Lecture 46

(Ch13:4)

- **Units of heat (Q):**
  - *calorie* (cal): heat 1 gram of water from 14.5° C to 15.5° C
  - *British thermal unit* (Btu): heat 1 lb of water from 63° F to 64° F
  - *Joule* (J): SI unit ; 1 cal = 4.186 J

1 cal = 3.969×10^{-3} Btu = 4.186 J

1 Food Calorie = 1,000 cal = 4186 J

Review: Absorption of Heat

- Heat Capacity $Q = C\,(T_f - T_i)$
- Specific Heat $Q = c\,m\,(T_f - T_i)$
- Molar Specific Heat $Q = C\,n\,(T_f - T_i)$

  C_V C_P
- Heats of Transformation: $Q = L\,m$

  $L_V,\ L_F$

- **Heats of transformation**

Phase changes

  - *phases* or *states*: solid, liquid, gas
  - When a *phase* transform into another (*phase transformation*) the temperature is constant
  - Needs ***heat of transformation***

$$Q = L\,m \qquad L = \frac{Q}{m}$$

  - Units for L: J/Kg
  - Examples (Table 18-4); Heat of vaporization $L_{V;}$ Heat of fusion L_F

TABLE 19-4 Some Heats of Transformation

	Melting		Boiling	
Substance	Melting Point (K)	Heat of Fusion L_F (kJ/kg)	Boiling Point (K)	Heat of Vaporization L_V (kJ/kg)
Hydrogen	14.0	58.0	20.3	455
Oxygen	54.8	13.9	90.2	213
Mercury	234	11.4	630	296
Water	273	333	373	2256
Lead	601	23.2	2017	858
Silver	1235	105	2323	2336
Copper	1356	207	2868	4730

P 25. Calculate the amount of energy, in joules, required to completely melt 130 g silver initially at 15 C°.

T K = T °C + 273.15

- 25. The melting point of silver is 1235 K, so the temperature of the silver must first be raised from 15.0° C (= 288 K) to 1235 K. This requires heat

$$Q = cm(T_f - T_i) = (236\,\mathrm{J/kg \cdot K})(0.130\,\mathrm{kg})(1235\,°\mathrm{K} - 288\,°\mathrm{K}) = 2.91 \times 10^4\ \mathrm{J}.$$

- Now the silver at its melting point must be melted. If *LF* is the heat of fusion for silver this requires

$$Q = mL_F = (0.130\,\mathrm{kg})(105 \times 10^3\ \mathrm{J/kg}) = 1.36 \times 10^4\ \mathrm{J}.$$

- The total heat required is (2.91×10^4 J + 1.36×10^4 J) = 4.27×10^4 J.

Sample Problem 18-4

A copper slug whose mass m_c is 75 g is heated in a laboratory oven to a temperature T of 312°C. The slug is then dropped in a glass beaker containing a mass $m_w = 220$ g of water. The heat capacity C_b of the beaker is 45 cal/K. The initial temperature T_i of the water and the beaker is 12°C. Assuming that the slug, beaker, and water are an isolated system and the water does not vaporize, find the temperature T_f of the system at thermal equilibrium.

$$\left.\begin{aligned} Q_w &= c_w m_w (T_f - T_i) \\ Q_b &= C_b (T_f - T_i) \\ Q_c &= c_c m_c (T_f - T_{\cancel{i}}^{c}) \\ Q_w + Q_b + Q_c &= 0 \end{aligned}\right\} c_w m_w (T_f - T_i) + C_b (T_f - T_i) + c_c m_c (T_f - T_{\cancel{i}}^{c}) = 0$$

$$c_w m_w T_f + C_b T_f + c_c m_c T_f = c_w m_w T_i + C_b T_i + c_c m_c T_{\cancel{i}}^{c}$$

$$T_f = \frac{c_w m_w T_i + C_b T_i + c_c m_c T_{\cancel{i}}^{c}}{c_w m_w + C_b + c_c m_c} = \frac{(1.0)(220)(12^o) + (45)(12^o) + (0.0923)(75)(312^o)}{(1.0 cal/g\cdot K)(220g) + (45 cal/K) + (0.0923 cal/g\cdot K)(75g)}$$

$$T_f = 19.64^o C \qquad Q_w \approx 1680 cal \quad Q_b \approx 344 cal \quad Q_c \approx -2024 cal$$

Figure 13.17

Conduction occurs due to the temperature difference. (and contact)

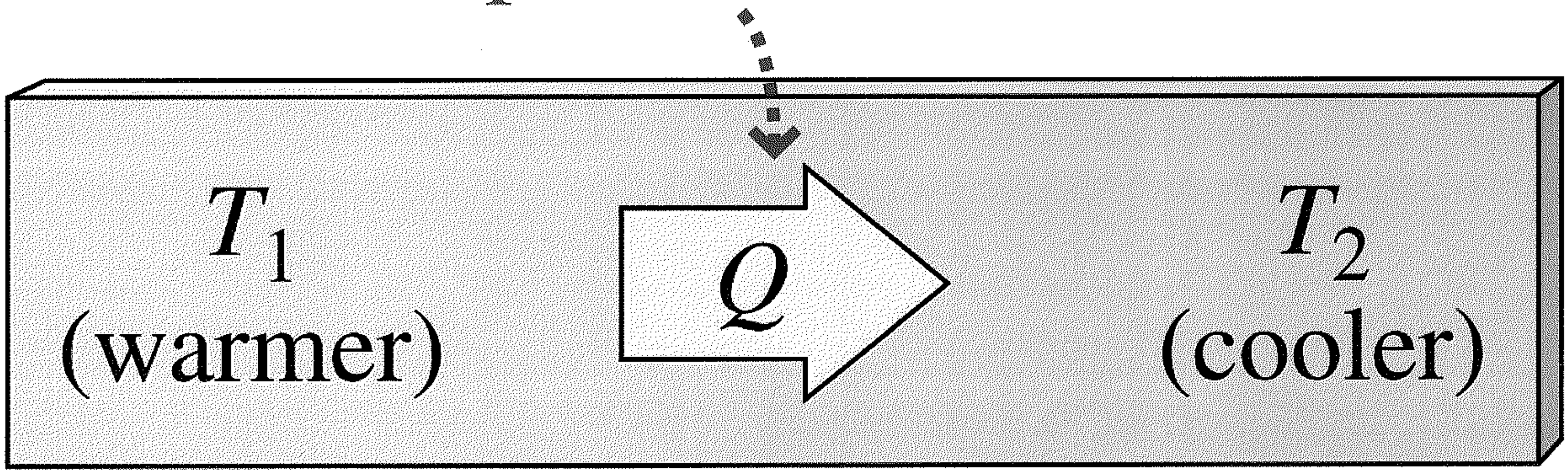
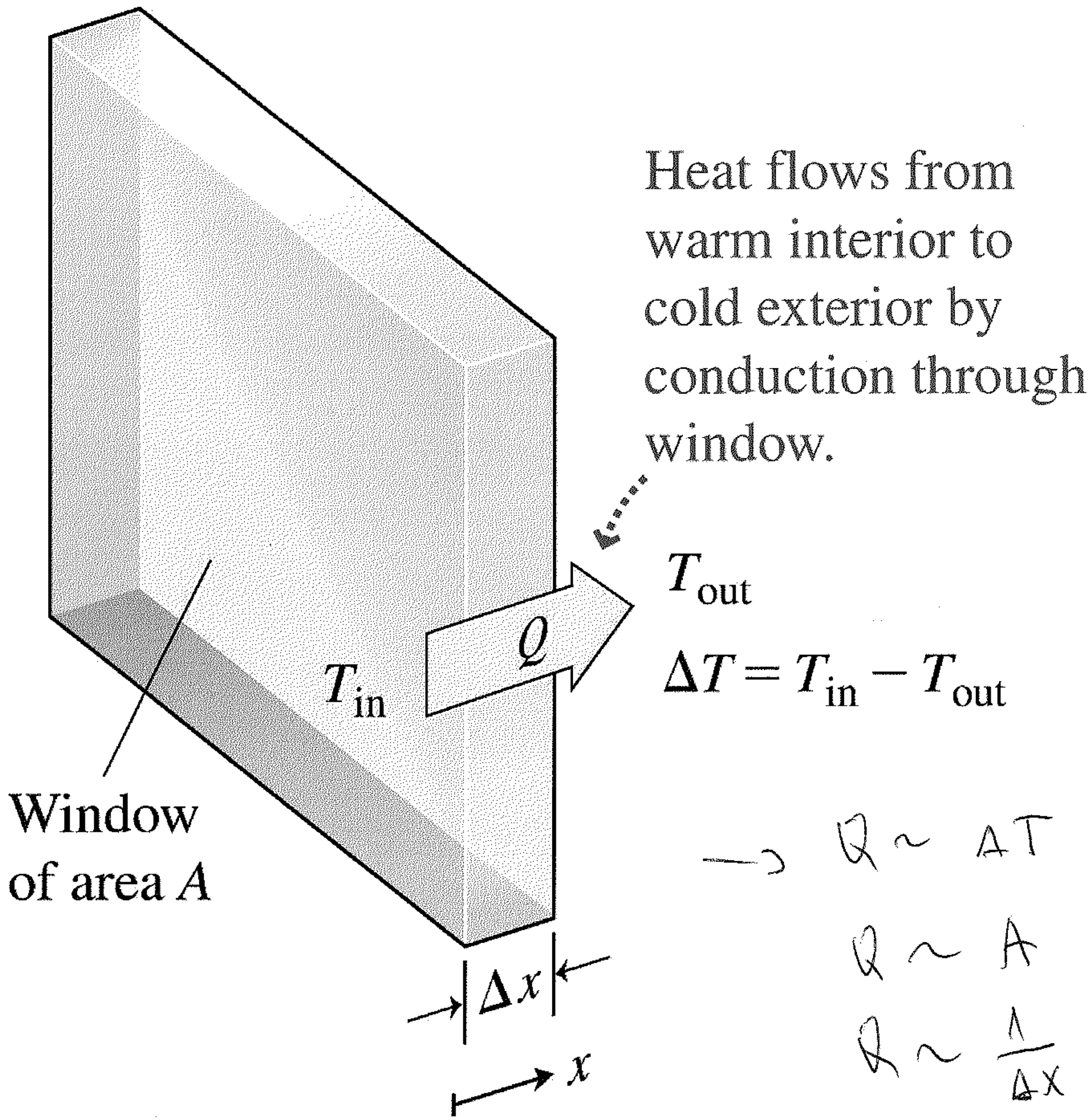


Figure 13.18



$\rightarrow Q \sim \Delta T$

$Q \sim A$

$Q \sim \frac{1}{\Delta x}$

Heat Transfer Mechanisms

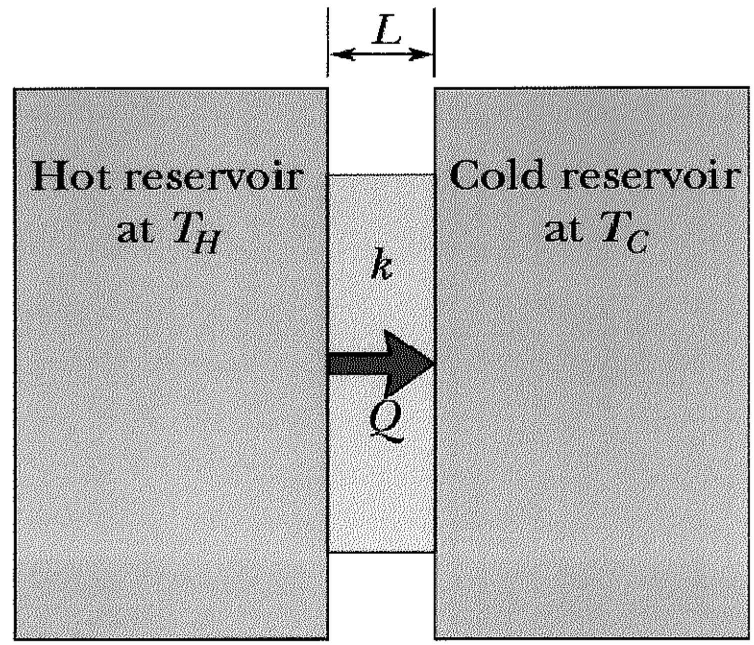
- ***Conduction***: through solids (metals) due to atomic vibration
  - Conduction through a slab (Fig. 19-18)

$$H = P_{cond} = \frac{Q}{t} = k\,A\,\frac{T_H - T_C}{L}$$

Heat-flow rate $P\ [J/s] \rightarrow [W]$

- P_{cond} – conduction rate (per unit time)
- k - thermal conductivity
- T_H (T_C) – hot(cold) reservoir temperature

$k\ \left[\frac{W}{{}^{\circ}C \cdot m}\right]$



$T_H > T_C$

Table 13-4

TABLE 13.4 Thermal Conductivities

Substance	Thermal conductivity k ($W/(°C \cdot m)$)
Metals	
Aluminum	240
Copper	390
Iron	52
Silver	420
Liquid	
Water	0.57
Gases	
Air	0.026
Hydrogen	0.17
Nitrogen	0.026
Oxygen	0.026
Other substances	
Brick	0.70
Concrete	1.28
Fiberglass	0.042
Glass (common)	0.80
Goose down	0.043
Human body (average)	0.20
Ice	2.2
Styrofoam	0.024
Wood (pine)	0.12

A window with area of 2 m^2 is made of 4 mm thick glass. If it is 20 °C colder outside than inside, what is the heat flow rate, H, through the window ?

By definition $H = k. A. (\Delta T/\Delta x)$

In our case thermal conductivity of glass $k = 0.8$ W/(C°.m), $A = 2$ m^2, $\Delta T = 20$ °C and $\Delta x = 0.004$ m

Therefore, $H = (0.8).(2).(20)/(0.004) = 8000$ W

Boou $\rightarrow | ? | \leftarrow$ concrete   So $R_c = R_{wood}(1.8\text{ cm})$

94. ORGANIZE AND PLAN We are asked to compare the insulation provided by two materials. In Problems 13.78 through 13.81, we were introduced to the *R*-value of a material, which is defined as the thickness divided by the thermal conductivity: $R = \Delta x / k$. To find the R-values for concrete and wood walls, we'll need their respective thermal conductivities from Table 13.4: $k_C = 1.28\ \text{W/°C·m}$ and $k_W = 0.12\ \text{W/°C·m}$.

Known: $\Delta x_W = 1.8$ cm.

$$\frac{\Delta x_c}{k_c} = \frac{\Delta x_{wood}}{k_{wood}} = R$$

SOLVE For a concrete wall to have the same R-value of a piece of wood, its thickness would need to be:

$$\Delta x_C = \Delta x_W \frac{k_C}{k_W} = (1.8\ \text{cm})\frac{(1.28\ \text{W/°C·m})}{(0.12\ \text{W/°C·m})} = 19.2\ \text{cm}$$

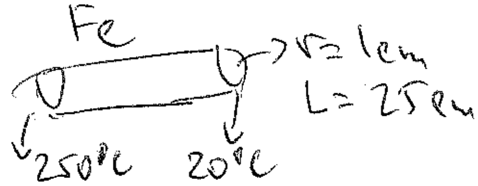
REFLECT To get the same insulation as a piece of wood, the thickness of a concrete wall has to be over ten times thicker. That's because concrete lets heat escape faster than wood does. Think of a cold concrete floor vs. a warm wooden one.

$$k_c \cancel{A} \frac{\cancel{\Delta T}}{\Delta x_c} = H = k_w \cancel{A} \frac{\cancel{\Delta T}}{\Delta x_w}$$

$$\frac{k_c}{\Delta x_c} = \frac{k_w}{\Delta x_w}$$

$$\Delta x_c = \Delta x_w \frac{k_c}{k_w}$$

Boon



Heat Flow Rate = ?

75. ORGANIZE AND PLAN The heat conduction is given in Equation 13.7: $H = kA\Delta T / \Delta x$. For iron, the thermal conductivity is: $k = 52\ \mathrm{W/{}^\circ C \cdot m}$, from Table 13.5. The heat flows along the length of the cylinder, through the round face $(A = \pi r^2)$. The temperature difference is: $\Delta T = 250^\circ\mathrm{C} - 20^\circ\mathrm{C} = 230^\circ\mathrm{C}$.

Known: $\Delta x = 25.0\ \mathrm{cm}$, $r = 1.0\ \mathrm{cm}$.

SOLVE Plugging the values into the heat conduction equation:

$$(P) = H = kA\frac{\Delta T}{\Delta x} = (52\ \mathrm{W/{}^\circ C \cdot m})\overbrace{\left(\pi(0.01\ \mathrm{m})^2\right)}^{A}\frac{(230^\circ\mathrm{C})}{(0.25\ \mathrm{m})} = 15\ \mathrm{W}$$

REFLECT For a metal, iron is not especially good at conducting heat. This is why you often find steel pots with copper bottoms, since the thermal conductivity of copper is almost 8 times that of iron.

- ***Thermal Resistance R***

$$R = \frac{L}{k} \quad R\left[\frac{m^2 \cdot {}^\circ C}{W}\right]$$

  - See Table 18-6 for values of k
  - Units for ***R*** in US:

square foot-Fahrenheit degree-hour/Btu

  - Conduction law:

$$P_{cond} = A\frac{T_H - T_C}{R}$$

TABLE 19-6 **Some Thermal Conductivities**[a]

Substance	k (W/m · K)
Metals	
Stainless steel	14
Lead	35
Aluminum	235
Copper	401
Silver	428
Gases	
Air (dry)	0.026
Helium	0.15
Hydrogen	0.18
Building Materials	
Polyurethane form	0.024
Rock wool	0.043
Fiberglass	0.048
White pine	0.11
Window glass	1.0

- ***Conduction through a composite slab***
  - Assume *steady-state* (rate of heat transfer does not change in time)

$$P_{cond} = \frac{k_2 A(T_H - T_X)}{L_2} = \frac{k_1 A(T_X - T_C)}{L_1} \quad \Rightarrow T_X = \frac{k_1 L_2 T_C + k_2 L_1 T_H}{k_1 L_2 + k_2 L_1}$$

$$P_{cond} = \frac{A(T_H - T_C)}{L_1 / k_1 + L_2 / k_2}$$

$$P_{cond} = \frac{A(T_H - T_C)}{\sum_i (L/k)} = \frac{A(T_H - T_C)}{\sum_i R}$$

for i = 1 Thermal resistance

$$P_{cond} = \frac{A(T_H - T_C)}{L/k}$$

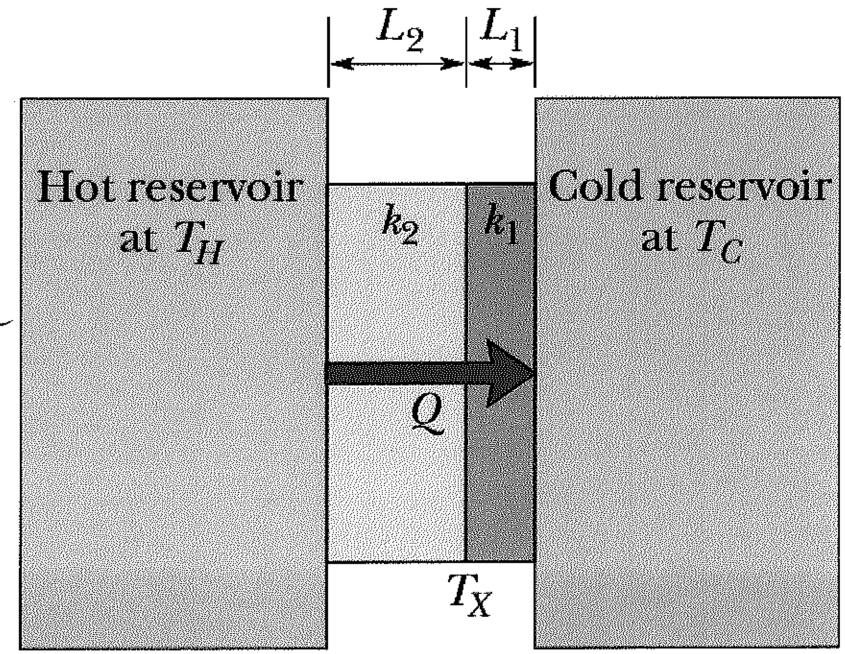
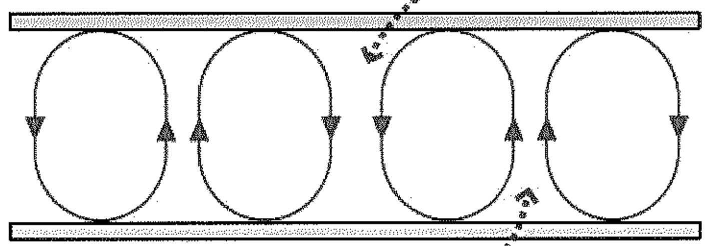
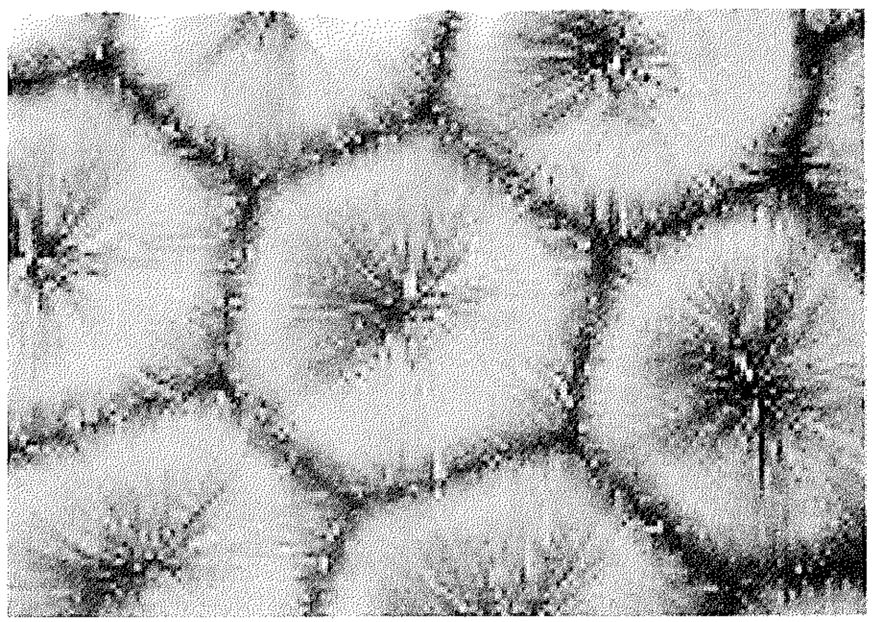


Figure 13.19

Convection



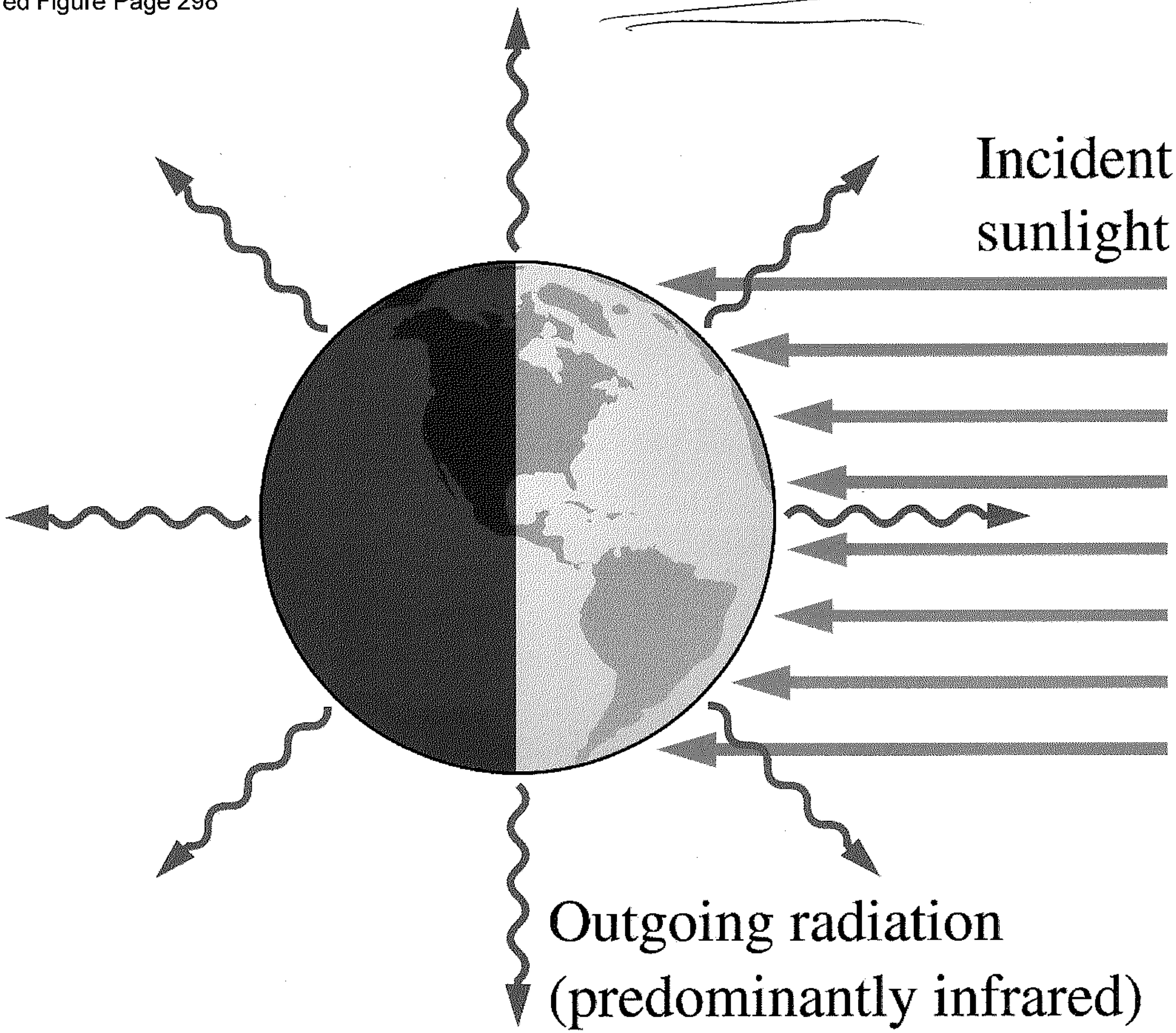
(a)

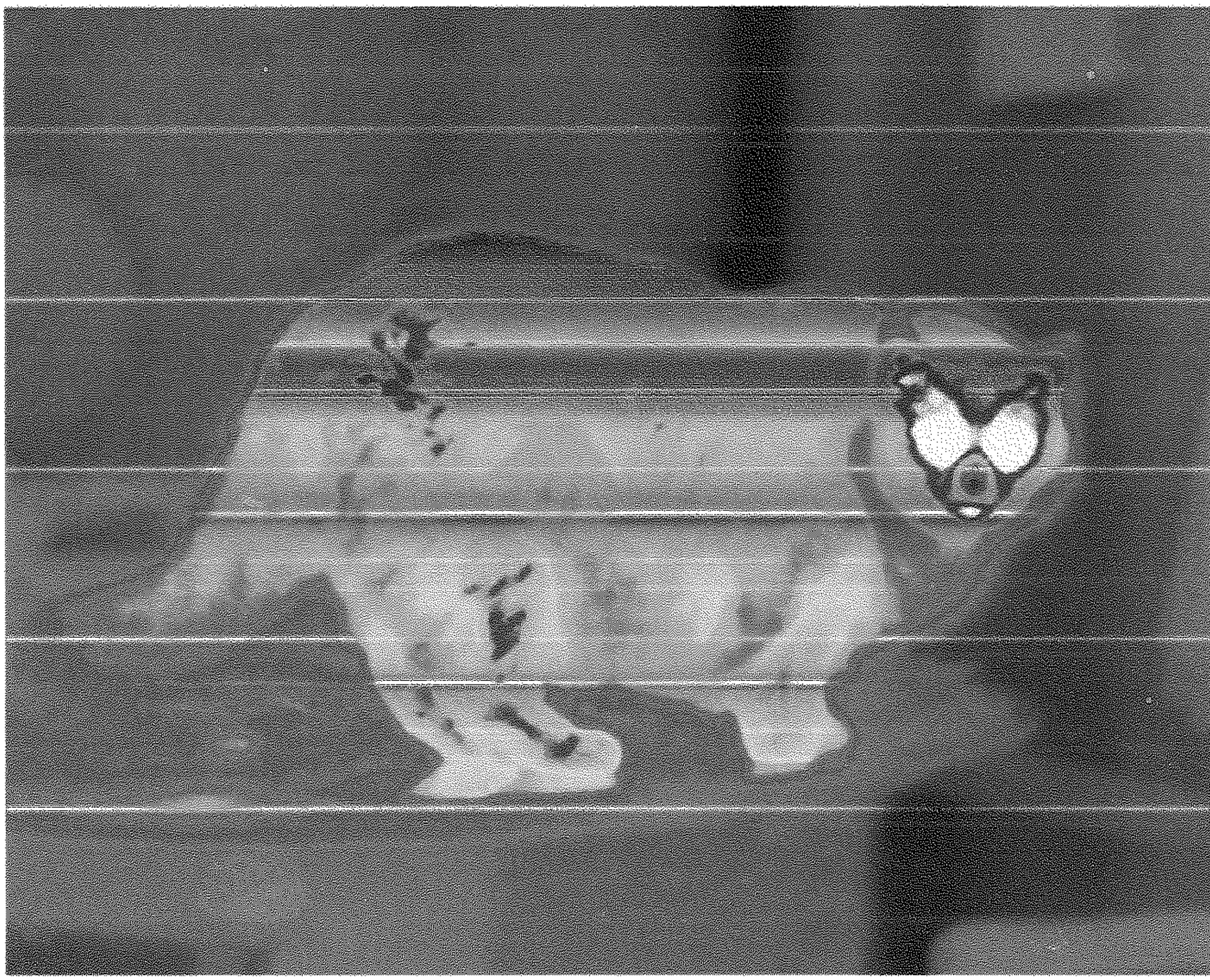


(b)

Radiation

Unnumbered Figure Page 298





- Convection – atmospheric convection
- Radiation –

$$P_{rad} = \sigma \varepsilon A T^4$$

where $\sigma = 5.673\times10^{-8}$ W/m^2 K

(Stefan-Boltzmann)

$$P_{abs} = \sigma \varepsilon A T^4_{(env)}$$

$$P_{net} = P_{abs} - P_{rad} = \sigma \varepsilon A \left(T^4_{(env)} - T^4\right)$$

ε – emissivity [0 – 1]

A sphere of surface area 2 m^2 and emissivity of 0.5 is at temperature of 300 °C. What is the rate at which the sphere radiates heat into empty space ?

The rate, P, at which an object at temperature T radiates energy is:

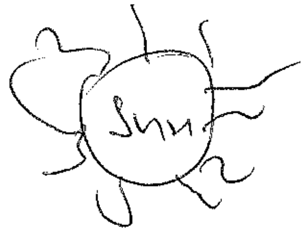
$P = e. \sigma. A. T^4$, where $\sigma = 5.67 \times 10^{-8}$ W/(m^2.K^2)

In our case e =0.5, A= 2 m^2 and T = 300 + 273.15 = 573.15 K

Therefore,

$P = (0.5). (5.67 \times 10^{-8}).(2). (573.15)^4 = 6118$ W

Book



$R_{sun} = 6.96 \times 10^{8}$ m

$T_{sun} = 5800$ K

82. **ORGANIZE AND PLAN** The Stefan-Boltzmann law (Equation 13.8) tells us the rate at which a body radiates energy: $P = e\sigma AT^4$. Saying the Sun is a blackbody means that its emissivity is one, i.e.: $e = 1$. The Stefan-Boltzmann constant is: $\sigma = 5.67 \times 10^{-8}\ \text{W/m}^2\text{K}^4$, and the surface area of a sphere is: $A = 4\pi r^2$.

Known: $r = 6.96 \times 10^8$ m, $T = 5800$ K.

SOLVE Substituting the values into the Stefan-Boltzmann law:

$$P = e\sigma AT^4 = (1)(5.67\times10^{-8}\ \text{W/m}^2\text{K}^4)\left(4\pi(6.96\times10^8\ \text{m})^2\right)(5800\ \text{K})^4 = 3.91\times10^{26}\ \text{W}$$

REFLECT Currently, the world uses somewhere around 15 TW (1.5×10^{13} W) of power. In comparison, the Sun emits over 10 quadrillion times the energy we use.

P 54. A sphere of radius 0.5 m, temperature 27°C, and emissivity 0.85 is located in an environment of temperature 77° C. At what rate does the sphere (a) emit and (b) absorb thermal radiation ? What is the sphere's net rate of energy exchange ?

- (a) The temperature of the sphere is T = (273.15 + 27.00) K = 300.15 K. Thus

$$P_r = \sigma \varepsilon A T^4 = \left(5.67\times10^{-8}\ \mathrm{W/m^2\cdot K^4}\right)(0.850)(4\pi)(0.500\,\mathrm{m})^2(300.15\,\mathrm{K})^4$$

$$= 1.23\times10^3\ \mathrm{W}.$$

- (b) Now, Tenv = 273.15 + 77.00 = 350.15 K so

$$P_a = \sigma \varepsilon A T_{\mathrm{env}}^4 = \left(5.67\times10^{-8}\ \mathrm{W/m^2\cdot K^4}\right)(0.850)(4\pi)(0.500\,\mathrm{m})^2(350.15\,\mathrm{K})^4$$

$4\pi \quad r^2$

$$= 2.28\times10^3\ \mathrm{W}.$$

- (c) From Eq. 18-40, we have

$$P_n = P_a - P_r = 2.28\times10^3\ \mathrm{W} - 1.23\times10^3\ \mathrm{W} = 1.05\times10^3\ \mathrm{W}.$$