}/dt$$

The First Law of Thermodynamics

Energy is a property, and the value of a property does not change unless the state of the system changes. Therefore, the energy change of a system is zero if the state of the system does not change during the process, that is, the process is steady. The energy balance in this case reduces to (Fig. 2-5)

$$\dot{E}_{in} = \dot{E}_{out}$$

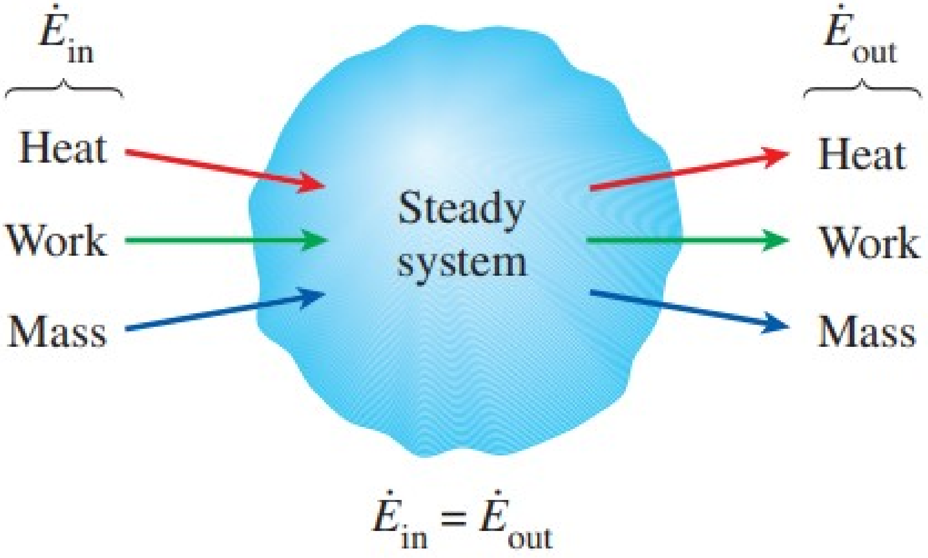

Figure 2-5
In steady operation, the rate of energy transfer to a system is equal to the rate of energy transfer from the system.

Energy Balance for Closed Systems

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A closed system consists of a fixed mass. The total energy E for most systems encountered in practice consists of the internal energy U. This is especially the case for stationary systems since they do not involve any changes in their velocity or elevation during a process. The energy balance relation in that case reduces to

Stationary closed system:

$$\boldsymbol{E_{in} - E_{out} = \Delta U = mc_v\Delta T \qquad (kJ)}$$

Energy Balance for Closed Systems

Stationary closed system, no work:

$$Q = mc_v\Delta T \quad (kJ)$$

The term steady means no change with time at a specified location.

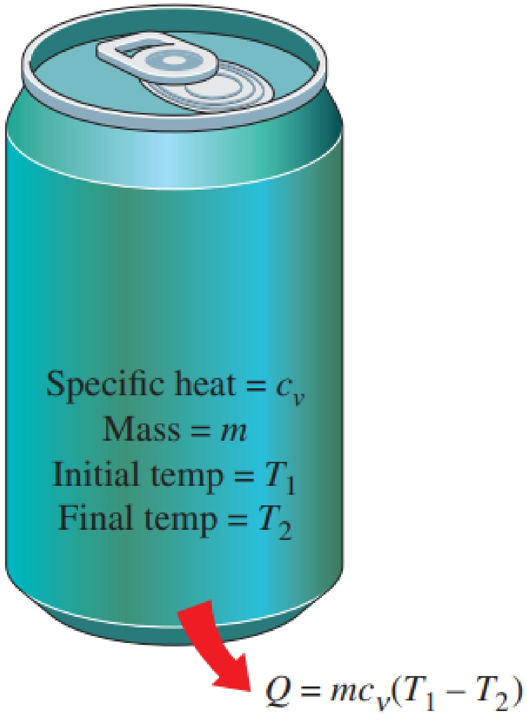

Figure 2-6
In the absence of any work interactions, the change in the energy content of a closed system is equal to the net heat transfer.

Energy Balance for Steady-Flow Systems

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The total energy content of a control volume during steady-flow process remains constant (E_{CV}=constant). That is, the change in the total energy of the control volume during such a process is zero (ΔE_{CV}=0). Thus the amount of energy entering a control volume in all forms (heat, work, mass transfer) for a steady-flow process must be equal to the amount of energy leaving it. In rate form, it is expressed as

$$\dot{E}_{in} = \dot{E}_{out}$$

Energy Balance for Steady-Flow Systems

The amount of mass flowing through a cross section of a flow device per unit time is called the mass flow rate, and is denoted by $\dot{m}$.

$$\dot{m} = \rho V A_c$$

The volume of a fluid flowing through a pipe or duct per unit time is called the volume flow rate $\dot{V}$, and is expressed as

$$\dot{V} = V A_c = \frac{\dot{m}}{\rho}$$

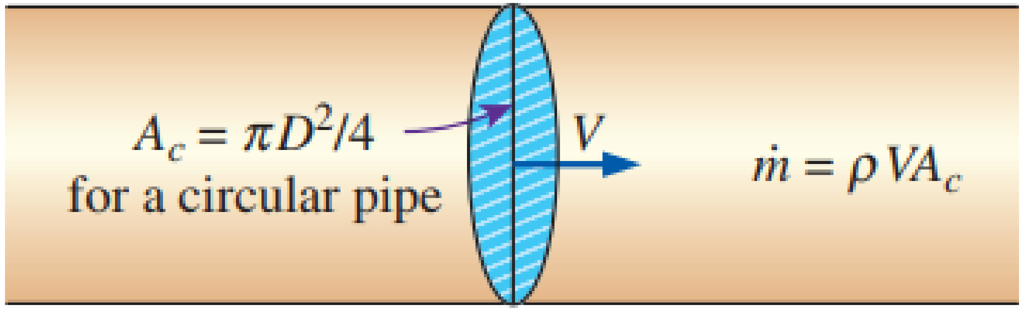

Figure 2-7
The mass flow rate of a fluid at a cross section.

Energy Balance for Steady-Flow Systems

For a steady-flow system with one inlet and one exit, the rate of mass flow into the control volume must be equal to the rate of mass flow out of it. That is, $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$. When the changes in kinetic and potential energies are negligible, which is usually the case, and there is no work interaction, the energy balance for such a steady-flow system reduces to

$$\dot{Q} = \dot{m}\Delta h = \dot{m}c_p\Delta T \qquad (kW)$$

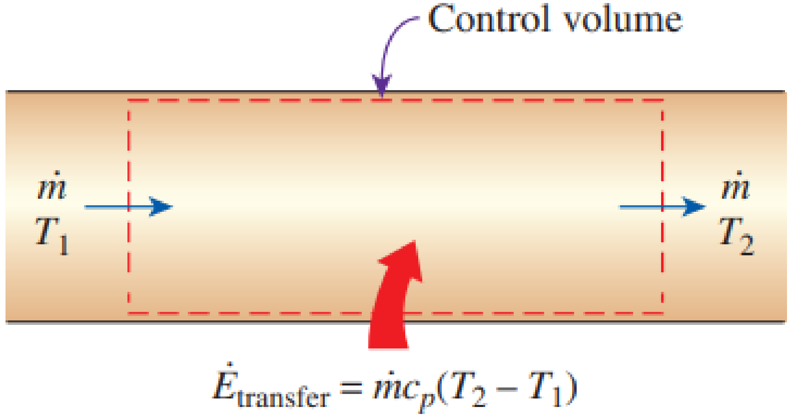

Figure 2-8
Under steady conditions, the net rate of energy transfer to a fluid i a control volume is equal to the rate of increase in the energy of the fluid stream flowing through the control volume.

Energy Balance for Steady-Flow Systems

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EXAMPLE 2-1 **A house has an electric heating system that consists of a 250-W fan and an electric resistance heating element placed in a duct (Fig. 2-9). Air flows steadily through the duct at a rate of 0.5 kg/s and experiences a temperature rise of 7°C. The rate of heat loss from the air in the duct is estimated to be 400 W. Determine the power rating of the electric resistance heating element.**

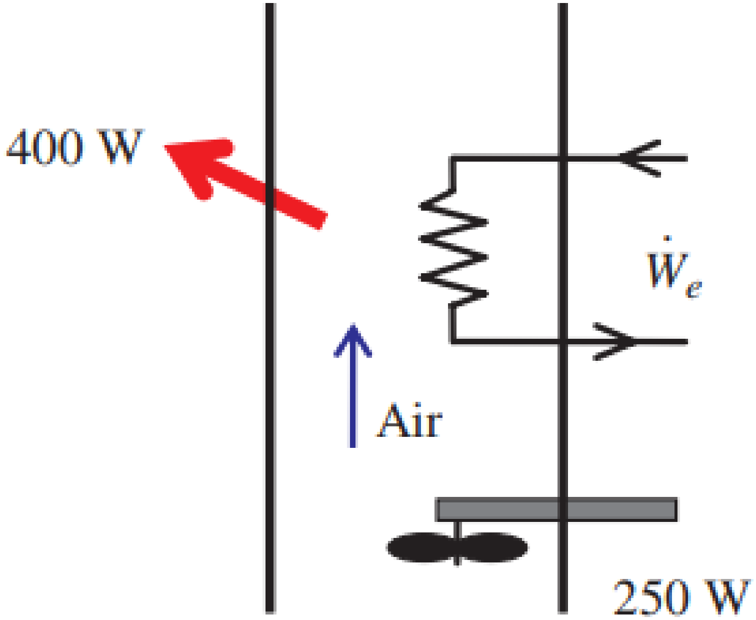

Figure 2-9
Schematic for Example 2-1.

Energy Balance for Steady-Flow Systems

SOLUTION Air is considered as an ideal gas and constant specific heats at room temperature can be used for air. The specific heat of air at room temperature is cp = 1.005 kJ/kg·°C (Table A-1). We take the heating duct as the system. This is a control volume since mass crosses the system boundary during the process. We observe that this is a steady-flow process since there is no change with time at any point and thus Δm_{cv} and ΔE_{cv}=0. Also, there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. The energy balance for this steady-flow system can be expressed in the rate form as

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{e,in} + \dot{W}_{fan,in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

$$\dot{W}_{e,in} = \dot{Q}_{out} - \dot{W}_{fan,in} + \dot{m}(h_2 - h_1)$$

$$\dot{W}_{e,in} = \dot{Q}_{out} - \dot{W}_{fan,in} + \dot{m}c_p\Delta T$$

Energy Balance for Steady-Flow Systems

Substituting, the power rating of the heating element is determined to be

$$\dot{W}_{e,in} = (0.400\ kW) - (0.250\ kW) + \left(0.5\,\frac{kg}{s}\right)(1.005\ kJ/kg.°C)(7\ °C) = 3.67\ kW$$

Saturation Temperature and Saturation Pressure

At a given pressure, the temperature at which a pure substance changes phase is called the saturation temperature Tsat. Likewise, at a given temperature, the pressure at which a pure substance changes phase is called the saturation pressure Psat. At a pressure of 101.3 kPa, Tsat is 100°C. Conversely, at a temperature of 100°C, Psat is 101.3 kPa.

Saturation Temperature and Saturation Pressure

Temperature (T, °C)	Saturation pressure (P_{sat}, kPa)
-5	0.403
0	0.611
5	0.872
10	1.23
15	1.71
20	2.34
25	3.17

Table 2-1
Saturation (Boiling) Pressure of Water at Various Temperatures.

Saturation Temperature and Saturation Pressure

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It takes a large amount of energy to melt a solid or vaporize a liquid. The amount of energy absorbed or released during a phase-change process is called the latent heat. More specifically, the amount of energy absorbed during melting is called the latent heat of fusion and is equivalent to the amount of energy released during freezing.

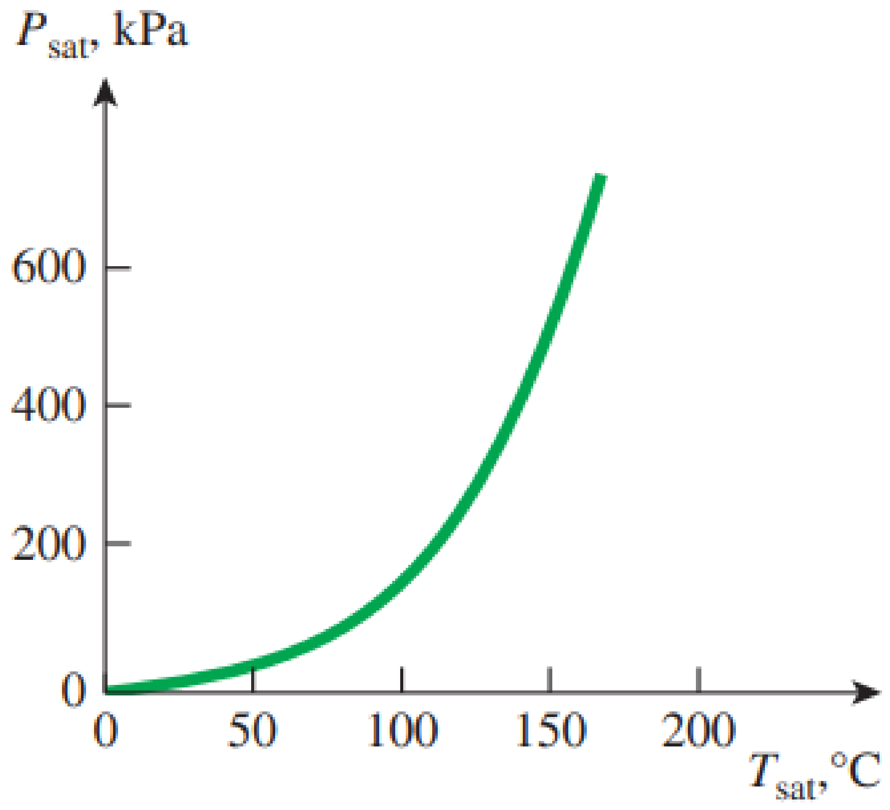

Figure 2-10
The liquid-vapor saturation curve of
a pure substance (numerical values are for water).

Saturation Temperature and Saturation Pressure

The atmospheric pressure, and thus the boiling temperature of water, decreases with elevation. Therefore, it takes longer to cook at higher altitudes than it does at sea level (unless a pressure cooker is used).

HEAT TRANSFER

We define heat as the form of energy that can be transferred from one system to another as a result of temperature difference.
The science that deals with the determination of the rates of such energy transfers is the heat transfer. The transfer of energy as heat is always from the higher-temperature medium to the lower temperature one, and heat transfer stops when the two mediums reach the same temperature.

Heat can be transferred in three different modes: conduction, convection, and radiation.

Conduction Heat Transfer

Conduction is the transfer of energy from the more energetic particles of substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids, liquids, or gases. In gases and liquids, conduction is due to the collisions and diffusion of the molecules during their random motion. In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.

Conduction Heat Transfer

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Consider steady heat conduction through a large plane wall of thickness Dx = L and area A, as shown in Fig. 2-11.

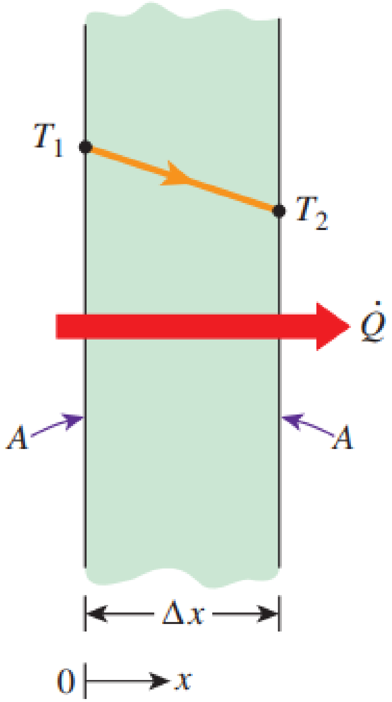

Figure 2-11
Heat conduction through a large plane wall.

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad (kW)$$

Conduction Heat Transfer

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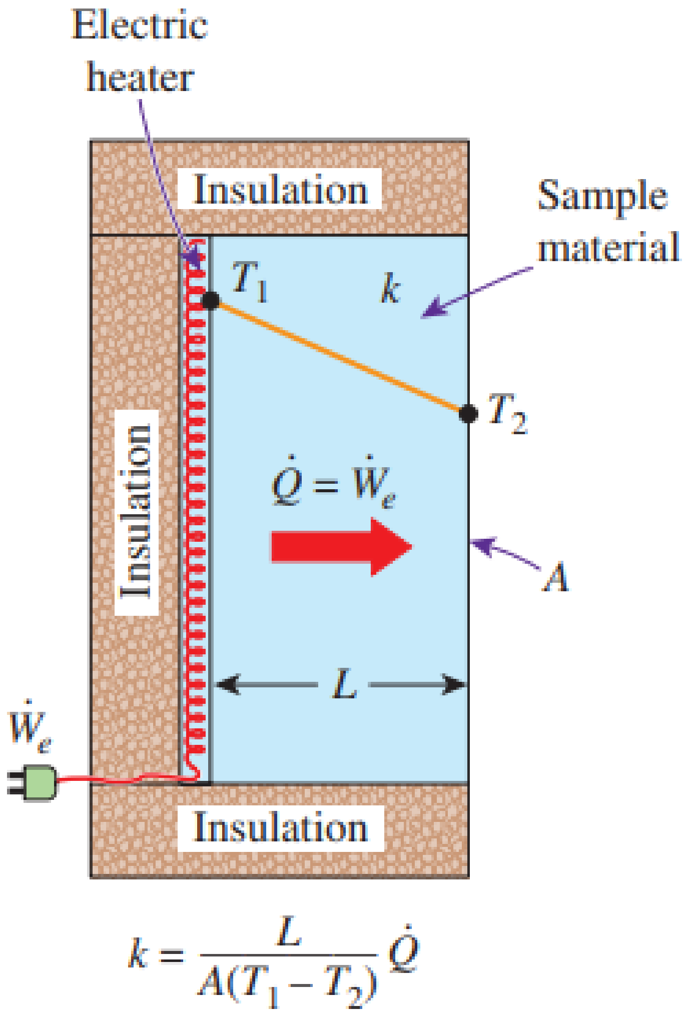
which is called Fourier's law of heat conduction after J. Fourier, who expressed it first in his heat transfer text in 1822. Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing x. The negative sign in Eq. (*) ensures that heat transfer in the positive x direction is a positive quantity

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \qquad (*)$$

Thermal Conductivity

A layer of material of known thickness and area can be heated from one side by an electric resistance heater of known output. If the outer surfaces of the heater are well insulated, all the heat generated by the resistance heater will be transferred through the material whose conductivity is to be determined.



$$k = \frac{L}{A(T_1 - T_2)}\dot{Q}$$

Figure 2-13
The rate of heat conduction through a solid is directly proportional to its thermal conductivity

Thermal Conductivity

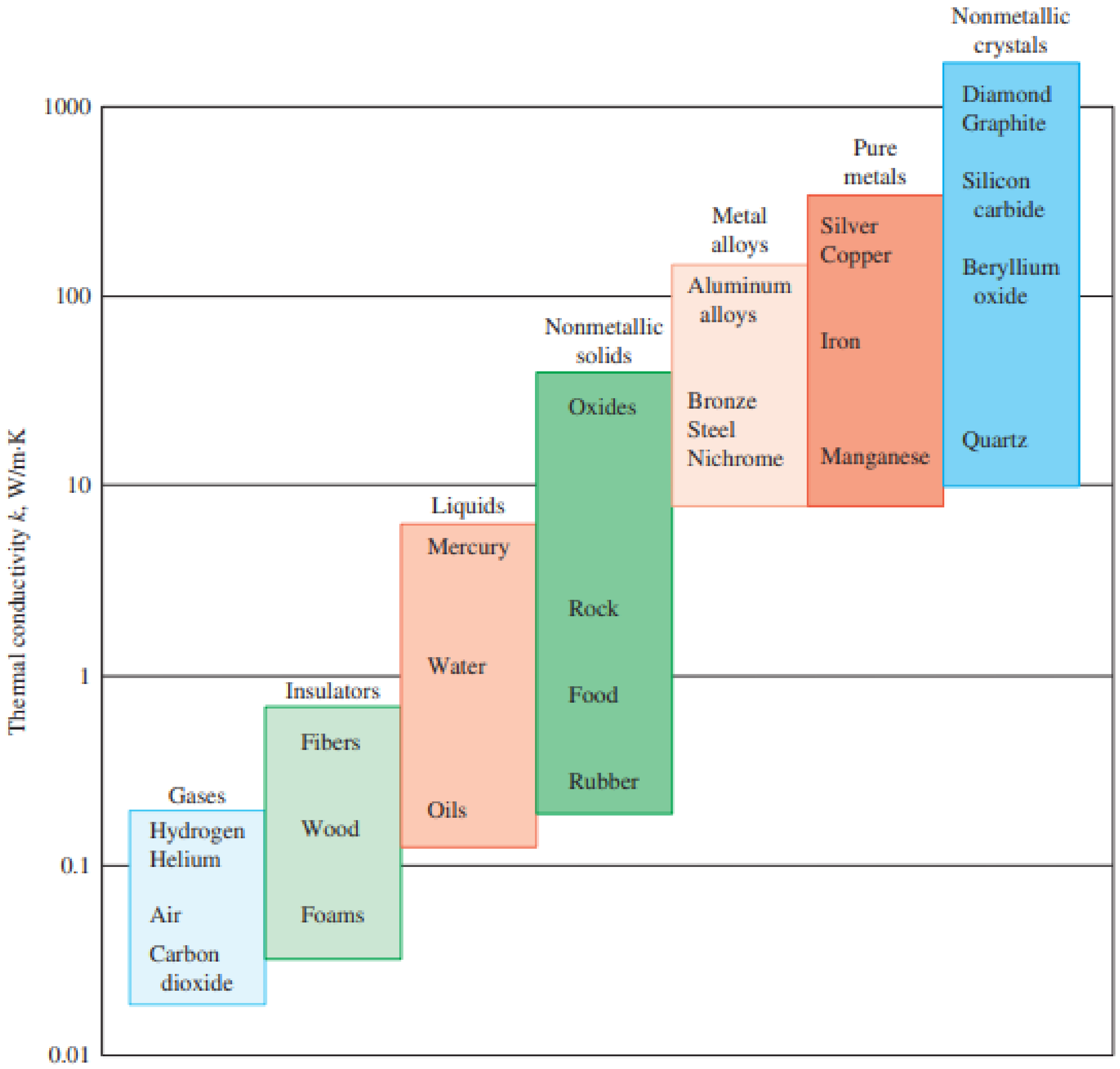
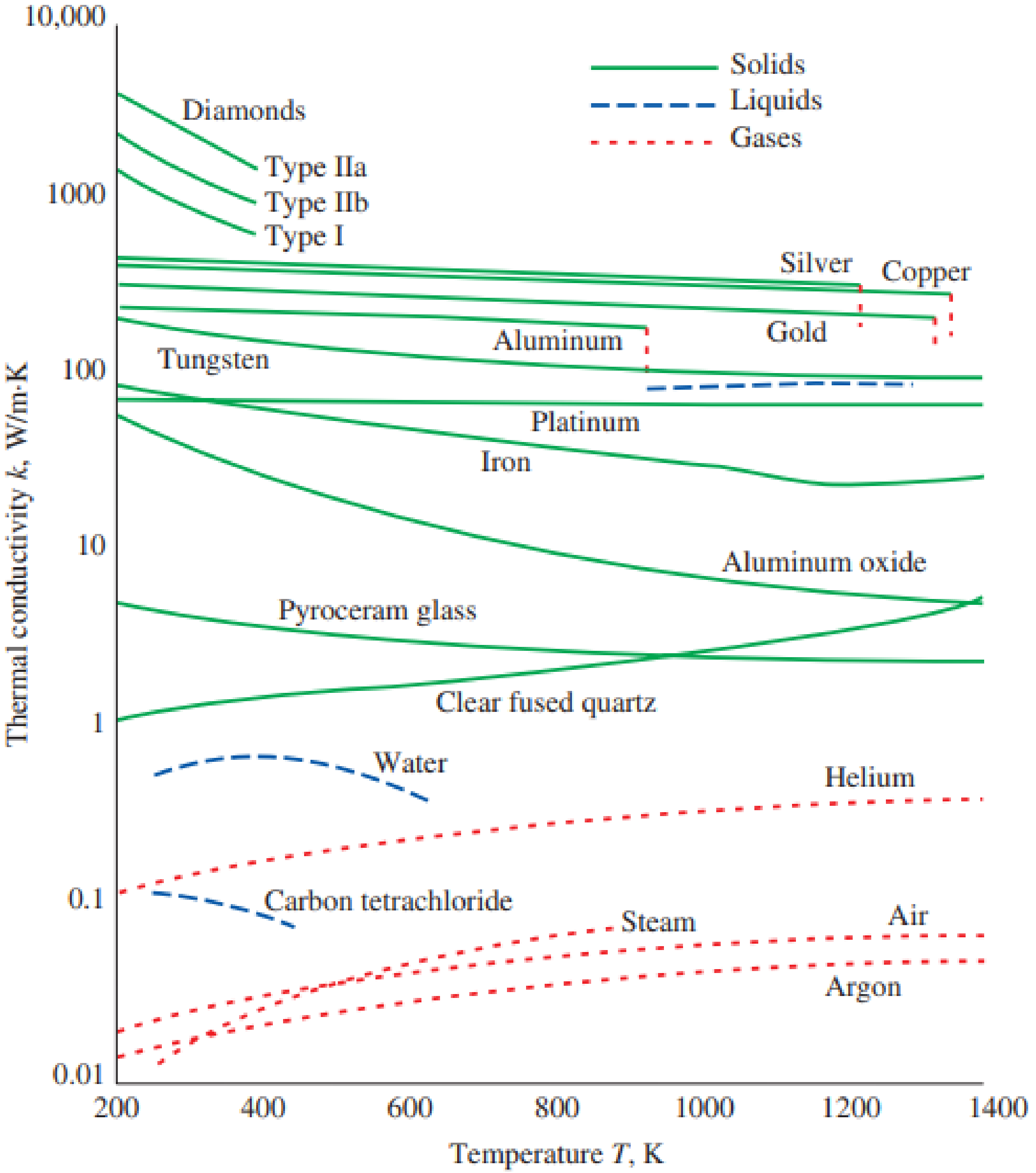


Figure 2-14
The range of thermal conductivity of various materials at room temperature/

Thermal Conductivity

In solids, heat conduction is due to two effects: the lattice vibrational waves induced by the vibrational motions of the molecules positioned at relatively fixed positions in a periodic manner called a lattice, and the energy transported via the free flow of electrons in the solid.

Thermal Conductivity



The thermal conductivities of liquids usually lie between those of solids and gases. The thermal conductivity of a substance is normally highest in the solid phase and lowest in the gas phase.

Unlike gases, the thermal conductivities of most liquids decrease with increasing temperature, with water being a notable exception.

Figure 2-15
The variation of the thermal conductivity of various solids, liquids, and gases with temperature.

Thermal Conductivity

In heat transfer analysis, a material is normally assumed to be isotropic; that is, to have uniform properties in all directions. This assumption is realistic for most materials, except those that exhibit different structural characteristics in different directions, such as laminated composite materials and wood. The thermal conductivity of wood across the grain, for example, is different than that parallel to the grain.

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion. The faster the fluid motion, the greater the convection heat transfer.

Convection Heat Transfer

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Consider the cooling of a hot block by blowing cool air over its top surface (Fig. 2-16). Heat is first transferred to the air layer adjacent to the block by conduction. This heat is then carried away from the surface by convection.

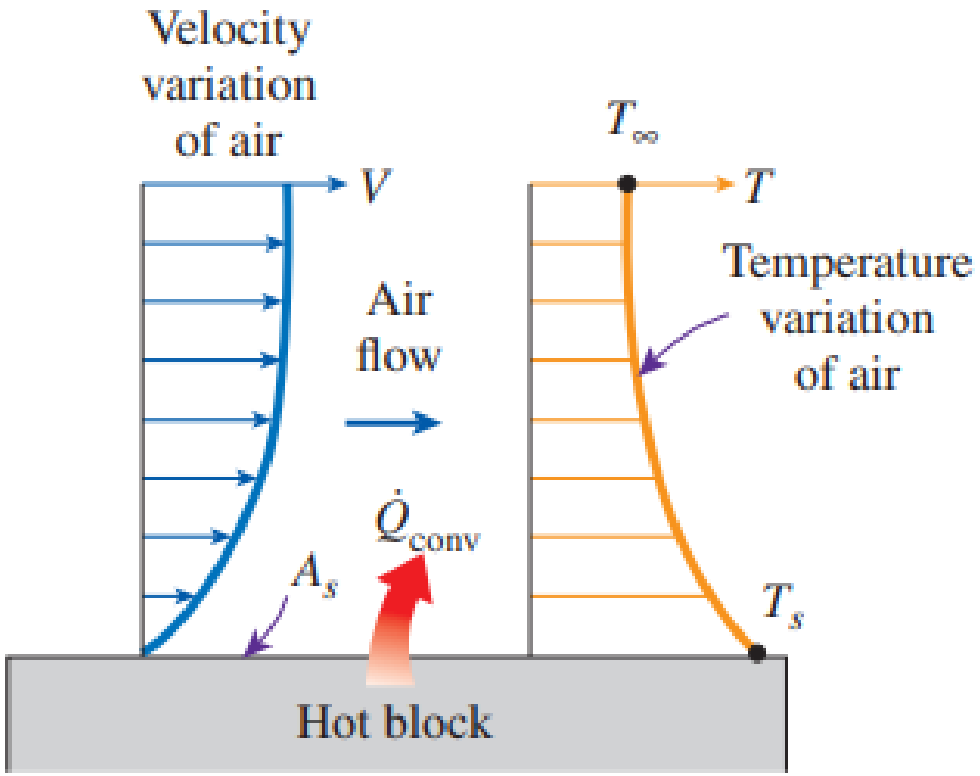

Figure 2-16
Heat transfer from a hot surface to air by convection.

Convection Heat Transfer

Convection is called forced convection if the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind. In contrast, convection is called natural (or free) convection if the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid (Fig. 2-17).

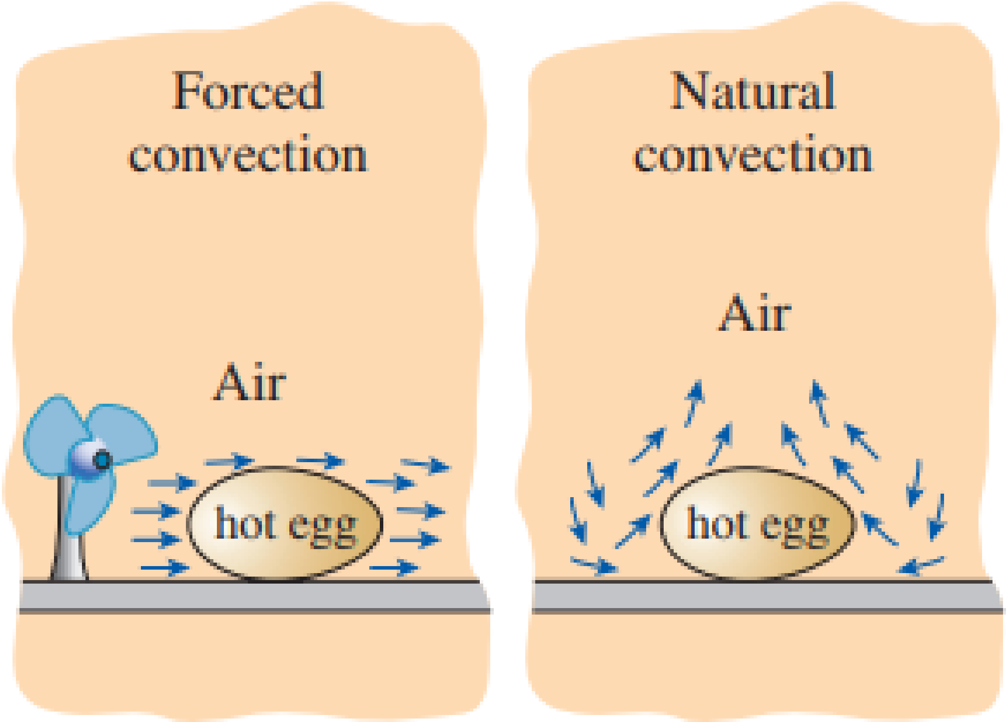

Figure 2-17
The cooling of a boiled egg by forced and natural convection.

Convection Heat Transfer

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Despite the complexity of convection, the rate of convection heat transfer is observed to be proportional to the temperature difference, and is conveniently expressed by Newton's law of cooling as

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \qquad (kW)$$

Convection Heat Transfer

The convection heat transfer coefficient h is not a property of the fluid. It is an experimentally determined parameter whose value depends on all the variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity. Typical values of h are given in Table 2-2.

Type of convection	Heat transfer coefficient h, W/m^2K
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500-100000

Table 2-2
Typical Values of Convection Heat Transfer Coefficient.

Radiation Heat Transfer

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Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules. Unlike conduction and convection, the transfer of heat by radiation does not require the presence of an intervening medium. In fact, heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.

Radiation Heat Transfer

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The maximum rate of radiation that can be emitted from a surface at a thermodynamic temperature Ts (in K or R) is given by the Stefan-Boltzmann law as

$$\dot{Q}_{emit,max} = \sigma A_s T_s^4 \qquad (kW)$$

where s = 5.670×10^{-8} W/$m^2.K^4$ or 0.1714×10^{-8} Btu/h·$ft^2.R^4$ is the Stefan-Boltzmann constant. The idealized surface that emits radiation at this maximum rate is called a blackbody, and the radiation emitted by a blackbody is called blackbody radiation.

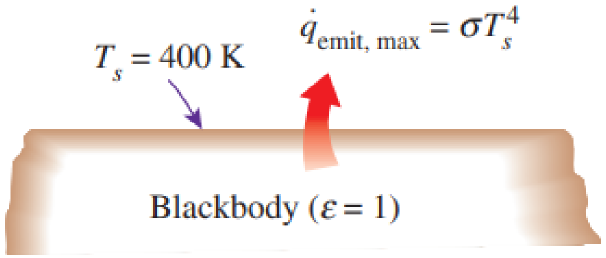

Figure 2-18
Blackbody radiation represents the maximum amount of radiation that can be emitted from a surface at a specified temperature.

Radiation Heat Transfer

The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

$$\dot{Q}_{emit,max} = \varepsilon\sigma A_s T_s^4 \qquad (kW)$$

where e is the emissivity of the surface. The property emissivity, whose value is in the range $0 < \varepsilon < 1$, is a measure of how closely a surface approximates blackbody for which $\varepsilon = 1$.

Radiation Heat Transfer

Another important radiation property of a surface is its absorptivity a, which is the fraction of the radiation energy incident on a surface that is absorbed by the surface. Like emissivity, its value is in the range $0 < \alpha < 1$. A blackbody absorbs the entire radiation incident on it. That is, a blackbody is a perfect absorber ($\alpha = 1$) as it is a perfect emitter

In general, both ε and α of a surface depend on the temperature and the wavelength of the radiation. Kirchhoff 's law of radiation states that the emissivity and the absorptivity of a surface at a given temperature and wavelength are equal.

Radiation Heat Transfer

In many practical applications, the surface temperature and the temperature of the source of incident radiation are of the same order of magnitude, and the average absorptivity of a surface is taken to be equal to its average emissivity. The rate at which a surface absorbs radiation is determined from

$$_{\boldsymbol{incident}} \qquad (\boldsymbol{kW})$$

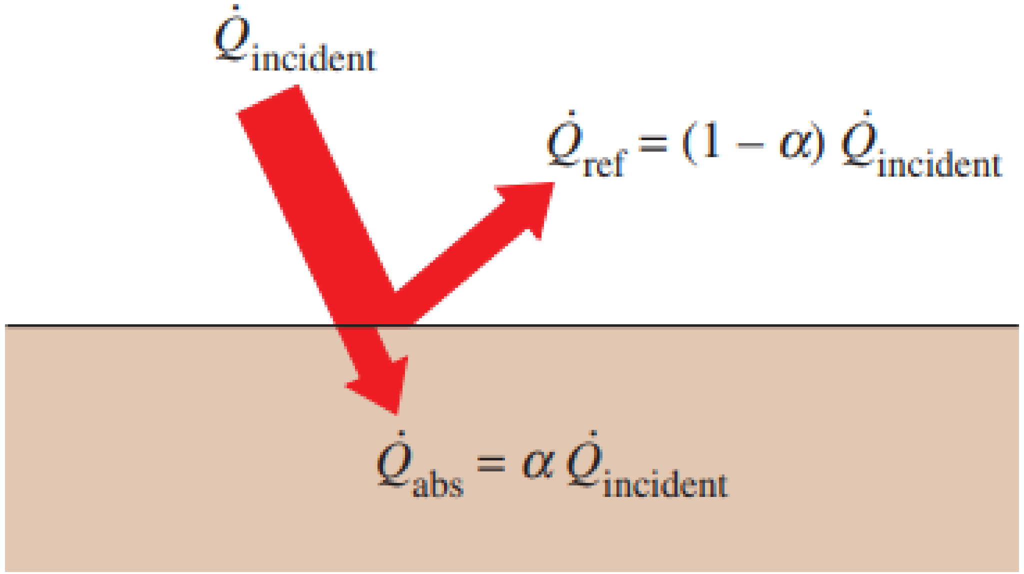

Figure 2-19
The absorption of radiation incident on an opaque surface of absorptivity .

Radiation Heat Transfer

When a surface of emissivity e and surface area A_s at a thermodynamic temperature T_s are completely enclosed by a much larger (or black) surface at thermodynamic temperature T_{surr} separated by a gas (such as air) that does not intervene with radiation, the net rate of radiation heat transfer between these two surfaces is given by

$$\dot{Q}_{rad} = \varepsilon\sigma A_s\left(T_s^4 - T_{surr}^4\right)$$

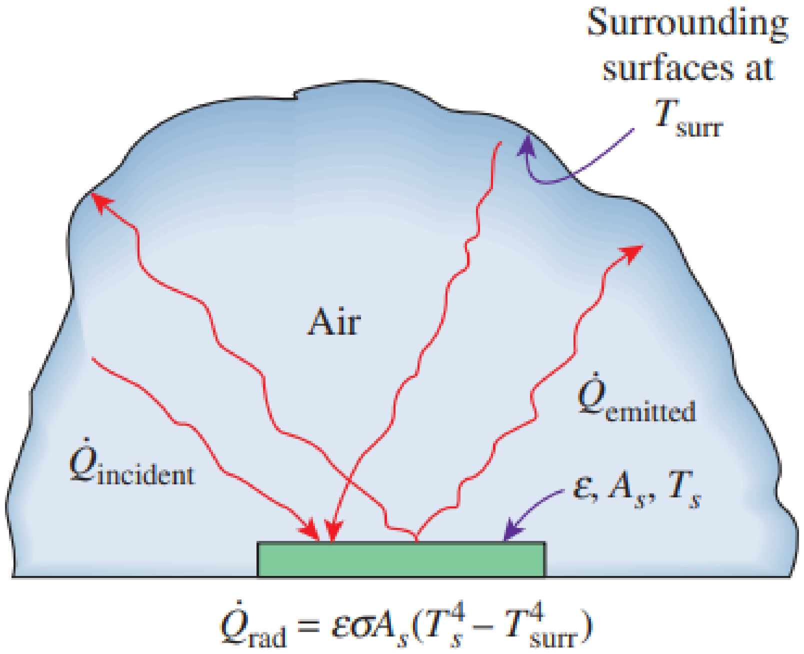

Figure 2-20
Radiation heat transfer between a surface and the surfaces surrounding it.

Radiation Heat Transfer

Radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection. Thus radiation in forced convection applications is usually disregarded, especially when the surfaces involved have low emissivities and low to moderate temperatures.

Radiation Heat Transfer

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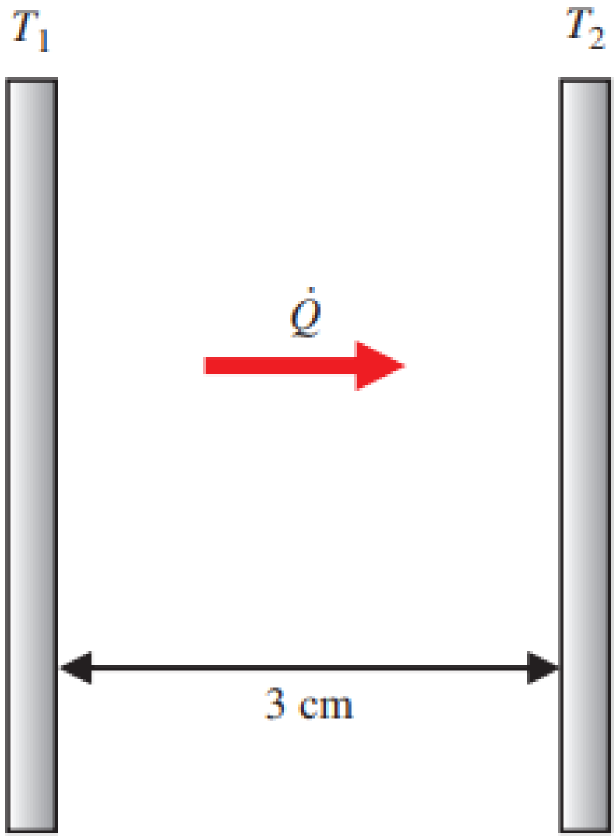
Example 2-2 Consider steady heat transfer between two large parallel plates at constant temperatures of $T_1 = 320$ K and $T_2 = 276$ K that are L = 3 cm apart (Fig. 2-21). Assuming the surfaces to be black (emissivity $\varepsilon = 1$), determine the rate of heat transfer between the plates per unit surface area assuming the gap between the plates is (a) filled with atmospheric air ($k_{air} = 0.02551$ W/m·K), (b) evacuated, (c) filled with fiberglass insulation ($k_{ins} = 0.036$ W/m·K), and (d) filled with superinsulation having an apparent thermal conductivity of 0.00015 W/m·K.

Radiation Heat Transfer

SOLUTION **(a) Disregarding any natural convection currents, the rates of conduction and radiation heat transfer are**



$\dot{Q}_{cond}$:

W/m .K)(1 m^2)(320 -276) K/0.03 m=37.4 W

$ad = \varepsilon\sigma A_s(T_1^4 - T_2^4)$

$= 1 ($

$)(1m^2)[(320\ K)^4 - (276K)^4] = 265.5\ W$

$\dot{Q}_{rad} = 37.4 + 265.5 = 303\ W$

Figure 2-21
Schematic for Example 2-2.

Radiation Heat Transfer

(b) When the air space between the plates is evacuated, there will be radiation heat transfer only. Therefore,

$$\dot{Q}_{total}=\dot{Q}_{rad}=266\ W$$

(c) In this case, there will be conduction heat transfer through the fiberglass insulation only,

$$\dot{Q}_{total}=\dot{Q}_{cond}=kA\frac{T_1-T_2}{L}=\left(0.036\frac{W}{m.K}\right)\left(1\ m^2\right)\frac{(320-276)K}{0.03\ m}=52.8\ W$$

Radiation Heat Transfer

(d) In the case of superinsulation, the rate of heat transfer will be

$$\dot{Q}_{total}=\dot{Q}_{cond}=kA\frac{T_1-T_2}{L}=\left(0.00015\,\frac{W}{m.K}\right)\left(1\,m^2\right)\frac{(320-276)K}{0.03\,m}=0.22\,W$$

Note that superinsulators are very effective in reducing heat transfer between the plates.

FLUID MECHANICS

Semnan University

Mechanics is the oldest physical science that deals with both stationary and moving bodies under the influence of forces. The branch of mechanics that deals with bodies at rest is called statics, while the branch that deals with bodies in motion is called dynamics. The subcategory fluid mechanics is defined as the science that deals with the behavior of fluids at rest (fluid statics) or in motion (fluid dynamics), and the interaction of fluids with solids or other fluids at the boundaries.

FLUID MECHANICS

Fluid mechanics itself is also divided into several categories. The study of the motion of fluids that can be approximated as incompressible (such as liquids, especially water, and gases at low speeds) is usually referred to as hydrodynamics. A subcategory of hydrodynamics is hydraulics, which deals with liquid flows in pipes and open channels. Gas dynamics deals with the flow of fluids that undergo significant density changes, such as the flow of gases through nozzles at high speeds. The category aerodynamics deals with the flow of gases (especially air) over bodies such as aircraft, rockets, and automobiles at high or low speeds. Some other specialized categories such as meteorology, oceanography, and hydrology deal with naturally occurring flows.

FLUID MECHANICS

You will recall from physics that a substance exists in three primary phases: solid, liquid, and gas. (At very high temperatures, it also exists as plasma.) A substance in the liquid or gas phase is referred to as a fluid. Distinction between a solid and a fluid is made on the basis of the substance's ability to resist an applied shear (or tangential) stress that tends to change its shape. A solid can resist an applied shear stress by deforming, whereas a fluid deforms continuously under the influence of a shear stress, no matter how small. In solids, stress is proportional to strain, but in fluids, stress is proportional to strain rate. When a constant shear force is applied, a solid eventually stops deforming at some fixed strain angle, whereas a fluid never stops deforming and approaches a constant rate of strain.

FLUID MECHANICS

In a liquid, groups of molecules can move relative to each other, but the volume remains relatively constant because of the strong cohesive forces between the molecules. As a result, a liquid takes the shape of the container it is in, and it forms a free surface in a larger container in a gravitational field. A gas, on the other hand, expands until it encounters the walls of the container and fills the entire available space. This is because the gas molecules are widely spaced, and the cohesive forces between them are very small. Unlike liquids, a gas in an open container cannot form a free surface.

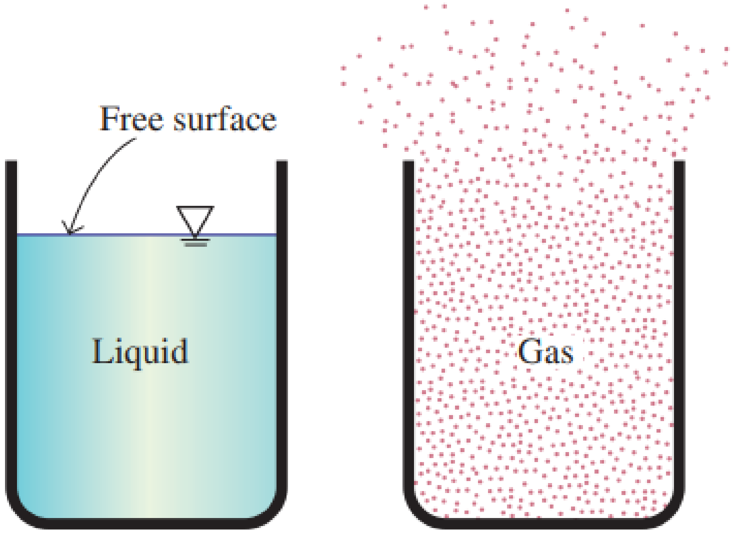


Figure 2-22
Unlike a liquid, a gas does not form a free surface, and it expands to fill the entire available space.

Viscosity

When two solid bodies in contact move relative to each other, a friction force develops at the contact surface in the direction opposite to motion. To move a table on the floor, for example, we have to apply a force to the table in the horizontal direction large enough to overcome the friction force. The magnitude of the force needed to move the table depends on the friction coefficient between the table legs and the floor.

Viscosity

It appears that there is a property that represents the internal resistance of a fluid to motion or the "fluidity," and that property is the viscosity. The force a flowing fluid exerts on a body in the flow direction is called the drag force, and the magnitude of this force depends, in part, on viscosity.

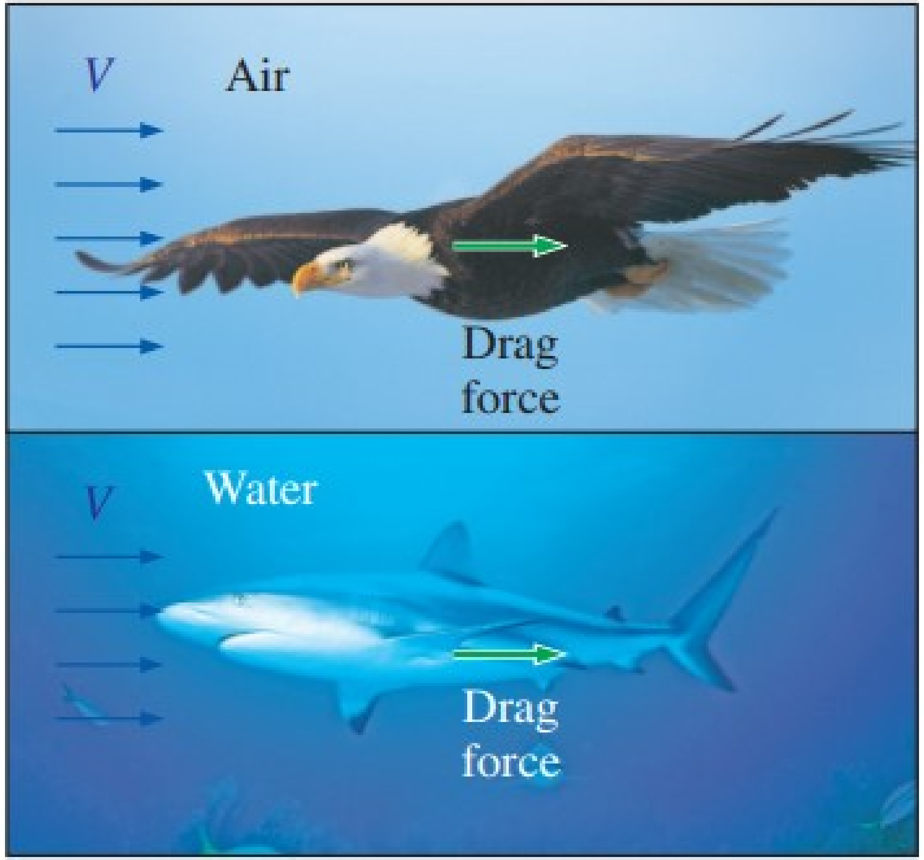


Figure 2-23
A fluid moving relative to a body exerts a drag force on the body, partly because of friction caused by viscosity.

Viscosity

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Fluids for which the rate of deformation is linearly proportional to the shear stress are called Newtonian fluids after Sir Isaac Newton, who expressed it first in 1687. Most common fluids such as water, air, gasoline, and oils are Newtonian fluids. Blood and liquid plastics are examples of non-Newtonian fluids.

In one-dimensional shear flow of Newtonian fluids, shear stress can be expressed by the linear relationship

$$\tau = \mu \frac{du}{dy} \qquad \left(\frac{N}{m^2}\right)$$

Viscosity

where the constant of proportionality μ is called the coefficient of viscosity or the dynamic (or absolute) viscosity of the fluid, whose unit is kg/m·s, or equivalently, N·s/m2 (or Pa·s where Pa is the pressure unit pascal). A common viscosity unit is poise, which is equivalent to 0.1 Pa·s (or centipoise, which is one-hundredth of a poise). The viscosity of water at 20°C is 1.002 centipoise, and thus the unit centipoise serves as a useful reference.

In fluid mechanics and heat transfer, the ratio of dynamic viscosity to density appears frequently. For convenience, this ratio is given the name kinematic viscosity n and is expressed as $\nu = \mu/\rho$. Two common units of kinematic viscosity are m2/s and stoke (1 stoke =1 cm2/s = 0.0001m2/s)

Viscosity

In general, the viscosity of a fluid depends on both temperature and pressure, although the dependence on pressure is rather weak. For liquids, both the dynamic and kinematic viscosities are practically independent of pressure, and any small variation with pressure is usually disregarded, except at extremely high pressures. For gases, this is also the case for dynamic viscosity (at low to moderate pressures), but not for kinematic viscosity since the density of a gas is proportional to its pressure.

Viscosity

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The viscosity of a fluid is directly related to the pumping power needed to transport a fluid in a pipe or to move a body (such as a car in air or a submarine in the sea) through a fluid. Viscosity is caused by the cohesive forces between the molecules in liquids and by the molecular collisions in gases, and it varies greatly with temperature. The viscosity of liquids decreases with temperature, whereas the viscosity of gases increases with temperature (Fig. 2-24). This is because in a liquid the molecules possess more energy at higher temperatures, and they can oppose the large cohesive intermolecular forces more strongly. As a result, the energized liquid molecules can move more freely.

Viscosity

In a gas, on the other hand, the intermolecular forces are negligible, and the gas molecules at high temperatures move randomly at higher velocities. This results in more molecular collisions per unit volume per unit time and therefore in greater resistance to flow. The kinetic theory of gases predicts the viscosity of gases to be proportional to the square root of temperature.

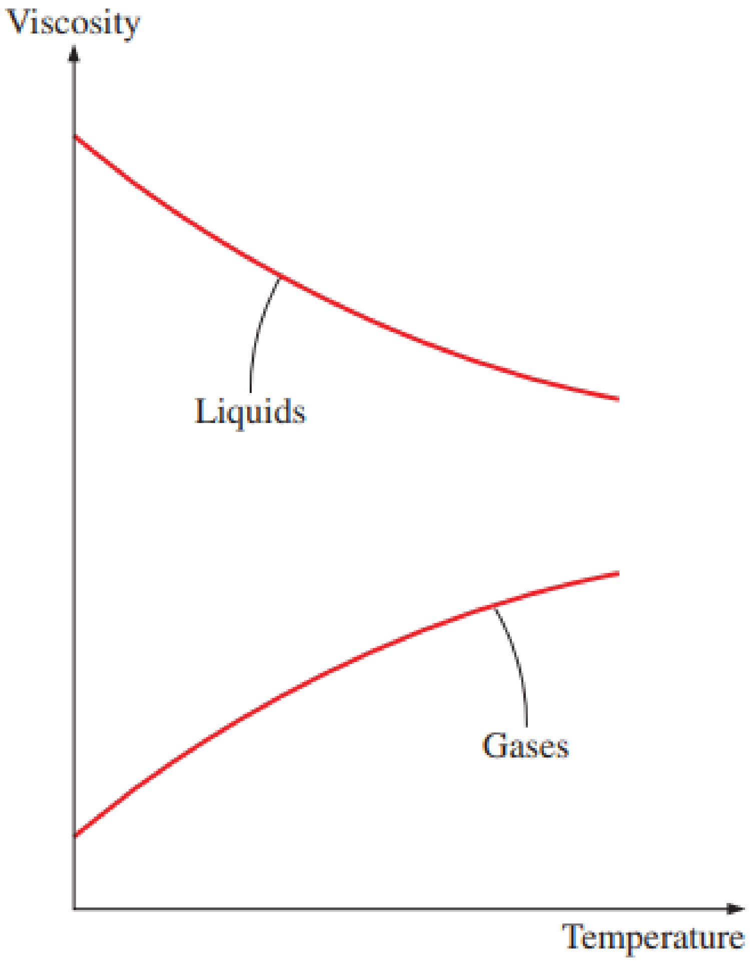

Figure 2-24
The viscosity of liquids decreases and the viscosity of gases increases with temperature.

Pressure Drop in Fluid Flow in Pipes

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The pressure loss and head loss for all types of internal flows (laminar or turbulent, in circular or noncircular pipes, smooth or rough surfaces) are expressed as

$$\Delta P_L = f\frac{L}{D}\frac{\rho V^2}{2}$$

$$h_L = \frac{\Delta P_L}{\rho g} = f\frac{L}{D}\frac{V^2}{2g}$$

where ρ is the density, V is average velocity of fluid, L is the pipe length, g is gravitational acceleration, $\frac{\rho V^2}{2}$ is the dynamic pressure, and the dimensionless quantity f is the friction factor.

Pressure Drop in Fluid Flow in Pipes

For fully developed laminar flow in a round pipe, the friction factor is f = 64/Re, where Re is Reynolds number Re = VD/υ. Here, υ is the kinematic viscosity. Note that the flow is laminar for Reynolds numbers smaller than 2300 and turbulent for Reynolds numbers greater than 4000.

The head loss represents the additional height that the fluid needs to be raised by a pump in order to overcome the frictional losses in the pipe. The head loss is caused by viscosity, and it is directly related to the wall shear stress.

Pressure Drop in Fluid Flow in Pipes

The pressure drop and the volume flow rate for laminar flow in a horizontal pipe are

$$\Delta P_L = \frac{32\mu L V_{ave}}{D^2}$$

$$\dot{V} = V_{ave}\,A_c = \frac{\Delta P \pi D^4}{128\mu L}$$

This equation is known as Poiseuille’s law, and this flow is called Hagen-Poiseuille flow in honor of the works of G. Hagen (1797–1884) and J. Poiseuille (1799–1869) on the subject.

Pressure Drop in Fluid Flow in Pipes

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For noncircular pipes, the diameter in the previous relations is replaced by the hydraulic diameter defined as Dh = 4Ac/p, where Ac is the cross-sectional area of the pipe and p is its wetted perimeter.

In fully developed turbulent flow, the friction factor depends on the Reynolds number and the relative roughness ε/D. The friction factor in turbulent flow is given by the Colebrook equation, expressed as

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)$$

The plot of this formula is known as the Moody chart.

Pressure Drop in Fluid Flow in Pipes

We routinely use the Colebrook equation to calculate the friction factor f for fully developed turbulent pipe flow. Indeed, the Moody chart is created using the Colebrook equation. However, in addition to being implicit, the Colebrook equation is valid only for turbulent pipe flow (when the flow is laminar, f = 64/Re). Thus we need to verify that the Reynolds number is in the turbulent range. An equation was generated by Churchill (1977) that is not only explicit, but is also useful for any Re and any roughness, even for laminar flow, and even in the fuzzy transitional region between laminar and turbulent flow. The Churchill e

$$\frac{1}{\sqrt{f}} = 8\left[\left(\frac{8}{Re}\right)^{12}+(A+B)^{-1.5}\right]^{\frac{1}{12}}$$

Pressure Drop in Fluid Flow in Pipes

where

$$A = \left\{-2.457.\ln\left[\left(\frac{7}{Re}\right)^{0.9} + 0.27\frac{\varepsilon}{D}\right]\right\}^{16}$$

The difference between the Colebrook and Churchill equations is less than 1 percent. Because it is explicit and valid over the entire range of Reynolds numbers and roughnesses, it is recommended that the Churchill equation be used for determination of friction factor *f*.

Pressure Drop in Fluid Flow in Pipes

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Once the pressure loss (or head loss) is known, the required pumping power to overcome the pressure loss is determined from

$$\dot{W}_{pump,L} = \dot{V}\Delta P_L = \dot{m} g h_L$$

where $\dot{V}$ is the volume flow rate and $\dot{m}$ is the mass flow rate.

Pressure Drop in Fluid Flow in Pipes

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EXAMPLE 2-4 **Water at 15°C (ρ= 999.1 kg/m3 and $\mu = 1.138 \times 10^{-3}$ kg/m·s) is flowing steadily in a 30-m-long and 5-cm-internal diameter horizontal pipe made of stainless steel at a rate of 9 L/s (Fig. 2-25). Determine the pressure drop, the head loss, and the pumping power requirement to overcome this pressure drop.**

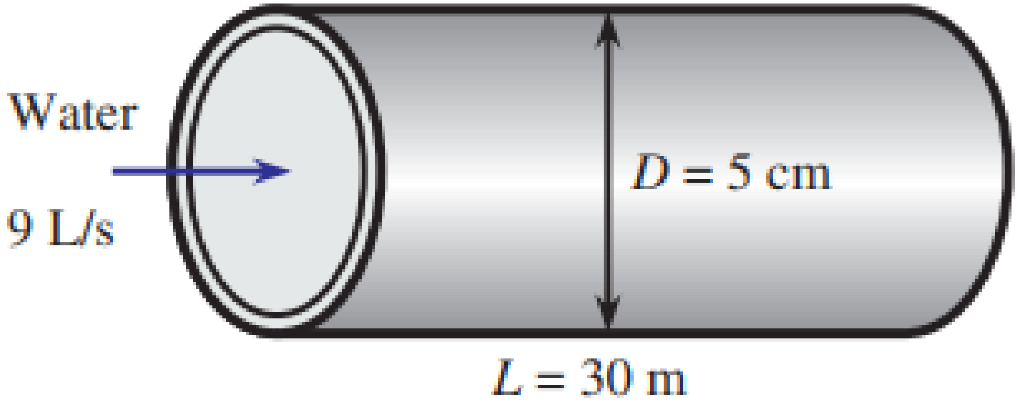
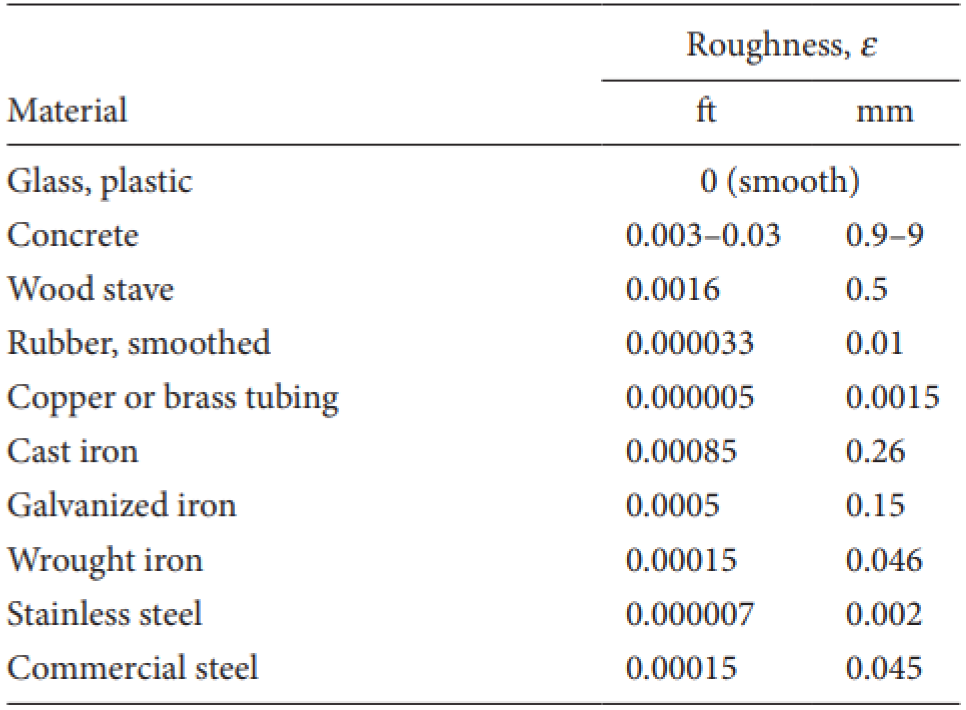


Figure 2-25
Schematic for Example 2-2.

Pressure Drop in Fluid Flow in Pipes

SOLUTION **The density and dynamic viscosity of water are given to be ρ = 999.1 kg/m3 and μ = 1.138 × 10^{-3} kg/m·s, respectively. The roughness of stainless steel is 0.002 mm (Table 2-2). First we calculate the average velocity and the Reynolds number to determine the flow regime:**



Material	Roughness, ε	
	ft	mm
Glass, plastic	0 (smooth)	
Concrete	0.003–0.03	0.9–9
Wood stave	0.0016	0.5
Rubber, smoothed	0.000033	0.01
Copper or brass tubing	0.000005	0.0015
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Wrought iron	0.00015	0.046
Stainless steel	0.000007	0.002
Commercial steel	0.00015	0.045

Table 2-2
Equivalent Roughness Values for New Commercial Pipes.

Pressure Drop in Fluid Flow in Pipes

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$$V = \frac{\dot{V}}{A_c} = \frac{\dot{V}}{\pi D^2/4} = \frac{0.009\ m^3/s}{\pi(0.05)^2/4} = 4.584\ m/s$$

$$Re = \frac{\rho V D}{\mu} = \frac{(999.1\ kg/m^3)(4.584\ m/s)(0.05\ m)}{1.138\times10^{-3}\ \frac{kg}{m.s}} = 2.012 \times 10^5$$

which is greater than 4000. Therefore, the flow is turbulent. The relative roughness of the pipe is

$$\varepsilon /D = \frac{2\times10^{-6}\ m}{0.05\ m} = 4 \times 10^{-5}$$

Pressure Drop in Fluid Flow in Pipes

The friction factor can be determined from the Moody chart, but to avoid the reading error, we determine it from the Colebrook equation using an equation solver (or an iterative scheme),

$$\frac{1}{\sqrt{f}} = -2log\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \rightarrow \frac{1}{\sqrt{f}} = -2log\left(\frac{4\times10^{-5}}{3.7} + \frac{2.51}{2.012\times10^{5}\sqrt{f}}\right)$$

It gives f = 0.01594. Then the pressure drop, head loss, and the required

$$\Delta P = \Delta P_L = f\frac{L}{}\frac{\rho V^2}{}$$

$$= 0.01594\frac{30\,m}{0.05\,m}\frac{(999.1\,kg/m^3)(4.584\,m/s)^2}{2}\left(\frac{1\,kN}{1000\,\frac{kg}{m.s}}\right)\left(\frac{1\,kPa}{1\,kN/m^2}\right)$$

=100.4 kPa≅ $100\,kPa$

Pressure Drop in Fluid Flow in Pipes

Semnan University

$$h_L = \frac{\Delta P_L}{\rho g} = f\frac{L}{D}\frac{V^2}{2g} = 0.01594\,\frac{30\ m}{0.05\ m}\,\frac{(4.584\ m/s)^2\ m}{2(9.81\frac{m}{s^2})} = 10.2\ m$$

$$\dot{W}_{pump,L} = \dot{V}\Delta P_L = 0.009\frac{m^3}{s} \times 100.4\ kPa\,\frac{1\ kW}{1\ kPa.m^3/s} = 0.904\ kW$$

Therefore, useful power input in the amount of 0.904 kW is needed to overcome the frictional losses in the pipe. The power input determined is the mechanical power that needs to be imparted to the fluid. The shaft power will be more than this due to pump inefficiency; the electrical power input will be even more due to motor inefficiency.

Fuels and Combustion

Fuel: Any material that can be burned to release thermal energy is called a fuel.

Combustion: A chemical reaction during which a fuel is oxidized and a large quantity of energy is released is called combustion.

The oxidizer most often used in combustion processes is air, for obvious reasons—it is free and readily available. Therefore, a few words about the composition of air are in order. On a mole or a volume basis, dry air is composed of 20.9 percent oxygen, 78.1 percent nitrogen, 0.9 percent argon, and small amounts of carbon dioxide, helium, neon, and hydrogen.

Fuels and Combustion

Therefore, each mole of oxygen entering a combustion chamber is accompanied by 0.79/0.21 = 3.76 mol of nitrogen. That is,

$$1\ kmol\ O_2 + 3.76\ kmol\ N_2 = 4.76\ kmol\ air$$

Keep in mind, however, that at very high temperatures, such as those encountered in internal combustion engines, a small fraction of nitrogen reacts with oxygen, forming hazardous gases such as nitric oxide.

Fuels and Combustion

During a combustion process, the components that exist before the reaction are called reactants and the components that exist after the reaction are called products. Consider, for example, the combustion of 1 kmol of carbon with 1 kmol of pure oxygen, forming carbon dioxide,

$$C + O_2 \rightarrow CO_2$$

Fuels and Combustion

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A frequently used quantity in the analysis of combustion processes to quantify the amounts of fuel and air is the air-fuel ratio AF. It is usually expressed on a mass basis and is defined as the ratio of the mass of air to the mass of fuel for a combustion process (Fig. 2-26). That is,

$$AF = \frac{m_{air}}{m_{fuel}}$$

The mass m of a substance is related to the number of moles N through the relation m = NM, where M is the molar mass.

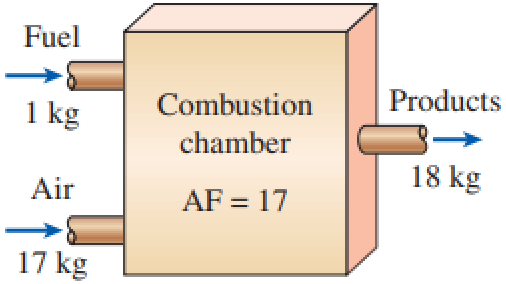

Figure 2-26
Schematic for Example 2-2.

Theoretical and Actual Combustion Processes

It is often instructive to study the combustion of a fuel by assuming that the combustion is complete. A combustion process is complete if all the carbon in the fuel burns to CO2, all the hydrogen burns to H2O, and all the sulfur (if any) burns to SO2. That is, all the combustible components of a fuel are burned to completion during a complete combustion process. Conversely, the combustion process is incomplete if the combustion products contain any unburned fuel or components such as C, H2 , CO, or OH.

Theoretical and Actual Combustion Processes

The minimum amount of air needed for the complete combustion of a fuel is called the stoichiometric or theoretical air. Thus, when a fuel is completely burned with theoretical air, no uncombined oxygen is present in the product gases. The theoretical air is also referred to as the chemically correct amount of air, or 100 percent theoretical air. A combustion process with less than the theoretical air is bound to be incomplete. The ideal combustion process during which a fuel is burned completely with theoretical air is called the stoichiometric or theoretical combustion of that fuel. For example, the theoretical combustion of methane is

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

Enthalpy of Formation and Enthalpy of Combustion

During a chemical reaction, some chemical bonds that bind the atoms into molecules are broken, and new ones are formed. The chemical energy associated with these bonds, in general, is different for the reactants and the products. Therefore, a process that involves chemical reactions involves changes in chemical energies, which must be accounted for in an energy balance. Assuming the atoms of each reactant remain intact (nonnuclear reactions) and disregarding any changes in kinetic and potential energies, the energy change of a system during a chemical reaction is due to a change in state and a change in chemical composition. That is,

$$\Delta E_{sys} = \Delta E_{state} + \Delta E_{chem}$$

Enthalpy of Formation and Enthalpy of Combustion

Therefore, when the products formed during a chemical reaction exit the reaction chamber at the inlet state of the reactants, we have $\Delta E_{state} = 0$ and the energy change of the system in this case is due to the changes in its chemical composition only.

Enthalpy of Formation and Enthalpy of Combustion

The process described above involves no work interactions. Therefore, from the steady flow energy balance relation, the heat transfer during this process must be equal to the difference between the enthalpy of the products and the enthalpy of the reactants. That is,

$$Q = H_{prod} - H_{react} = -393.520\ kJ/kmol$$

Enthalpy of Formation and Enthalpy of Combustion

For combustion processes, the enthalpy of reaction is usually referred to as the enthalpy of combustion h_c, which represents the amount of heat released during a steady-flow combustion process when 1 kmol (or 1 kg) of fuel is burned completely at a specified temperature and pressure (Fig. 2-27). It is expressed as

$$h_R = h_c = H_{prod} - H_{react}$$

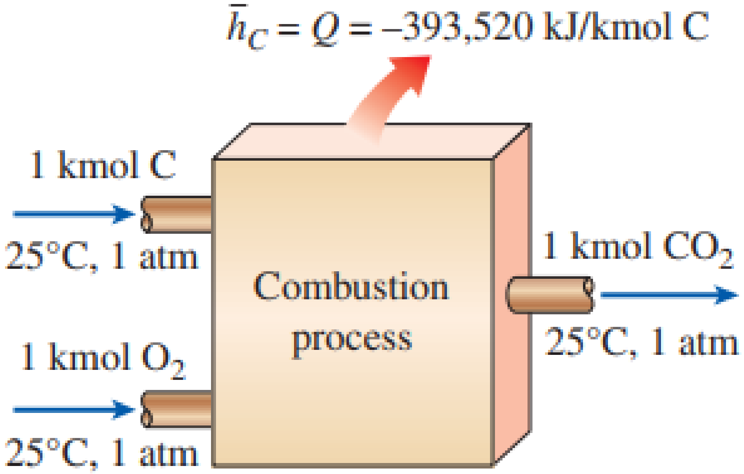

Figure 2-27
The enthalpy of combustion represents the amount of energy released as a fuel is burned during a steady-flow process at a specified state.

Enthalpy of Formation and Enthalpy of Combustion

To establish a starting point, we assign the enthalpy of formation of all stable elements (such as O2, N2, H2, and C) a value of zero at the standard reference state of 25°C and 1 atm. That is, o hf = 0 for all stable elements.

Enthalpy of Formation and Enthalpy of Combustion

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Another term commonly used in conjunction with the combustion of fuels is the heating value of the fuel, which is defined as the amount of heat released when a fuel is burned completely in a steady-flow process and the products are returned to the state of the reactants.

$$\boldsymbol{Heating\ value = |h_c| \qquad kJ/kg fuel}$$

Enthalpy of Formation and Enthalpy of Combustion

The heating value depends on the phase of the H2O in the products. The heating value is called the higher heating value (HHV) when the H2O in the products is in the liquid form, and it is called the lower heating value (LHV) when the H2O in the products is in the vapor form (Fig. 2-28). The two heating values are related by

$$HHV = LHV + (mh_{fg})_{H_2O} \qquad kJ/kgfuel$$

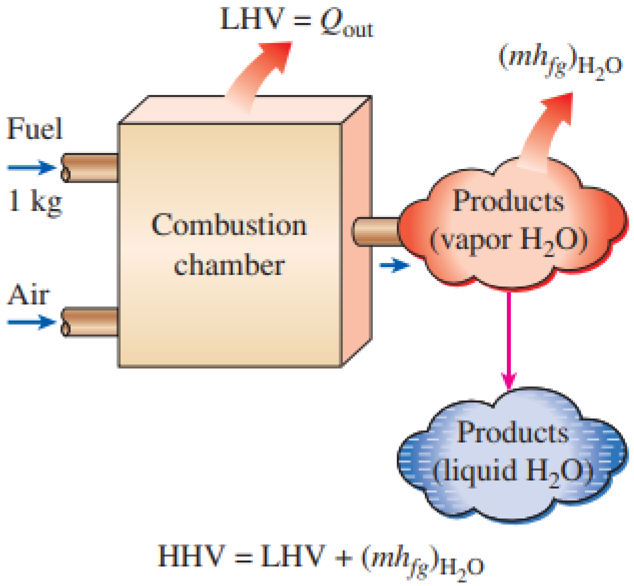

Figure 2-28
The higher heating value of a fuel is equal to the sum of the lower heating value of the fuel and the latent heat of vaporization of the H2O in the products.

First-Law Analysis of Reacting Systems

$$Enthalpy = \overline{h_f^o} = \left(\bar{h} - \overline{h^o}\right) \qquad kJ/kmol$$

where the term in the parentheses represents the sensible enthalpy relative to the standard reference state, which is the difference between (the sensible enthalpy at the specified state) and (the sensible enthalpy at the standard reference state of 25°C and 1 atm). This definition enables us to use enthalpy values from tables regardless of the reference state used in their construction. The sensible enthalpy can be approximated as $(\bar{h} - \overline{h^o}) \cong \overline{c_p}\Delta T$, where $\overline{c_p}$ is the specific heat on a molar basis and ΔT is the difference in product temperature and reference state temperature.

First-Law Analysis of Reacting Systems

Semnan University

When the changes in kinetic and potential energies are negligible, the steady-flow energy balance relation $\dot{E}_{in} = \dot{E}_{out}$ can be expressed for a chemically reacting steady-flow system more explicitly as

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{n}_r(\overline{h_f^o} + \overline{h} - \overline{h^o})_r = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{n}_p(\overline{h_f^o} + \overline{h} - \overline{h^o})_p$$

where $\dot{n}_p$ and $\dot{n}_r$ represent the molal flow rates of the product p and the reactant r, respectively. In combustion analysis, it is more convenient to work with quantities expressed per mole of fuel.

First-Law Analysis of Reacting Systems

Semnan University

Such a relation is obtained by dividing each term of the equation above by the molal flow rate of the fuel, yielding

$$Q_{in} + W_{in} + \sum N_r(\overline{h_f^o} + \overline{h} - \overline{h^o})_r = Q_{out} + W_{out} + \sum N_p(\overline{h_f^o} + \overline{h} - \overline{h^o})_p$$

First-Law Analysis of Reacting Systems

A combustion chamber normally involves heat output but no heat input. Then the energy balance for a typical steady-flow combustion process becomes

$$Q_{out} = \sum N_r(\overline{h_f^o} + \overline{h} - \overline{h^o})_r - \sum N_p(\overline{h_f^o} + \overline{h} - \overline{h^o})_p$$

It expresses that the heat output during a combustion process is simply the difference between the energy of the reactants entering and the energy of the products leaving the combustion chamber.

First-Law Analysis of Reacting Systems

EXAMPLE 2-5 A gaseous fuel mixture that is 40 percent propane (C_3H_8) and 60 percent methane (CH_4) by volume is burned at a rate of 3.75 kg/h with 50 percent excess dry air (Fig. 2-34) in the combustion chamber of an equipment producing heat (such as a boiler). Both the fuel and air enter the combustion chamber at 25°C and 100 kPa and undergo a complete combustion process. Combustion products leave the combustion chamber at 125°C. Determine (a) the balanced combustion equation, (b) the air-fuel ratio, (c) the dew-point temperature of product gases, (d) the mass of CO_2 formed per unit mass of the fuel, and (e) the rate of heat produced in the equipment. Enthalpy of formation, molar mass, and specific heat data for the species are given in the following table.

First-Law Analysis of Reacting Systems

SOLUTION **(a) The process is shown in Fig. 2-29. The balanced reaction equation with the stoichiometric air is**

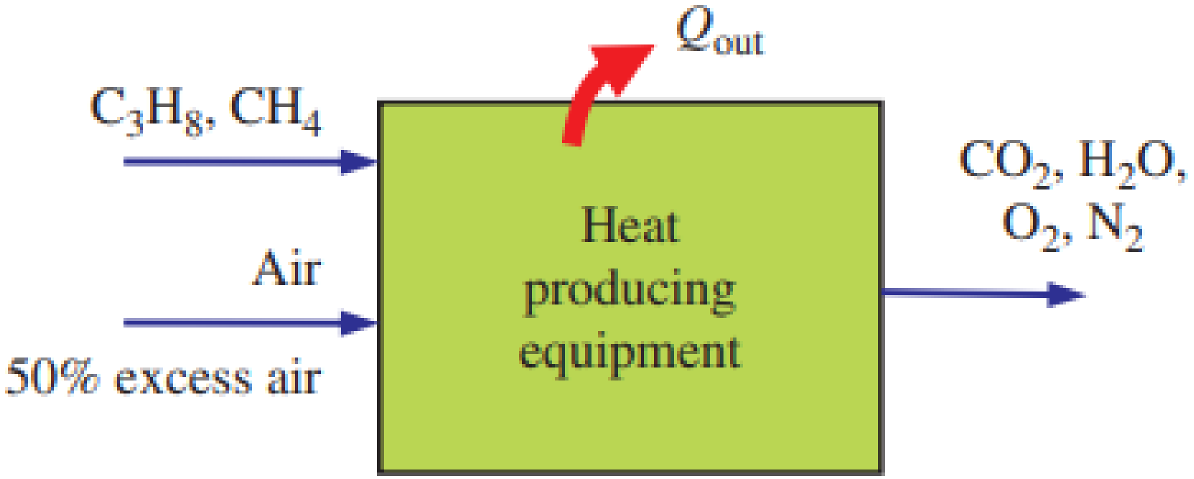

Figure 2-29
Schematic for Example 2-5.

First-Law Analysis of Reacting Systems

$$0.4C_3H_8 + 0.6CH_4 + a_{th}[O_2 + 3.76N_2] \rightarrow 1.8CO_2 + 2.8H_2O + a_{th} \times 3.76N_2$$

The stoichiometric coefficient ath is determined from an O2 balance:

$$a_{th} = 1.8 + 1.4 = 3.2$$

Substituting,

$$0.4C_3H_8 + 0.6CH_4 + 3.2[O_2 + 3.76N_2] \rightarrow 1.8CO_2 + 2.8H_2O + 12.032N_2$$

There will be extra O2 formed in the products when the reaction takes place with 50 percent excess air. Also, more N2 will be formed:

$$0.4C_3H_8 + 0.6CH_4 + 1.5 \times 3.2[O_2 + 3.76N_2]$$
$$\rightarrow 1.8CO_2 + 2.8H_2O + 1.5 \times 12.032N_2 + 0.5 \times 3.2O_2$$

First-Law Analysis of Reacting Systems

That is,

$$0.4C_3H_8 + 0.6CH_4 + 4.8[O_2 + 3.76N_2]$$
$$\rightarrow 1.8CO_2 + 2.8H_2O + 18.05N_2 + 1.6O_2$$

(b) The air-fuel ratio is

$$AF = \frac{m_{air}}{m_{fuel}} = \frac{(4.8 \times 4.76 \times 29)kg}{(0.4 \times 44 \times +0.6 \times 16)kg} = 24.36\ kg\ air/kgfuel$$

(c) The partial pressure of water vapor is determined by multiplying the molar fraction of water in the products (yH2O = NH2O/Ntotal) by the total pressure of the product gases:

$$P_v = y_{H_2O}P_{total} = \frac{N_{H_2O}}{N_{total}}P_{total} = \frac{2.8}{(1.8 + 2.8 + 18.05 + 1.6)}$$
$$= \frac{2.8\ kmol}{24.25\ kmol}(100\ kPa) = 11.55\ kPa$$

First-Law Analysis of Reacting Systems

The dew point temperature of the product gases is the saturation temperature of water at this pressure:

$$T_{dp} = T_{sat@11.55\,kPa} = 48.7°C \quad \text{(TableA-4)}$$

Since the temperature of the product gases is at 398 K (125°C), which is greater than the dew point temperature, there will be no condensation of water vapor in the product gases. If the temperature of exhaust gases drop below this temperature as it flows in piping and chimney, water vapor will start condensing.

First-Law Analysis of Reacting Systems

(d) The mass of CO2 formed per unit mass of the fuel is

$$\frac{m_{CO_2}}{m_{fuel}} = \frac{N_{CO_2} M_{CO_2}}{(N_{C_3H_8} M_{C_3H_8}) + (N_{CH_4} M_{CH_4})}$$

$$= \frac{(1.8\ kmol)(44\ ^{kg}/_{kmol})}{(0.4\ kmol)\left(44\ ^{kg}/_{kmol}\right) + (0.6\ kmol)\left(16\ ^{kg}/_{kmol}\right)}$$

$$= \frac{79.2\ kg}{27.2\ kg} = 2.92\ ^{kg\ CO_2}/_{kg\ fuel}$$

When 1 kg of this fuel mixture is burned, 2.92 kg of CO2 gas (a major greenhouse gas causing global warming) is formed in the product gases. Note that the amount of CO2 production is the same when the combustion is with theoretical air or with excess air as long as the combustion is complete. That is, using excess air does not affect the amount of CO2 production.

First-Law Analysis of Reacting Systems

(e) The heat transfer for this combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with W =0. It reduces to

$$-Q_{out} = \sum N_p(\overline{h_f^o} + \overline{h} - \overline{h^o})_p - \sum N_r(\overline{h_f^o} + \overline{h} - \overline{h^o})_r$$

The products are at 125°C, and the enthalpy of products can be expressed as

$$(\overline{h} - \overline{h^o}) = \overline{c_p}\Delta T$$

where ΔT=125 − 25 =100°C=100 K. Then, using the values given in the table,

First-Law Analysis of Reacting Systems

(e) The heat transfer for this combustion process is determined from the energy balance $E_{in} - E_{out} = \Delta E_{system}$ applied on the combustion chamber with W =0. It reduces to

$$-Q_{out} = (1.8)(-393,52 + 41.16 \times 100) + (2.8)(-241,820 + 34.28 \times 100) + (18.05)(0 + 29.27 \times 100) + (1.6)(0 + 30.14 \times 100) - (0.4)(-103,850) - (0.6)(-74,850) = -1,224,320\ {}^{kJ}/_{kmol\ fuel}$$

The rate of heat output from the equipment for a fuel consumption rate of 3.75 kg/h is

$$\dot{Q}_{out} = \dot{m}_{fuel}\frac{Q_{out}}{M_{fuel}} = (3.75\ kg\ fuel/h)\frac{1,224,320\,kJ\ /kmolfuel}{(0.4 \times 44 + 0.6 \times 16)\,kJ\ /kmol}$$

$$= 168,794\,kJ\ /h = 46.9\ kW$$

HEAT ENGINES AND POWER PLANTS

Semnan University

Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the working fluid.

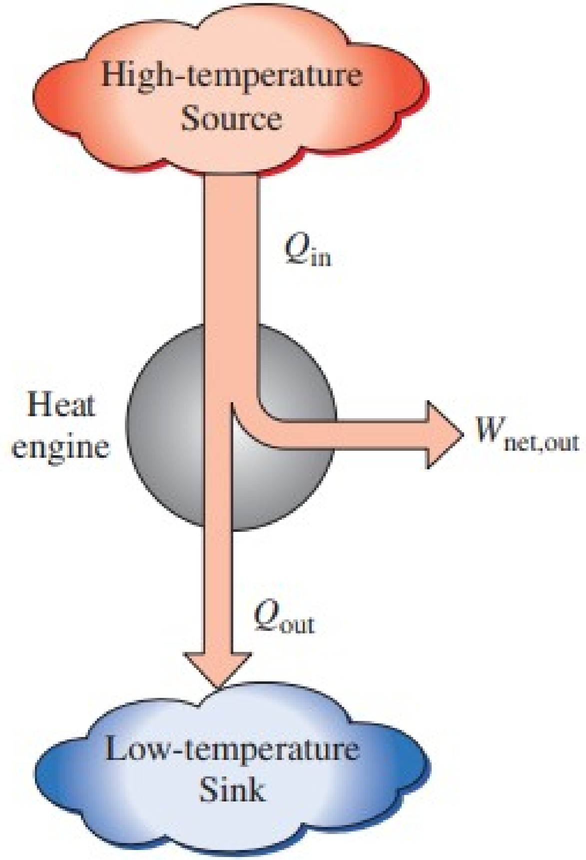

Figure 2-30
Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

HEAT ENGINES AND POWER PLANTS

The term heat engine is often used in a broader sense to include work-producing devices that do not operate in a thermodynamic cycle. Engines that involve internal combustion such as gas turbines and car engines fall into this category. These devices operate in a mechanical cycle but not in a thermodynamic cycle since the working fluid (the combustion gases) does not undergo a complete cycle. Instead of being cooled to the initial temperature, the exhaust gases are purged and replaced by fresh air-and-fuel mixture at the end of the cycle.

HEAT ENGINES AND POWER PLANTS

The work-producing device that best fits into the definition of a heat engine is the steam power plant, which is an external-combustion engine. That is, combustion takes place outside the engine, and the thermal energy released during this process is transferred to the steam as heat. The schematic of a basic steam power plant is shown in Fig. 2-31. The various quantities shown on this figure are as follows:

Qin = amount of heat supplied to steam in boiler from a high-temperature source (furnace)
Qout = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)
Wout = amount of work delivered by steam as it expands in turbine
Win = amount of work required to compress water to boiler pressure

HEAT ENGINES AND POWER PLANTS

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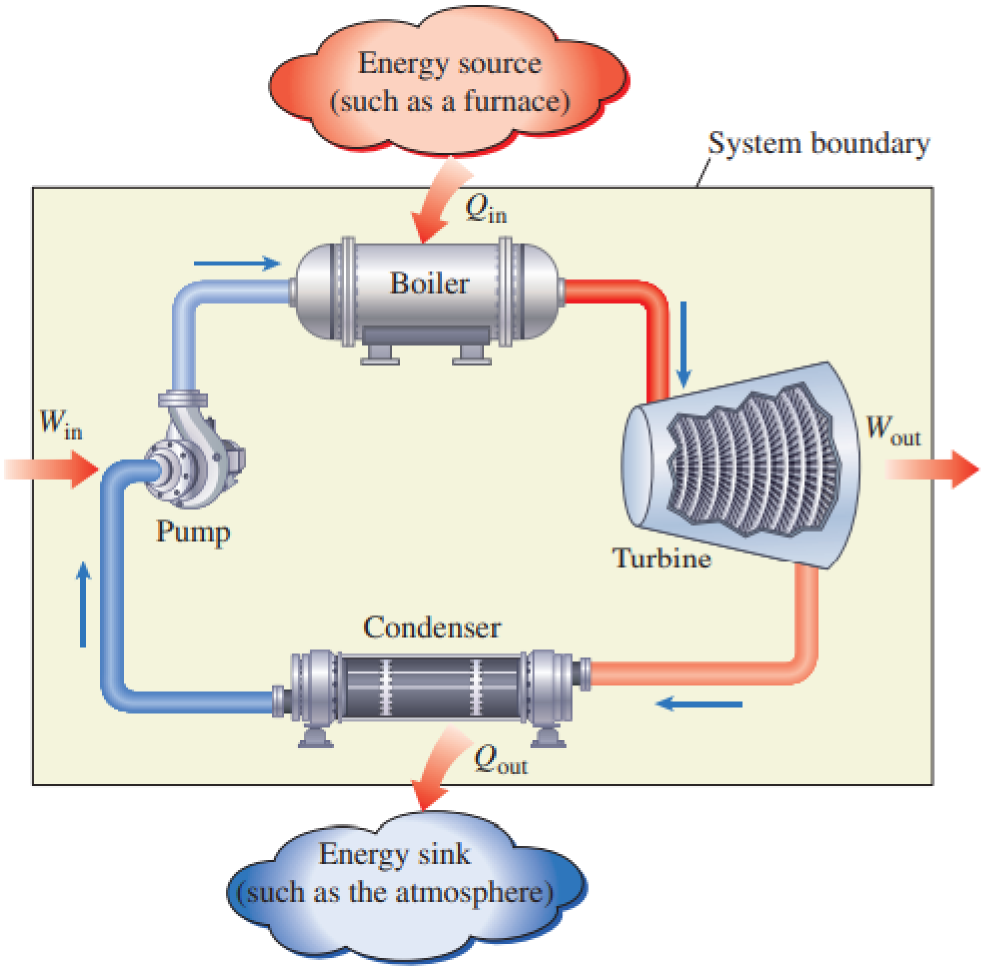

Figure 2-31
Schematic of a steam power plant.

HEAT ENGINES AND POWER PLANTS

Notice that the directions of the heat and work interactions are indicated by the subscripts in and out. Therefore, all four of the described quantities are always positive. The network output of this power plant is simply the difference between the total work output of the plant and the total work input (Fig. 2-32):

$$W_{net,out} = W_{out} - W_{in} \quad (\text{kJ})$$

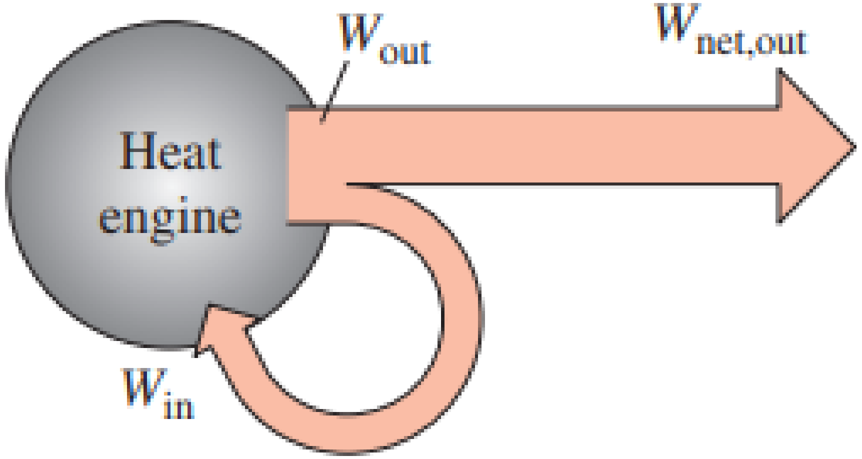

Figure 2-32
A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

HEAT ENGINES AND POWER PLANTS

The network can also be determined from the heat transfer data alone. The four components of the steam power plant involve mass flow in and out, and therefore should be treated as open systems. These components, together with the connecting pipes, however, always contain the same fluid (not counting the steam that may leak out, of course). No mass enters or leaves this combination system, which is indicated by the shaded area on Fig. 2-33; thus, it can be analyzed as a closed system. Recall that for a closed system undergoing a cycle, the change in internal energy DU is zero, and therefore the net work output of the system is also equal to the net heat transfer to the system:

$$W_{net,out} = Q_{in} - Q_{out} \quad \text{(kJ)}$$

HEAT ENGINES AND POWER PLANTS

$$W_{net,out} = Q_{in} - Q_{out} \quad \text{(kJ)}$$

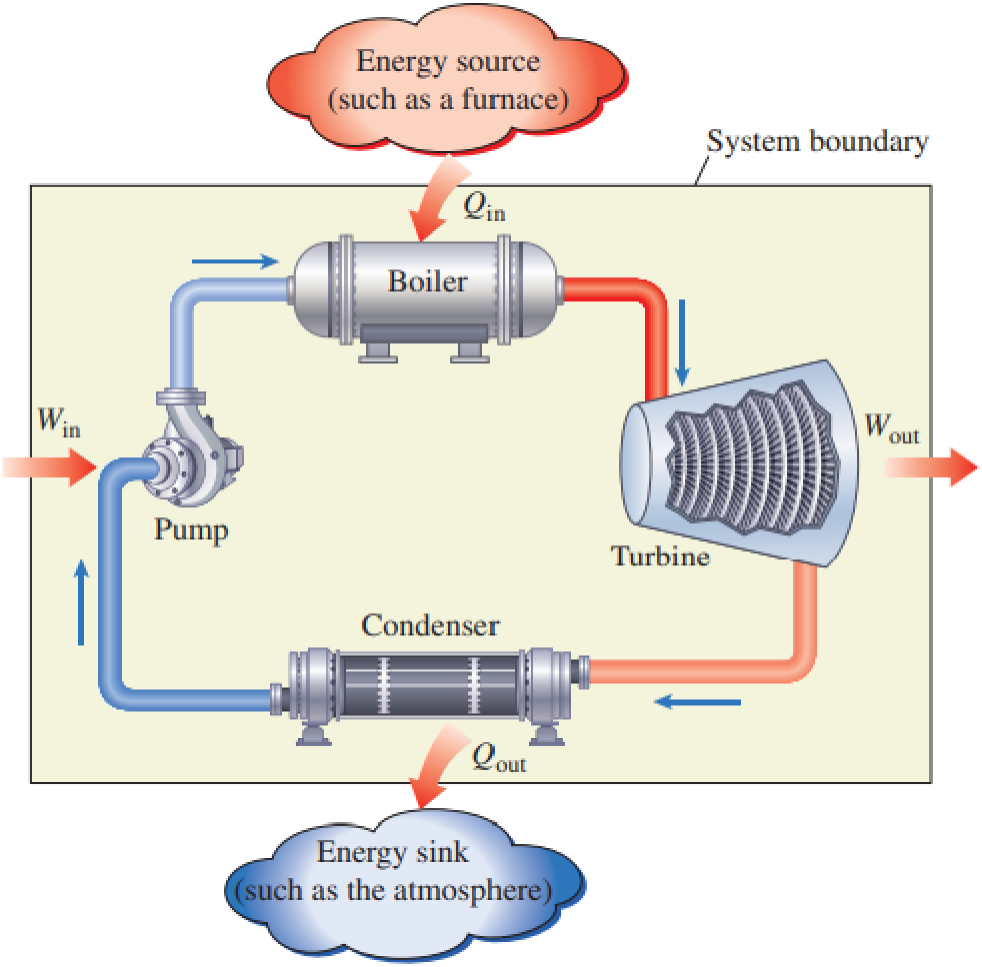

Figure 2-31
Schematic of a steam power plant.

Thermal Efficiency

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For heat engines, the desired output is the net work output, and the required input is the amount of heat supplied to the working fluid. Then the thermal efficiency of a heat engine can be expressed as

$$\eta_{th} = \frac{\textit{Net work output}}{\textit{Total heat input}} = \frac{W_{net,out}}{Q_{in}}$$

Using net power and rate of heat input,

$$\eta_{th} = \frac{\textit{Net poweroutput}}{\textit{Total rate of heat input}} = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}}$$

It can also be expressed as

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

Thermal Efficiency

since Wnet,out = Qin − Qout.

The most efficient heat engine cycle is referred to as Carnot cycle, which consists of totally reversible processes. The thermal efficiency of Carnot cycle can be expressed in terms of temperatures as

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$

Overall Plant Efficiency

We may define an overall plant efficiency based on the total energy of the fuel consumed in the plant:

$$\eta_{plant} = \frac{Net\ work\ output}{Total\ amount\ of\ heat\ input\ by\ fuel} = \frac{W_{net,out}}{m_{fuel} \times HV_{fuel}}$$

Overall Plant Efficiency

Semnan University

EXAMPLE 2-6 A coal-fired power plant generates 1100 MW power with an overall plant efficiency of 44 percent. The plant operates 75 percent of time a year. The coal used in the plant has a heating value of 26,000 kJ/kg. Determine the amount of coal consumed in the plant per year.

SOLUTION The plant operates 75 percent of the time. Then, the annual operating hours is

$$operating\ days = (0.75)(365 \times 24\ h/yr) = 6570\ h/yr$$

Overall Plant Efficiency

Semnan University

The rate of heat input to the plant is determined using plant efficiency as

$$\eta_{plant} = \frac{\dot{W}_{electric}}{\dot{Q}_{in}} \rightarrow \dot{Q}_{in} = \frac{\dot{W}_{electric}}{\eta_{plant}} = \frac{1100\ MW}{0.44} = 2500\ MW$$

The amount of heat input to the plant per year is

$$Q_{in} = \dot{Q}_{in} \times operating\ days = (2500\ MJ/s)(6570yr)\left(\frac{3600s}{1h}\right)\left(\frac{1000kJ}{1MJ}\right)$$

$$= 5.913 \times 10^{13}\ kJ/yr$$

The corresponding coal consumption of the plant per year is

$$Q_{in} = m_{coal} HV_{coal} \rightarrow m_{coal} = \frac{HV_{coal}}{Q_{in}} = \frac{5.913 \times 10^{13}\ kJ/yr}{26000\ kJ/kg}$$

$$= 2.274\ \times 10^{9}\ kg/yr$$

REFRIGERATORS AND HEAT PUMPS

We all know from experience that heat flows in the direction of decreasing temperature, that is, from high-temperature regions to low-temperature ones. This heat-transfer process occurs in nature without requiring any devices. The reverse process, however, cannot occur by itself. The transfer of heat from a low-temperature region to a high-temperature one requires special devices called refrigerators.

REFRIGERATORS AND HEAT PUMPS

Refrigerators are cyclic devices, and the working fluids used in the refrigeration cycles are called refrigerants. A refrigerator is shown schematically in Fig. 2-34a. Here QL is the magnitude of the heat removed from the refrigerated space at temperature TL, QH is the magnitude of the heat rejected to the warm space at temperature TH, and Wnet,in is the net work input to the refrigerator. Note that, QL and QH represent magnitudes and thus are positive quantities.

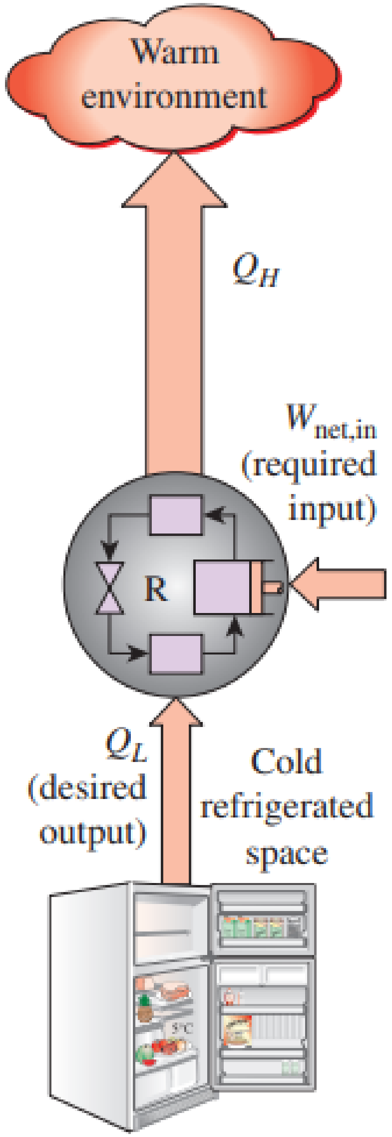

Figure 2-34
(a) Refriger

REFRIGERATORS AND HEAT PUMPS

Another device that transfers heat from a low-temperature medium to a high temperature one is the heat pump.

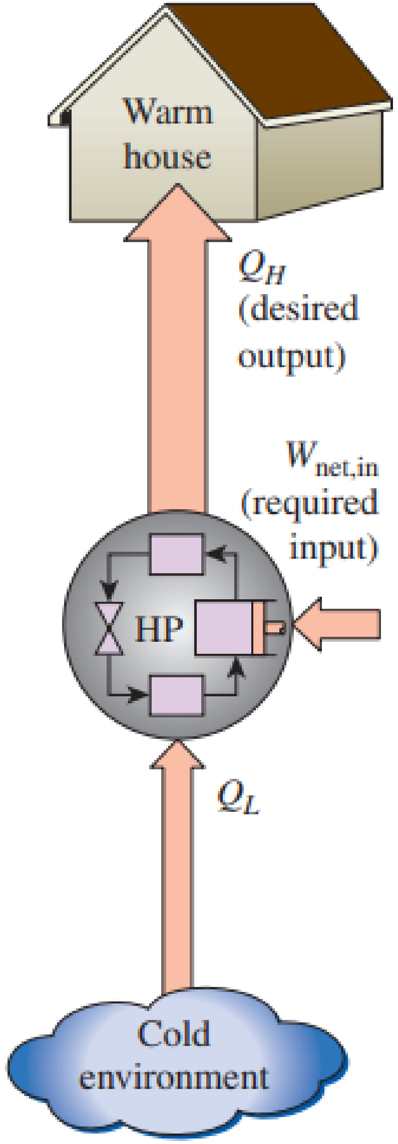

Figure 2-34b
(b) Heat pump

REFRIGERATORS AND HEAT PUMPS

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The performance of refrigerators and heat pumps is expressed in terms of the coefficient of performance (COP), defined as

$$COP_R = \frac{Cooling\ effect}{Work\ input} = \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} = \frac{Heating\ effect}{Work\ input} = \frac{Q_H}{W_{net,in}}$$

or in rate form

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net.in}}$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}}$$

REFRIGERATORS AND HEAT PUMPS

Notice that both COPR and COPHP can be greater than 1.

$$COP_{HP} = 1 + COP_R$$

REFRIGERATORS AND HEAT PUMPS

EXAMPLE 2-7 A heat pump is used to heat water from 80 to 125°F. The heat absorbed in the evaporator is 32,000 Btu/h and the power input is 4.3 kW. Determine the rate at which water is heated in gal/min and the COP of the heat pump.

SOLUTION The rate of heat transfer in the condenser is

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{in} = 32000\,\frac{Btu}{h} + (4.3\ kW)\left(\frac{3412\ Btu/h}{1kW}\right) = 46{,}672\ Btu/h$$

Taking the specific heat of water to be 1.0 Btu/lbm·°F, the mass flow rate of water is determined to be

$$\dot{Q}_H = \dot{m}c_p(T_2 - T_1) \rightarrow \dot{m} = \frac{\dot{Q}_H}{c_p(T_2 - T_1)} = \frac{46{,}672\ Btu/h}{(1.0\ Btu/lbm\ F)(125 - 80)F} = 1037\ lbm/h$$

REFRIGERATORS AND HEAT PUMPS

Semnan University

Taking density of water to be 62.1 lbm/ft3, the volume flow rate of water is determined to be

$$\dot{V} = \frac{\dot{m}}{\rho} = \frac{1037\frac{lbm}{h}}{62.1\frac{lbm}{ft^3}}\left(\frac{264.17\ gal}{35.315\ ft^3}\right)\left(\frac{1\ h}{60\ min}\right) = \mathbf{2.08\ gal/min}$$

Finally, the COP of the heat pump is determined from its definition to

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} = \frac{46{,}672\ Btu/h}{(4.3\ kW)\left(\frac{3412\ Btu/h}{1\ kW}\right)} = 3.18$$

REFRIGERATORS AND HEAT PUMPS

The most efficient refrigeration and heat pump cycles are referred to as Carnot refrigerators and heat pumps, which consist of totally reversible processes. The coefficients of performance of Carnot refrigerators and heat pumps can be expressed in terms of temperatures as

$$COP_{R,Carnot} = \frac{1}{T_H/T_L - 1} = \frac{T_L}{T_H - T_L}$$

and

$$COP_{H,Carnot} = \frac{1}{1 - T_L/T_H} = \frac{T_H}{T_H - T_L}$$