Chapter 25

Heat

Units of Chapter 25: Heat

- Temperature
- HEAT: ENERGY IN TRANSIT
- HEAT CAPACITY AND SPECIFIC HEAT
- HEAT CAPACITIES OF SOLIDS
- THE TRANSFER OF HEAT

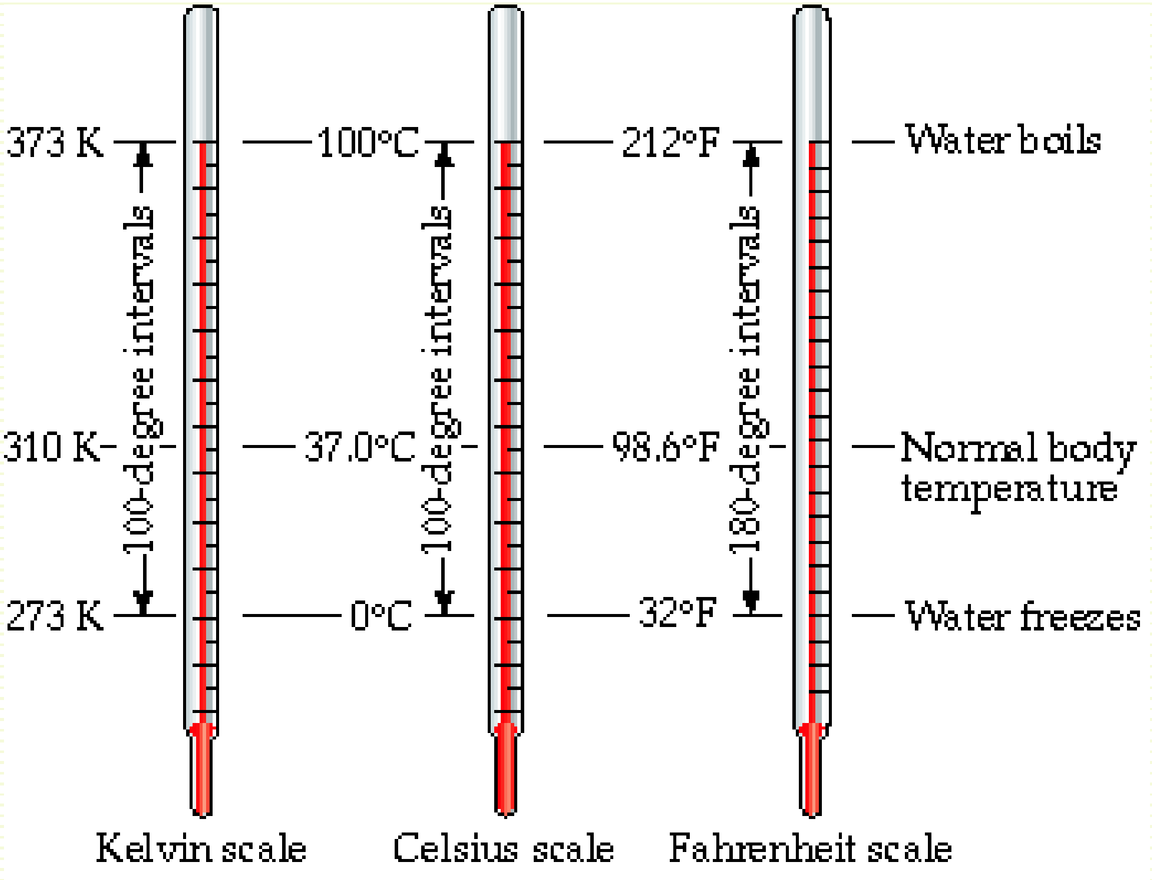
Learning goals of this chapter

- **On completing this chapter, the student will be able to :**
- Define the following terms:
  - Temperature of a body and its units.
  - heat capacity of a body and its unit.
  - specific heat of the material and its unit.
  - quantity of sensible heat and its unit.
  - quantity of latent heat and its unit.
- Calculate the amount of heat give to a system.
- Convert the degree of temperature from scale to another.
- Differentiate between the different methods of heat transfer.
- Define the thermal conductivity of the material and its unit.

Temperature

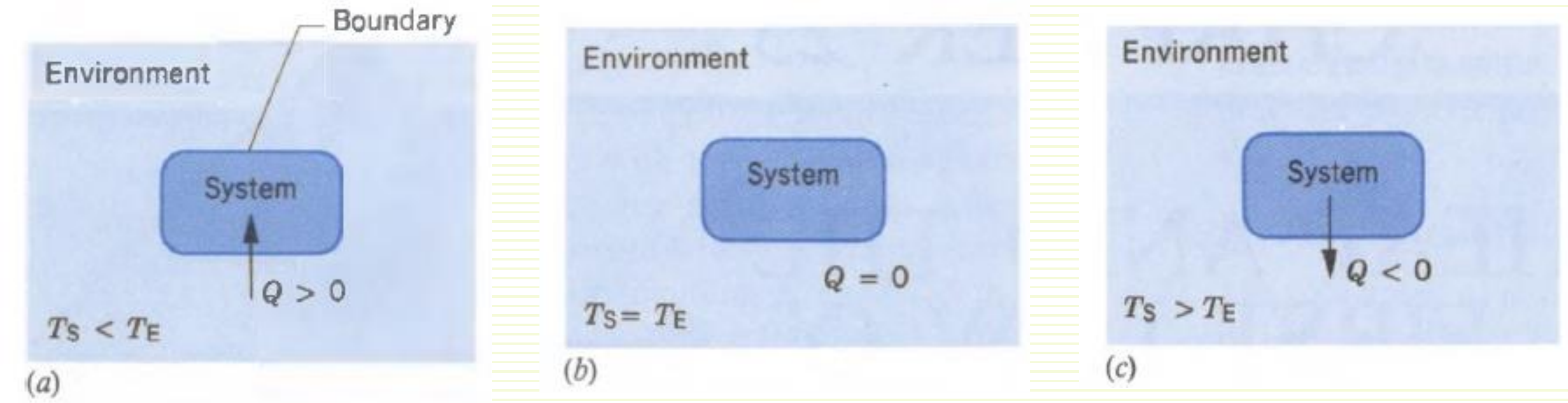
- **Temperature** is an SI base quantity related to our sense of hot and cold. It is measured with a thermometer, which contains a working substance with a measurable property, such as length or pressure, that changes in a regular way as the substance becomes hotter or colder.
- **Temperature scale**
- **Kelvin scale K is SI unit;**
- Water freeze at 273.16 K
- Water boil at 373.16 K
- **Celsius scale ^{o}C**
- Freezing point at 0 and boiling point 100 ^{o}C
- $T_C = T(K) - 237.15 \quad (^{o}C)$
- **Fahrenheit scale ^{o}F**
- Freezing point at 32 and boiling point 212 ^{o}F
- $T_F = \frac{9}{5} T_C + 32 \quad (^{o}F)$

Temperature



HEAT: ENERGY IN TRANSIT

- Heat (Q): is energy that flows between a system and its environment by virtue of a temperature difference between them.



Q is positive, zero, or negative

HEAT: ENERGY IN TRANSIT

Units of Heat

- Because heat is a form of energy, its units are those of energy, namely, the joule (J) in the SI system.
- Before it was recognized that heat is a form of energy, other units were assigned to it. In some cases these units, specifically the *calorie* (cal) and the *British thermal unit* (Btu), are still in use today.

1 cal = 4.186 J and 1 Btu = 1055 J.

- The "calorie" in common use as a measure of nutrition (Cal) is in reality a kilocalorie; that is,

1 Cal = 1000 cal = 4186 J.

HEAT: ENERGY IN TRANSIT

Misconceptions About Heat

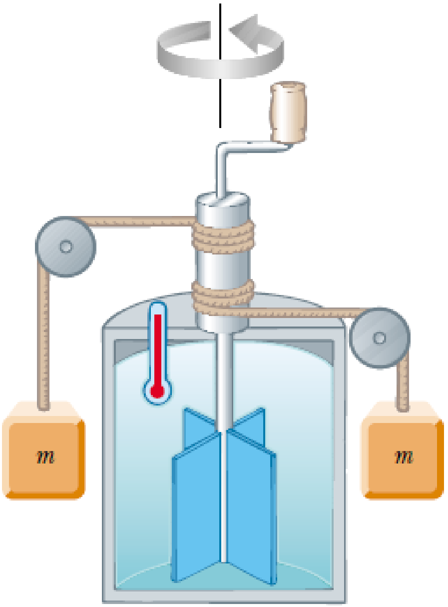
- Heat is similar to work in that both represent a means for the transfer of energy.
- Neither heat nor work is an intrinsic property of a system; that is, we cannot say that a system "contains" a certain amount of heat or work. Instead, we say that it can transfer a certain amount of energy as heat or work under certain specified conditions.
- Often heat is used when what is really meant is temperature or perhaps internal energy. When we hear about heat in relation to weather, or when cooking instructions indicate "heat at 300 degrees," it is temperature .

HEAT: ENERGY IN TRANSIT

The Mechanical Equivalent of Heat

- The mechanical work W done by the falling weights (measured in joules) produces a measurable temperature rise of the water.
- The calorie was originally defined as the quantity of heat necessary to raise the temperature of 1 g of water from 14.5 to 15.5° C.
- From the measured temperature increase of the water, Joule was able to deduce the number of calories of heat Q that, if transferred from some external source to an equal quantity of water at the same initial temperature, would have produced the same temperature increase.
- The work W done on the water by the falling weights (in joules) therefore produced a temperature rise equivalent to the absorption by the water of a certain heat Q (in calories), and from this equivalence it is possible to determine the relationship between the calorie and the joule.

$$1\ cal = 4.186\, J$$



HEAT CAPACITY AND SPECIFIC HEAT

Heat Capacity

- The heat capacity C' of a body as the ratio of the amount of heat Q supplied to a body in any process to its corresponding temperature change ΔT

$$C' = \frac{Q}{\Delta T} \quad (J/K)$$

Specific Heat Capacity

- The heat capacity per unit mass of a body, called specific heat capacity or usually just specific heat, is characteristic of the material of which the body is composed

$$c = \frac{C'}{m} = \frac{Q}{m\,\Delta T} \quad (J\,kg^{-1}\,K^{-1})$$

- The heat capacity is characteristic of a particular object, but the specific heat characterizes a substance. Both depend on the temperature.

The quantity of heat *Q* over the temperature interval $\Delta T = T_f - T_i$, is

$$Q = mc(T_f - T_i)$$

HEAT CAPACITY AND SPECIFIC HEAT

Heats of Transformation

- When energy is absorbed as heat by a solid or liquid, the temperature of the sample does not necessarily rise. Instead, the sample may change from one *phase,* or *state,* to another.
- The amount of energy per unit mass that must be transferred as heat when a sample completely undergoes a phase change is called the **heat of transformation (or latent heat) L.**
- The total heat transferred in a phase change is then

$$Q = Lm$$

- Where m is the mass of the sample

TABLE 1 HEAT CAPACITIES OF SOME SUBSTANCES[a]

Substance	*Specific Heat Capacity* (J/kg·K)	*Molar Heat Capacity* (J/mol·K)
Elemental solids		
Lead	129	26.7
Tungsten	135	24.8
Silver	236	25.5
Copper	387	24.6
Carbon	502	6.02
Aluminum	900	24.3
Other solids		
Brass	380	
Granite	790	
Glass	840	
Ice (−10°C)	2220	
Liquids		
Mercury	139	
Ethyl alcohol	2430	
Seawater	3900	
Water	4190	

[a] Measured at room temperature and atmospheric pressure, except where noted.

Sample Problem 1

- A copper sample whose mass m_C is $75\ g$ is heated in an oven to temperature T of $312\ ^oC$. The copper is then dropped into a glass beaker containing a mass m_W $(220g)$ of water. The effective heat capacity of the beaker C_b' is 190 J/K. The initial temperature T_i of the water and beaker is 12.0 °C. What is the common final temperature T_f of the copper, the beaker, and the water?
- Solution:

heat flow into the water: $Q_w = m_w c_w (T_f - T_i)$,

heat flow into the beaker: $Q_b = C_b'(T_f - T_i)$,

heat flow into the copper: $Q_c = m_c c_c (T_f - T)$.

$$\sum Q = 0$$

Or

$$Q_w + Q_b + Q_c = 0.$$

Sample Problem 1

Substituting the heat transfer expressions above yields

$$m_w c_w (T_f - T_i) + C'_b (T_f - T_i) + m_c c_c (T_f - T) = 0.$$

Solving for T_f and substituting, we have

$$T_f = \frac{m_w c_w T_i + C'_b T_i + m_c c_c T}{m_w c_w + C'_b + m_c c_c}$$

$$= \frac{(0.220\ \mathrm{kg})(4190\ \mathrm{J/kg\cdot K})(12^\circ\mathrm{C}) + (190\ \mathrm{J/K})(12^\circ\mathrm{C}) + (0.075\ \mathrm{kg})(386\ \mathrm{J/kg\cdot K})(312^\circ\mathrm{C})}{(0.220\ \mathrm{kg})(4190\ \mathrm{J/kg\cdot K}) + 190\ \mathrm{J/K} + (0.075\ \mathrm{kg})(386\ \mathrm{J/kg\cdot K})}$$

$$= 19.6^\circ\mathrm{C}.$$

From the given data you can show that

$$Q_w = 7010\ \mathrm{J}, \quad Q_b = 1440\ \mathrm{J}, \quad \text{and} \quad Q_c = -8450\ \mathrm{J}.$$

HEAT CAPACITIES OF Solids

Molar specific heat

In many instances the most convenient unit for specifying the amount of a substance is the mole (mol), where

1 mol = 6.02 X 10^{23} elementary units

When quantities are expressed in moles, specific heats must also involve moles (rather than a mass unit); they are then called molar specific heats. The molar heat capacity of the substance, defined as:

$$C = \frac{C'}{n} = \frac{Q}{n\,\Delta T}$$

where n is the number of moles of the substance having heat capacity *C'*.

The molar heat capacities vary with temperature, approaching zero at T $\rightarrow$ 0K

The Transfer of Heat

1-Conduction

There are three mechanisms for the transfer of heat:

1-Conduction 2-Convection, 3-Radiation.

1-Conduction.

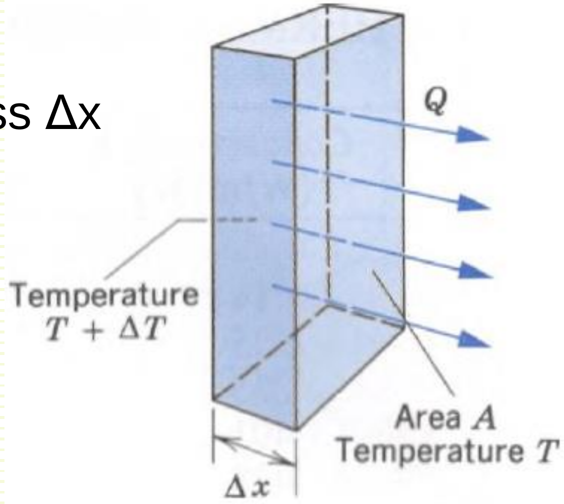
Consider a thin slab of homogeneous material of thickness Δx and cross-sectional area *A*

The rate of heat flow through the slab is:

(1) directly proportional to A

(2) inversely proportional to Δx

(3) directly proportional to Δ T



Mathematically, we can summarize these results as $H = \frac{Q}{\Delta t} \propto A \frac{\Delta T}{\Delta x}$.

Introducing a proportionality constant *k,* called the *thermal conductivity* , we can write

$$H = \frac{Q}{\Delta t} = kA \frac{\Delta T}{\Delta x}.$$

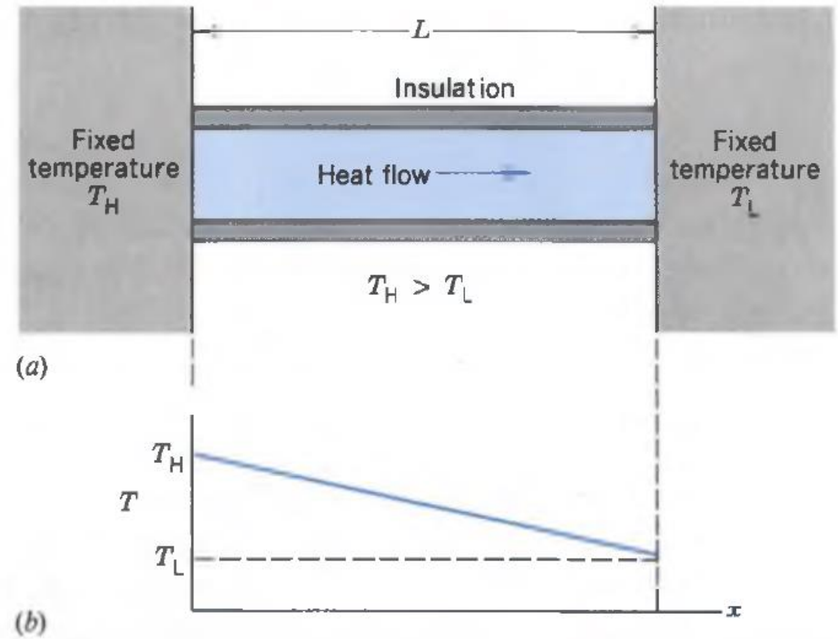
A substance with a large value of κ is a good heat conductor; one with a small value of κ is a poor conductor or a good insulator

The Transfer of Heat

1-Conduction

steady state situation: the temperatures and the rate of heat transfer are constant in time. In this situation, every increment of heat Q that enters the rod at the hot end leaves it at the cold end. Put another way, through any cross section along the length of the rod, we would measure the same rate of heat transfer.

For this case, we can write:



$$H = kA\frac{T_H - T_L}{L}$$

Here *L* is the thickness of the material in the direction of heat transfer

The Transfer of Heat

1-Conduction

Thermal resistance or R-value

$$R = \frac{L}{k}.$$

Thus the lower the conductivity, the higher the R-value: good insulators have high R-values.

The case in which the slab has infinitesimal thickness *dx* and temperature difference *dT* across its thickness, in this limit, we obtain

$$H = -kA\frac{dT}{dx}.$$

The derivative $\frac{dT}{dx}$ is often known as the *temperature gradient*

The Transfer of Heat

2- Convection

Heat transfer by convection occurs when a fluid, such as air or water, is in contact with an object whose temperature is higher than that of its surroundings. The temperature of the fluid that is in contact with the hot object increases, and (in most cases) the fluid expands. Being less dense than the surrounding cooler fluid, it rises because of buoyant forces; see Fig. 18. The surrounding cooler fluid fells to take the place of the rising warmer fluid, and a convective circulation is set up.

The outer region of the Sun, called *the photosphere,* contains a vast array of convection cells that transport energy to the solar surface and give the surface a granulated appearance.

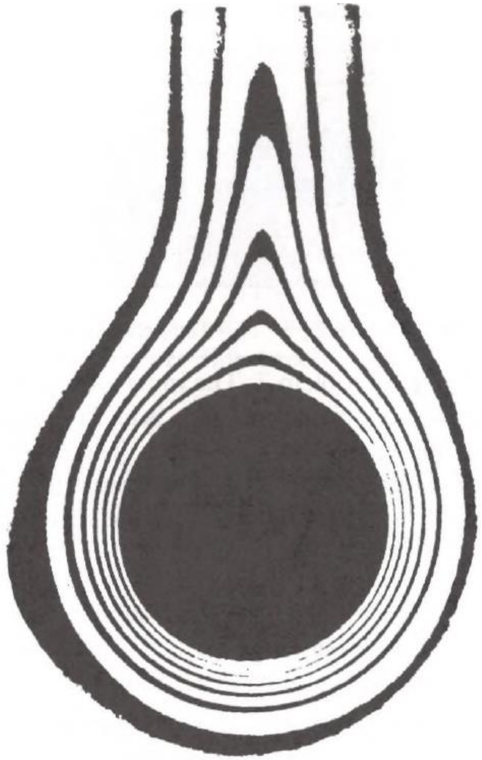


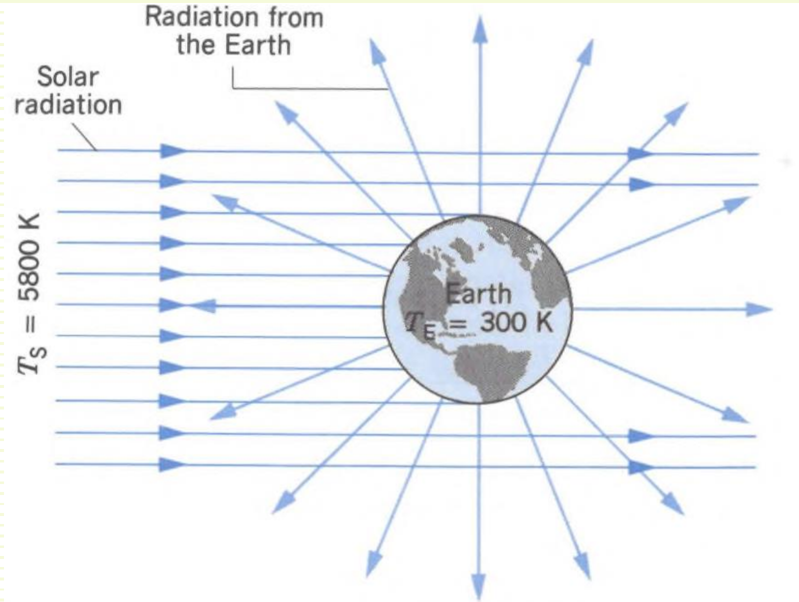
Figure 18 Air rises by convection around a heated cylinder. The dark areas represent regions of uniform temperature.

The Transfer of Heat

3- Radiation

Energy is carried from the Sun to US by electromagnetic waves that travel freely through the near vacuum of the intervening space.

All objects emit such electromagnetic radiation because of their temperature and also absorb some of the radiation that falls on them from other objects. The higher the temperature of an object, the more it radiates.



Sample Problem 6

Consider a compound slab, consisting of two materials having different thicknesses, L1 and L2, and different thermal conductivities, k1 and k2. If the temperatures of the outer surfaces are T2 and T1, find the rate of heat transfer through the compound slab (Fig. 20) in a steady state.

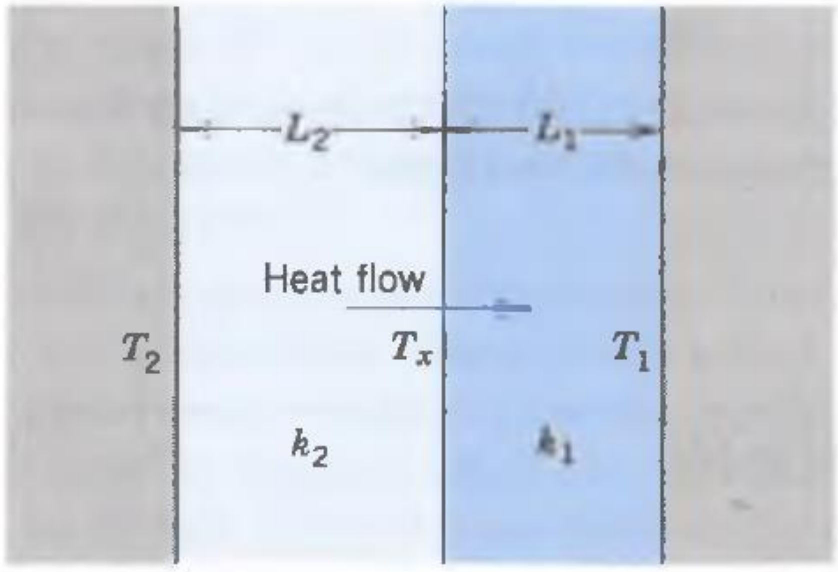


Figure 20. Conduction of heat through two layers of matter with different thermal conductivities.

Sample Problem 6

Solution

Let T_x be the temperature at the interface between the two materials. Then the rate of heat transfer through slab 2 is

$$H_2 = \frac{k_2 A(T_2 - T_x)}{L_2}$$

and that through slab 1 is

$$H_1 = \frac{k_1 A(T_x - T_1)}{L_1}.$$

In a steady state $H_2 = H_1$ so that

$$\frac{k_2 A(T_2 - T_x)}{L_2} = \frac{k_1 A(T_x - T_1)}{L_1}$$

Sample Problem 6

Let H be the rate of heat transfer (the same for all sections). Then, solving for T_x and substituting into either of the equations for H_1 or H_2, we obtain

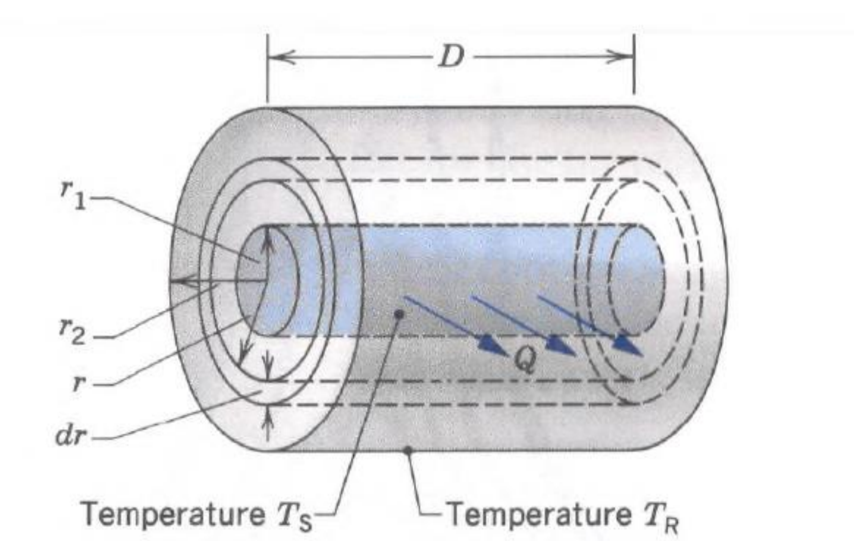
$$H = \frac{A(T_2 - T_1)}{(L_1/k_1) + (L_2/k_2)} = \frac{A(T_2 - T_1)}{R_1 + R_2}.$$

The extension to any number of sections in series is

$$H = \frac{A(T_2 - T_1)}{\Sigma(L_i/k_i)} = \frac{A(T_2 - T_1)}{\Sigma R_i}.$$

Sample Problem 7

- A thin cylindrical metal pipe is carrying steam at a temperature of $T_s = 100\ ^oC$. The pipe has a diameter of $5.4\ cm$ and is wrapped with a thickness of5.2 cm of fiberglass insulation. A length $D\ =\ 6.2\ m$ of the pipe passes through a room in which the temperature is $T_R = 11\ °C$. (a) How much heat is lost through the insulation? (b) How much additional insulation must be added to reduce the heat loss by half?



Sample Problem 7

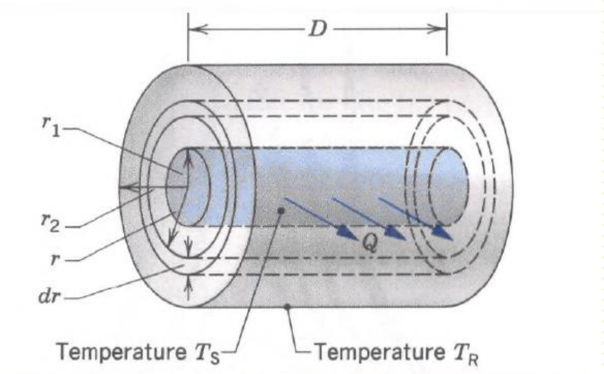
Solution

(**a**) Figure 21 illustrates the geometry appropriate to the calculation. In the steady state, the same constant rate of heat flow H will cross every thin cylindrical shell, such as the one indicated by the dashed lines in Fig. 21. We can regard this shell as a slab of material, having a thickness *dr* and an area *2πrD.*

we have

$$H = -kA\frac{dT}{dr} = -k(2\pi rD)\frac{dT}{dr}$$

$$H\frac{dr}{r} = -2\pi kD\,dT.$$



We integrate from the inner radius r_1 of the insulation at temperature T_s to the outer radius r_2 at temperature T_R:

$$\int_{r_1}^{r_2} H\frac{dr}{r} = -2\pi kD\int_{T_S}^{T_R} dT.$$

Sample Problem 7

Removing the constant H from the integral on the left and carrying out the integrations, we obtain

$$H \ln \frac{r_2}{r_1} = -2\pi k D(T_R - T_S) = 2\pi k D(T_S - T_R).$$

Solving for H and inserting the numerical values, we find

$$H = \frac{2\pi k D(T_S - T_R)}{\ln(r_2/r_1)} = \frac{2\pi(0.048\ \mathrm{W/m\cdot K})(6.2\ \mathrm{m})(89\ \mathrm{K})}{\ln(7.9\ \mathrm{cm}/2.7\ \mathrm{cm})} = 155\ \mathrm{W}.$$

(**b**) To reduce the heat loss by half we must increase r_2 to the value r_2' such that the denominator in the above expression for H becomes twice as large; that is.

$$\frac{\ln(r_2'/r_1)}{\ln(r_2/r_1)} = 2. \quad \Longrightarrow \quad r_2' = \frac{r_2^2}{r_1} = \frac{(7.9\ \mathrm{cm})^2}{2.7\ \mathrm{cm}} = 23\ \mathrm{cm}.$$

Homework

1- A small electric immersion heater is used to boil 100g of water for a cup of instant coffee. The heater is labeled 200 watts. Calculate the time required to bring this water from 23.5^{o}C to the boiling point, ignoring any hat losses.?

2-What mass of steam at **100°C** must be mixed with 150g of ice at **0°C, ** in a thermally insulated container, to produce liquid water at **50°C?**

3- The ceiling of a single-family dwelling in a cold climate should have an *R*-value of 30.To give such insulation, how thick would a layer of (a) polyurethane foam and (b) silver have to be?

3- Ice has formed on a shallow pond, and a steady state has been reached, with the air above the ice at - 5.0°C and the bottom of the pond at 4.0°C. If the total depth of *ice +water* is 1.4 m, how thick is the ice? (Assume that the thermal conductivities of ice and water are 0.40 and 0.12 cal/m C° s, respectively.)?