CHAPTER 14

Heat

Heat as Energy Transfer

Heat flows naturally from a warm body to a cool body in contact until they reach the same temperature, a state known as **thermal equilibrium.**

- One **calorie,** a unit of heat, represents the amount of heat that must be added to increase the temperature of 1 gram of water by 1 Celsius degree. In practice, the **kilocalorie,** abbreviated kcal or Calorie, is usually used. A kilocalorie represents the amount of heat that must be added to increase the temperature of 1 kilogram of water by 1 Celsius degree.
- The **mechanical equivalent of heat,** 4.186 joules, is the amount of work equal to the transfer of one calorie of heat.

Distinction Between Temperature, Heat, and Internal Energy

Both **internal energy** and **thermal energy** refer to the aggregate energy of an object's constituent molecules. While temperature depends on the average kinetic energy of a single molecule, heat is the energy transferred as objects seek thermal equilibrium. Heat is usually measured in joules, the unit of work.

Internal Energy of an Ideal Gas

The internal energy of a monatomic ideal gas, U, is a function of the mass of molecules and their temperature, $U = 3/2nRT = 3/2NkT$. For non-monatomic ideal gas molecules, the rotational and vibrational motion of the individual molecules will cause an increase in internal energy. Note that the internal energy of ideal gases (unlike that of real gases) is independent of pressure and volume.

Specific Heat and Calorimetry

Every material has a proportionality constant, called **specific heat,** c, which relates the transfer of heat to its change in temperature.

- The heat transferred, Q, is a function of its mass, the change in temperature, and the specific heat. $Q = mc\Delta T$.
- Conservation of energy applies to the heat transfer within an isolated system as thermal equilibrium is sought, such that the amount of heat removed from part of a system is equal to the amount of heat acquired in another part of a system. All heat is accounted for.
- **Calorimetry** is the quantitative measurement of heat transfer.

Latent Heat

For a material to change its state, a gain or loss of energy is required, quantified in values called **latent heats.**

- Every material has a **heat of fusion,** a constant representing the amount of energy needed to change 1 kg of that substance from solid to liquid form. Every material also has a **heat of vaporization,** another constant representing the amount of energy needed to change 1 kg of a substance from liquid to gas.
- When change of state occurs in the opposite direction, the values of latent heats refer to the quantity of energy released during the change of state.
- Heat added to a solid substance raises the temperature of that substance until it reaches its **melting point.** Then heat added converts the solid to liquid without raising the temperature until the substance is entirely liquid. If more heat is added, the temperature again increases.
- Heat added to a liquid substance raises the temperature until it reaches its **boiling point.** Then, heat added converts the liquid to gas without raising the temperature until the substance is entirely gas. If more heat is added, the temperature again increases.
- The heat required for a phase change is equal to the product of the mass and the latent heat of that substance, $Q = mL$.

Heat Transfer by Conduction, Convection, and Radiation

- **Conduction** is heat transfer resulting from molecular collisions. When part of an object is heated, the molecules in that location increase their motion and their collisions with molecules in adjacent parts of the object. Their energy is transferred, causing these adjacent molecules to increase their motions and collisions. The process repeats throughout the object, transferring heat. The rate of heat flow is given by $\Delta Q/\Delta t = kA\Delta T/l$ where k is a proportionality constant known as the **thermal conductivity,** A is the cross-sectional area, and l is the distance between the two points (which are at temperatures T_1 and T_2). High values of k indicate that a substance is a good **conductor** of heat, whereas substances with low values of k are **insulators** of heat.
- **Convection** results from movement of molecules over relatively long distances, as opposed to movement due to collisions. Fluids such as water and air can transfer heat through convection. Heated molecules move in swirls, bringing cooler molecules toward the heating element; those cooler molecules, in turn, begin to move in swirls when heated. As a continuous process, heat is transferred from a warmer region to a cooler region.
- **Radiation** requires no matter as a medium; instead, it relies on electromagnetic waves to transfer energy. The rate of transfer is given by $\Delta Q/\Delta t = e\sigma AT^4$, where σ is the constant of proportionality known as the **Stefan-Boltzmann constant,** equal to $5.67 \times 10^{-8}\ W/m^2K^4$, and e (**emissivity**) is a constant of proportionality whose value depends on the material receiving the radiation. In practice, if the emitting object at temperature T_1 is in an environment of T_2, the equation becomes $\Delta Q/\Delta t = e\sigma A(T_1^4 - T_2^4)$.

For Additional Review

Consider specific examples in which a substance's specific and latent heats are considered in determining its functional uses.

Multiple-Choice Questions

1. How many Calories are worked off by a 50 kg person climbing a 5 m rope, assuming 100% efficiency?
   (A) 0.59 Calories
   (B) 59 Calories
   (C) 1200 Calories
   (D) 2450 Calories
   (E) 5900 Calories

2. How much heat is necessary to raise a 1.1 kg copper pot filled with 1.1 kg of water from 20°C to 100°C, if water has a specific heat of 4186 J/kg·°C and copper has a specific heat of 390 J/kg·°C?
   (A) 1.4×10^4 J
   (B) 8.8×10^4 J
   (C) 1.7×10^5 J
   (D) 3.7×10^5 J
   (E) 4.1×10^5 J

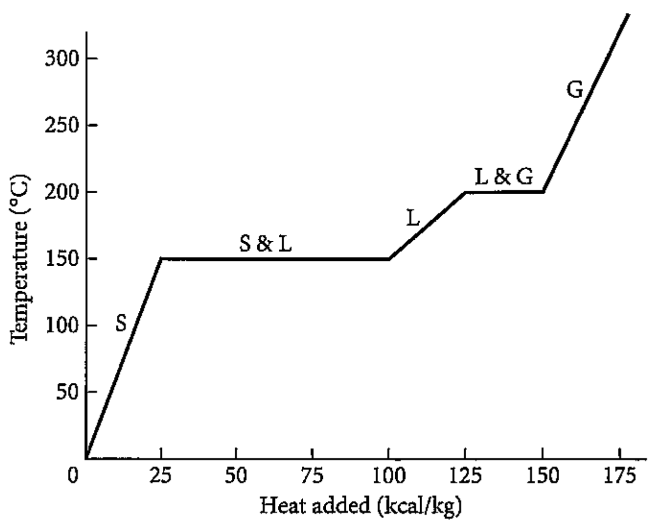
3. Thermometers often consist of mercury and glass. 10 g of mercury at 20°C are poured into a 20 gram glass vessel at 10°C. If the specific heat of mercury is 140 J/kg·°C and of glass is 840 J/kg·°C, what will the final temperature be?
   (A) 11°C
   (B) 13°C
   (C) 15°C
   (D) 17°C
   (E) 19°C

4. How much energy is required to convert 3.0 kg of water at 20°C entirely into steam, if water has a heat of vaporization of 22.6×10^5 J/kg and a specific heat of 4186 J/kg·°C?
   (A) 1.1×10^4 J
   (B) 5.5×10^5 J
   (C) 7.3×10^5 J
   (D) 9.1×10^5 J
   (E) 7.8×10^6 J

5. What is the rate of heat flow between the opposite surfaces of a 3-meter thick cube of steel in which the temperature on the opposite surfaces is 0°C and 100°C? The thermal conductivity for steel is 40 J/s·m·°C.
   (A) 3.6×10^3 J/s
   (B) 1.2×10^4 J/s
   (C) 3.6×10^4 J/s
   (D) 1.2×10^5 J/s
   (E) 3.6×10^5 J/s

6. A light bulb of surface area $3.60 \times 10^{-3} m^2$ at a temperature of 75°C shines in a white room of temperature 20°C. Given $e = 0.3$, calculate the rate of heat loss by radiation.
   (A) 60 W
   (B) 45 W
   (C) 30 W
   (D) 10 W
   (E) 0.45 W

Questions 7, 8, and 9 refer to the following diagram. The relation between temperature and heat added for 1 kg of an unknown substance is shown below. The state at each temperature is also indicated.



7. What is the heat of vaporization for this substance?
   (A) 25 kcal/kg
   (B) 50 kcal/kg
   (C) 75 kcal/kg
   (D) 100 kcal/kg
   (E) 125 kcal/kg

8. What is the heat of fusion for this substance?
   (A) 25 kcal/kg
   (B) 50 kcal/kg
   (C) 75 kcal/kg
   (D) 100 kcal/kg
   (E) 125 kcal/kg

9. How much heat would have to be added for 10 kg of the substance to change from gas to liquid at 200°C?
   (A) −250 kcal
   (B) −100 kcal
   (C) 0 kcal
   (D) 100 kcal
   (E) 250 kcal

10. What is the absolute temperature of −73°C?
    (A) 346 K
    (B) 273 K
    (C) 200 K
    (D) 127 K
    (E) 0 K

Free-Response Questions

1. (a) What is the rate of heat flow for a 2.0 cm thick wool blanket of length 7.0 m and width 5.0 m, if the temperature under the blanket is 22°C and the temperature outside the blanket is 12°C? The thermal conductivity for wool is 0.040 J/s·m·°C.
   (b) What would the rate of heat flow be if the blanket were folded in half along its shorter side?
   (c) Assuming the same thickness and surface area, what length and width would minimize the rate of heat flow?

2. An electric sphere of radius 5 cm loses 120 watts by radiation at a temperature of 60°C in a freezer of temperature −5°C.
   (a) Determine the emissivity of the room.
   (b) What would be the percentage difference in the rate of heat loss by radiation if the radius were doubled?

ANSWERS AND EXPLANATIONS

Multiple-Choice Questions

1. (A) is correct. Using the expression for work, $W = mgh = (50\text{ kg})(9.8\text{ m/s}^2)(5\text{ m}) = 2450\text{ J}$. If 1 calorie = 4.186 J, a Calorie = 4.186×10^3 J. So, $W =$ 0.59 Calories are worked off, assuming 100% efficiency.

2. (E) is correct. The total heat necessary will be equal to the heat necessary to raise the pot and the water 80°C. Using the equation $Q = Q_{water} + Q_{pot}$
$= (1.1\text{ kg})(4186\text{ J/kg·°C})(80\text{°C}) + (1.1)(390\text{ J/kg·°C})(80\text{°C})$
$= 370000\text{ J} + 34000\text{ J} = 410000\text{ J}$ or 4.1×10^5 J.

3. (A) is correct. At some point, the two substances will converge on a final temperature T_f. As such, you can apply $Q = mc\Delta T$ to the system. The heat lost by the mercury will be equal to the heat gained by the glass, so
$m_{mercury}\, c_{mercury}\, (20\text{°C} - T_f) = m_{glass}\, c_{glass}\, (T_f - 10\text{°C})$
$(0.010\text{ kg})(140\text{ J/kg·°C})(20\text{°C} - T_f) = (0.020\text{ kg})(840\text{ J/kg·°C})(T_f - 10\text{°C})$

$(28.0\ J) - (1.40\ J/°C)T_f = (16.80\ J/°C)T_f - 168\ J/kg$
$196\ J = 18.20\ J/°CT_f$
and $T_f = 11°C$.

- **4. (E) is correct.** First the water will need to be heated to the boiling point; then sufficient heat must be added to vaporize the sample entirely.
$Q = mc_w(100°C - 20°C) + mL_V$
$Q = (3.0\ kg)(4186\ J/kg{\cdot}°C)(80°C) + (3.0\ kg)(22.6 \times 10^5\ J/kg)$
$= 1.0 \times 10^6\ J + 6.8 \times 10^6\ J = 7.8 \times 10^6\ J.$
- **5. (B) is correct.** Rate of heat flow is expressed by the equation
$\Delta Q/\Delta t = kA\Delta T/l = (40\ J/s{\cdot}m{\cdot}°C)(9.0\ m^2)(100°C)/(3\ m) = 12000\ J/s$
$= 1.2 \times 10^4\ J/s.$
- **6. (E) is correct.** The rate of heat loss by radiation is $\Delta Q/\Delta t = e\sigma A(T_1^4 - T_2^4)$
$= (.3)(5.67 \times 10^{-8}\ W/m^2K^4)(3.60 \times 10^{-3}m^2)(348^4 - 293^4) = 4.47 \times 10^{-1}\ W.$
- **7. (A) is correct.** At a boiling point of approximately 200°C, heat added does not raise the temperature, but instead it changes the state of the material from liquid to gas. This occurs between the addition of 125 kcal/kg and 150 kcal/kg, so the heat of vaporization is 25 kcal/kg.
- **8. (C) is correct.** At a melting point of approximately 150°C, heat added does not raise the temperature, but instead it changes the state of the material from solid to liquid. This occurs between the addition of 25 kcal/kg and 100 kcal/kg, so the heat of fusion is 75 kcal/kg.
- **9. (A) is correct.** Heat would be released when the substance changes from gas to liquid, so the heat "added" will be a negative value:
$-Q = mL_v = (10\ kg)(25\ kcal/kg)$, which is –250 kcal.
- **10. (C) is correct.** Absolute temperature is degrees Celsius + 273.
–73°C + 273 = 200 K.

Free-Response Questions

1. (a) The rate of heat flow is given by the equation $\Delta Q/\Delta t = kA\Delta T/l$
$= (0.040\ J/s{\cdot}m{\cdot}°C)(35\ m^2)(10°C)/(0.02\ m) = 700\ J/s.$
(b) If the blanket were folded in half, it would be twice as thick, but its area would decrease. $\Delta Q/\Delta t = kA\Delta T/l$
$= (0.040\ J/s{\cdot}m{\cdot}°C)(17.5\ m^2)(10°C)/(0.04\ m) = 175\ J/s.$
(c) If the blanket's area were kept constant, the length and width that make up those dimensions would not matter, as only the area is taken into account.

This response correctly applies the heat flow equation as a function of area, change in temperature, and thickness and thermal conductivity of material for part a. The response for part b demonstrates that the situation presented alters two of the values used in part a. The response to part c expresses that the area dimensions are irrelevant to the solution.

2. (a) A restatement of the radiation by heat loss equation yields
$e = \Delta Q/\Delta t \sigma A(T_1^4 - T_2^4)$
$= (120\text{ W})/(5.67 \times 10^{-8}\text{ W/m}^2\text{K}^4)(4\pi(0.05\text{ M})^2)(333^4 - 268^4) = 9.4.$
(b) If the radius were doubled, surface area would be four times greater, since $A = 4\pi R^2$. Since $\Delta Q/\Delta t = e\sigma A(T_1^4 - T_2^4)$, all factors are the same except for the surface area, and the rate of heat loss would increase to four times the original value.

This response uses the relation between temperatures, surface area, and emissivity for part a. The response to part b is similar, expressing the percentage change in heat loss as a function of the change in radius.