

CHAPTER 19: Heat and the First Law of Thermodynamics

Responses to Questions

26. At night, the Earth cools primarily through radiation of heat back into space. Clouds reflect energy back to the Earth and so the surface cools less on a cloudy night than on a clear one.
30. A thermos bottle is designed to minimize heat transfer between the liquid contents and the outside air, even when the temperature difference is large. Heat transfer by radiation is minimized by the silvered lining. Shiny surfaces have very low emissivity, e , and thus the net rate of energy flow by radiation between the contents of the thermos and the outside air will be small. Heat transfer by conduction and convection will be minimized by the vacuum between the inner and outer walls of the thermos, since both these methods require a medium to transport heat.

Solutions to Problems

58. The heat conduction rate is given by Eq. 19-16a.

$$\frac{Q}{t} = kA \frac{T_1 - T_2}{l} = (380 \text{ J/s}\cdot\text{m}\cdot\text{g}\cdot\text{C}^\circ) \pi (0.010 \text{ m})^2 \frac{(460^\circ\text{C} - 22^\circ\text{C})}{0.45 \text{ m}} = 116 \text{ W} \approx \boxed{120 \text{ W}}$$

61. (a) The rate of heat transfer due to radiation is given by Eq. 19-17. We assume that each teapot is a sphere that holds 0.55 L. The radius and then the surface area can be found from that.

$$V = \frac{4}{3} \pi r^3 \rightarrow r = \left(\frac{3V}{4\pi} \right)^{1/3} \rightarrow S.A. = 4\pi r^2 = 4\pi \left(\frac{3V}{4\pi} \right)^{2/3}$$

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A (T_1^4 - T_2^4) = 4\pi \varepsilon \sigma \left(\frac{3V}{4\pi} \right)^{2/3} (T_1^4 - T_2^4)$$

$$\left(\frac{\Delta Q}{\Delta t} \right)_{\text{ceramic}} = 4\pi (0.70) \left(5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \cdot \text{gK}^4} \right) \left(\frac{3(0.55 \times 10^{-3} \text{ m}^3)}{4\pi} \right)^{2/3} \left[(368 \text{ K})^4 - (293 \text{ K})^4 \right]$$

$$= 14.13 \text{ W} \approx \boxed{14 \text{ W}}$$

$$\left(\frac{\Delta Q}{\Delta t} \right)_{\text{shiny}} = \left(\frac{\Delta Q}{\Delta t} \right)_{\text{ceramic}} \left(\frac{0.10}{0.70} \right) = 2.019 \text{ W} \approx \boxed{2.0 \text{ W}}$$

(b) We assume that the heat capacity comes primarily from the water in the teapots, and ignore the heat capacity of the teapots themselves. We apply Eq. 19-2, along with the results from part (a). The mass is that of 0.55 L of water, which would be 0.55 kg.

$$\Delta Q = mc\Delta T \rightarrow \Delta T = \frac{1}{mc} \left(\frac{\Delta Q}{\Delta t} \right)_{\text{radiation}} \Delta t_{\text{elapsed}}$$

$$(\Delta T)_{\text{ceramic}} = \frac{14.13 \text{ W}}{(0.55 \text{ kg}) \left(4186 \frac{\text{J}}{\text{kg}\text{gC}^\circ} \right)} (1800 \text{ s}) = \boxed{11 \text{ C}^\circ}$$

$$(\Delta T)_{\text{shiny}} = \frac{1}{7} (\Delta T)_{\text{ceramic}} = \boxed{1.6 \text{ C}^\circ}$$

62. For the temperature at the joint to remain constant, the heat flow in both rods must be the same. Note that the cross-sectional areas and lengths are the same. Use Eq. 19-16a for heat conduction.

$$\left(\frac{Q}{t} \right)_{\text{Cu}} = \left(\frac{Q}{t} \right)_{\text{Al}} \rightarrow k_{\text{Cu}} A \frac{T_{\text{hot}} - T_{\text{middle}}}{l} = k_{\text{Al}} A \frac{T_{\text{middle}} - T_{\text{cool}}}{l} \rightarrow$$

$$T_{\text{middle}} = \frac{k_{\text{Cu}} T_{\text{hot}} + k_{\text{Al}} T_{\text{cool}}}{k_{\text{Cu}} + k_{\text{Al}}} = \frac{(380 \text{ J/s}\text{m}\text{gC}^\circ)(225^\circ\text{C}) + (200 \text{ J/s}\text{m}\text{gC}^\circ)(0.0^\circ\text{C})}{380 \text{ J/s}\text{m}\text{gC}^\circ + 200 \text{ J/s}\text{m}\text{gC}^\circ} = \boxed{147^\circ\text{C}}$$

63. (a) The cross-sectional area of the Earth, perpendicular to the Sun, is a circle of radius R_{Earth} , and

so has an area of πR_{Earth}^2 . Multiply this area times the solar constant to get the rate at which the Earth is receiving solar energy.

$$\frac{Q}{t} = \pi R_{\text{Earth}}^2 (\text{solar constant}) = \pi (6.38 \times 10^6 \text{ m})^2 (1350 \text{ W/m}^2) = \boxed{1.73 \times 10^{17} \text{ W}}$$

(b) Use Eq. 19-18 to calculate the rate of heat output by radiation, and assume that the temperature of space is 0 K. The whole sphere is radiating heat back into space, and so we use the full surface area of the Earth, $4\pi R_{\text{Earth}}^2$.

$$\frac{Q}{t} = e\sigma AT^4 \rightarrow T = \left(\frac{Q}{t} \frac{1}{e\sigma A} \right)^{1/4}$$

$$= \left[\frac{(1.73 \times 10^{17} \text{ J/s})}{(1.0)(5.67 \times 10^{-8} \text{ W/m}^2 \text{ gK}^4) 4\pi (6.38 \times 10^6 \text{ m})^2} \right]^{1/4} = \boxed{278 \text{ K} = 5^\circ\text{C}}$$

64. This is an example of heat conduction. The temperature difference can be calculated by Eq. 19-16a.

$$\frac{Q}{t} = P = kA \frac{T_1 - T_2}{l} \rightarrow \Delta T = \frac{Pl}{kA} = \frac{(95 \text{ W})(5.0 \times 10^{-4} \text{ m})}{(0.84 \text{ J/s gmg}^\circ\text{C}^0) 4\pi (3.0 \times 10^{-2} \text{ m})^2} = \boxed{5.0^\circ\text{C}}$$

CHAPTER 20: Second Law of Thermodynamics

Responses to Questions

1. Yes, mechanical energy can be transformed completely into heat or internal energy, as when an object moving over a surface is brought to rest by friction. All of the original mechanical energy is converted into heat. No, the reverse cannot happen (second law of thermodynamics) except in very special cases (reversible adiabatic expansion of an ideal gas). For example, in an explosion, a large amount of internal energy is converted into mechanical energy, but some internal energy is lost to heat or remains as internal energy of the explosion fragments.
2. Yes, you can warm a kitchen in winter by leaving the oven door open. The oven converts electrical energy to heat and leaving the door open will allow this heat to enter the kitchen. However, you cannot cool a kitchen in the summer by leaving the refrigerator door open. The refrigerator is a heat engine which (with an input of work) takes heat from the low-temperature reservoir (inside the refrigerator) and exhausts heat to the high-temperature reservoir (the room). As shown by the second law of thermodynamics, there is no "perfect refrigerator," so more heat will be exhausted into the room than removed from the inside of the refrigerator. Thus, leaving the refrigerator door open will actually warm the kitchen.
5. A 10°C decrease in the low-temperature reservoir will give a greater improvement in the efficiency of a Carnot engine. By definition, T_L is less than T_H , so a 10°C change will be a larger percentage change in T_L than in T_H , yielding a greater improvement in efficiency.

11. The isothermal process will result in a greater change in entropy. The entropy change for a reversible process is the integral of dQ/T . $Q = 0$ for an adiabatic process, so the change in entropy is also 0.

Solutions to Problems

1. The efficiency of a heat engine is given by Eq. 20-1a. We also invoke energy conservation.

$$e = \frac{W}{Q_H} = \frac{W}{W + Q_L} = \frac{2600 \text{ J}}{2600 \text{ J} + 7800 \text{ J}} = 0.25 = \boxed{25\%}$$

6. (a) For the net work done by the engine to be positive, the path must be carried out clockwise. Then the work done by process bc is positive, the work done by process ca is negative, and the work done by process ab is 0. From the shape of the graph, we see that $|W_{bc}| > |W_{ca}|$.

- (b) The efficiency of the engine is given by Eq. 20-1a. So we need to find the work done and the heat input. At first glance we might assume that we need to find the pressure, volume, and temperature at the three points on the graph. But as shown here, only the temperatures and the first law of thermodynamics are needed, along with ratios that are obtained from the ideal gas law.

$$\text{ab: } W_{ab} = P\Delta V = 0 ; Q_{ab} = \Delta E_{\text{int}} = nC_V(T_b - T_a) = \frac{3}{2}nR(T_b - T_a) > 0$$

$$\text{bc: } \Delta E_{\text{int}} = nC_V(T_c - T_b) = 0 ; Q_{bc} = W_{bc} = nRT_b \ln \frac{V_c}{V_b} = nRT_b \ln \frac{V_c}{V_a} = nRT_b \ln \frac{T_c}{T_a} > 0$$

$$\text{ca: } W_{ca} = P_a(V_a - V_c) = \frac{nRT_a}{V_a}(V_a - V_c) = nRT_a \left(1 - \frac{V_c}{V_a}\right) = nRT_a \left(1 - \frac{T_c}{T_a}\right) = nR(T_a - T_c)$$

$$Q_{ca} = nC_P(T_a - T_c) = \frac{5}{2}nR(T_a - T_c) < 0$$

$$e = \frac{W}{Q_{\text{input}}} = \frac{W_{bc} + W_{ca}}{Q_{ab} + Q_{bc}} = \frac{nRT_b \ln \frac{T_c}{T_a} + nR(T_a - T_c)}{\frac{3}{2}nR(T_b - T_a) + nRT_b \ln \frac{T_c}{T_a}} = \frac{T_b \ln \frac{T_c}{T_a} + (T_a - T_c)}{\frac{3}{2}(T_b - T_a) + T_b \ln \frac{T_c}{T_a}} = \frac{T_b \ln \frac{T_b}{T_a} + (T_a - T_b)}{\frac{3}{2}(T_b - T_a) + T_b \ln \frac{T_b}{T_a}}$$

$$= \frac{(423 \text{ K}) \ln \frac{423 \text{ K}}{273 \text{ K}} + (273 \text{ K} - 423 \text{ K})}{\frac{3}{2}(423 \text{ K} - 273 \text{ K}) + (423 \text{ K}) \ln \frac{423 \text{ K}}{273 \text{ K}}} = 0.0859 = \boxed{8.59\%}$$

Of course, individual values could have been found for the work and heat on each process, and used in the efficiency equation instead of referring everything to the temperatures.

8. The maximum efficiency is the Carnot efficiency, given in Eq. 20-3.

$$e = 1 - \frac{T_L}{T_H} = 1 - \frac{(365 + 273) \text{ K}}{(550 + 273) \text{ K}} = \boxed{0.225 \text{ or } 22.5\%}$$

We assume that both temperatures are measured to the same precision – the nearest degree.

12. This is a perfect Carnot engine, and so its efficiency is given by Eq. 20-1a and Eq. 20-3. Use these two expressions to solve for the rate of heat output.

$$e = 1 - \frac{T_L}{T_H} = 1 - \frac{(45 + 273) \text{ K}}{(210 + 273) \text{ K}} = 0.3416 \quad e = \frac{W}{Q_H} = \frac{W}{W + Q_L} \rightarrow Q_L = W(1/e - 1)$$

$$Q_L/t = W/t(1/e - 1) = (950 \text{ W})(1/0.3416 - 1) = 1831 \text{ W} \approx \boxed{1800 \text{ W}}$$

18. The heat input must come during the isothermal expansion.

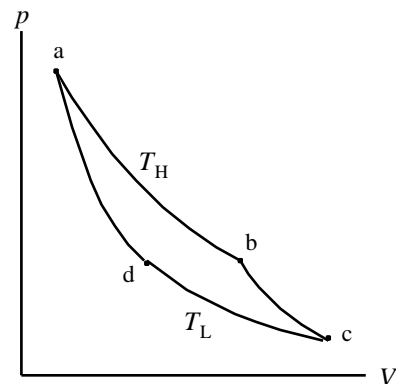
From section 20-3, page 534, we have

$$Q_H = nRT_H \ln \frac{V_b}{V_a} = nRT_H \ln 2. \text{ Since this is a Carnot cycle, we may}$$

use Eq. 20-3 combined with Eq. 20-1.

$$e = 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} \rightarrow$$

$$W = Q_H \left(\frac{T_H - T_L}{T_H} \right) = (nRT_H \ln 2) \left(\frac{T_H - T_L}{T_H} \right) = nR(T_H - T_L) \ln 2$$



The adiabatic relationship between points b and c and the ideal

gas law are used to express the temperature ratio in terms of the volume ratio.

$$P_b V_b^\gamma = P_c V_c^\gamma \rightarrow \frac{nRT_H}{V_b} V_b^\gamma = \frac{nRT_L}{V_c} V_c^\gamma \rightarrow T_H = T_L \left(\frac{V_c}{V_b} \right)^{\gamma-1} = T_L (5.7^{2/3})$$

$$W = nR(T_H - T_L) \ln 2 = nRT_L (5.7^{2/3} - 1) \ln 2 \rightarrow$$

$$T_L = \frac{W}{nR \ln 2 [5.7^{2/3} - 1]} = \frac{920 \text{ J}}{(1.00 \text{ mol})(8.314 \text{ J/molgK}) \ln 2 [5.7^{2/3} - 1]} = 72.87 \text{ K} \approx \boxed{73 \text{ K}}$$

$$T_H = (72.87 \text{ K})(5.7^{2/3}) = 232.52 \text{ K} \approx \boxed{233 \text{ K}}$$

20. (a) We use the ideal gas law and the adiabatic process

relationship to find the values of the pressure and volume at each of the four points.

$$P_a = \boxed{8.8 \text{ atm}}; T_a = 623 \text{ K};$$

$$V_a = \frac{nRT_a}{P_a} = \frac{(1.00 \text{ mol})(0.0821 \text{ Lg atm/molgK})(623 \text{ K})}{8.8 \text{ atm}} \\ = 5.81 \text{ L} \approx \boxed{5.8 \text{ L}}$$

$$T_b = 623 \text{ K}; V_b = 2V_a = 2(5.81 \text{ L}) = 11.62 \text{ L} \approx \boxed{11.6 \text{ L}}$$

$$P_b = P_a \frac{V_a}{V_b} = \frac{1}{2} P_a = \boxed{4.4 \text{ atm}}$$

$$T_c = 483 \text{ K}; P_b V_b^\gamma = P_c V_c^\gamma \rightarrow \frac{nRT_b}{V_b} V_b^\gamma = \frac{nRT_c}{V_c} V_c^\gamma \rightarrow$$

$$V_c = V_b \left(\frac{T_b}{T_c} \right)^{\frac{1}{\gamma-1}} = (11.62 \text{ L}) \left(\frac{623 \text{ K}}{483 \text{ K}} \right)^{3/2} = 17.02 \text{ L} \approx \boxed{17.0 \text{ L}}$$

$$P_c = \frac{nRT_c}{V_c} = \frac{(1.00 \text{ mol})(0.0821 \text{ Lg atm/molgK})(483 \text{ K})}{17.02 \text{ L}} = 2.33 \text{ atm} \approx \boxed{2.3 \text{ atm}}$$

$$T_d = 483 \text{ K}; V_d = V_a \left(\frac{T_a}{T_d} \right)^{\frac{1}{\gamma-1}} = (5.81 \text{ L}) \left(\frac{623 \text{ K}}{483 \text{ K}} \right)^{3/2} = 8.51 \text{ L} \approx \boxed{8.5 \text{ L}}$$

$$P_d = \frac{nRT_d}{V_d} = \frac{(1.00 \text{ mol})(0.0821 \text{ Lg atm/molgK})(483 \text{ K})}{8.51 \text{ L}} = 4.66 \text{ atm} \approx \boxed{4.7 \text{ atm}}$$

To summarize: $P_a = \boxed{8.8 \text{ atm}}; V_a = \boxed{5.8 \text{ L}}; P_b = \boxed{4.4 \text{ atm}}; V_b = \boxed{11.6 \text{ L}}$

$$P_c = \boxed{2.3 \text{ atm}}; V_c = \boxed{17.0 \text{ L}}; P_d = \boxed{4.7 \text{ atm}}; V_d = \boxed{8.5 \text{ L}}$$

(b) Isotherm ab: $\Delta E_{\text{int}} = \boxed{0}$;

$$Q_{\text{ab}} = W_{\text{ab}} = nRT_a \ln \frac{V_b}{V_a} = (1.00 \text{ mol})(8.314 \text{ J/molgK})(623 \text{ K}) \ln 2 = 3590 \text{ J} \approx \boxed{3600 \text{ J}}$$

Adiabat bc: $Q_{\text{bc}} = \boxed{0}$;

$$\begin{aligned} \Delta E_{\text{int}}_{\text{bc}} &= nC_V (T_c - T_b) = \frac{3}{2} nR (T_c - T_b) = \frac{3}{2} (1.00 \text{ mol})(8.314 \text{ J/molgK})(-140 \text{ K}) \\ &= -1746 \text{ J} \approx \boxed{-1700 \text{ J}} ; W_{\text{bc}} = Q_{\text{bc}} - \Delta E_{\text{int}}_{\text{bc}} = 1746 \text{ J} \approx \boxed{1700 \text{ J}} \end{aligned}$$

Isotherm cd: $\Delta E_{\text{int}} = \boxed{0}$;

$$Q_{\text{cd}} = W_{\text{cd}} = nRT_c \ln \frac{V_d}{V_c} = (1.00 \text{ mol})(8.314 \text{ J/molgK})(483 \text{ K}) \ln \frac{1}{2} = -2783 \text{ J} \approx \boxed{-2800 \text{ J}}$$

Adiabat da: $Q_{\text{da}} = \boxed{0}$;

$$\begin{aligned} \Delta E_{\text{int}}_{\text{bc}} &= nC_V (T_c - T_b) = \frac{3}{2} nR (T_c - T_b) = \frac{3}{2} (1.00 \text{ mol})(8.314 \text{ J/molgK})(140 \text{ K}) \\ &= 1746 \text{ J} \approx \boxed{1700 \text{ J}} ; W_{\text{bc}} = Q_{\text{bc}} - \Delta E_{\text{int}}_{\text{bc}} = 1746 \text{ J} \approx \boxed{-1700 \text{ J}} \end{aligned}$$

To summarize: ab: $\Delta E_{\text{int}} = 0$; $Q = 3600 \text{ J}$; $W = 3600 \text{ J}$

bc: $\Delta E_{\text{int}} = -1700 \text{ J}$; $Q = 0$; $W = 1700 \text{ J}$

cd: $\Delta E_{\text{int}} = 0$; $Q = -2800 \text{ J}$; $W = -2800 \text{ J}$

da: $\Delta E_{\text{int}} = 1700 \text{ J}$; $Q = 0$; $W = -1700 \text{ J}$

(c) Using Eq. 20-1: $e = \frac{W}{Q_{\text{input}}} = \frac{3590 \text{ J} + 1746 \text{ J} - 2783 \text{ J} - 1746 \text{ J}}{3590 \text{ J}} = \frac{807 \text{ J}}{3590 \text{ J}} = 0.2248 \approx \boxed{0.22}$

Using Eq. 20-3: $e = 1 - \frac{T_L}{T_H} = 1 - \frac{(273 + 210) \text{ K}}{(273 + 350) \text{ K}} = 0.2247 \approx \boxed{0.22}$

The slight disagreement is due to rounding of various calculations.

26. The coefficient of performance for an ideal refrigerator is given by Eq. 20-4c, with temperatures in Kelvins. Use that expression to find the temperature inside the refrigerator.

$$\text{COP} = \frac{T_L}{T_H - T_L} \rightarrow T_L = T_H \frac{\text{COP}}{1 + \text{COP}} = [(32 + 273) \text{ K}] \frac{5.0}{6.0} = 254 \text{ K} = \boxed{-19^\circ\text{C}}$$

27. The efficiency of a perfect Carnot engine is given by Eq. 20-1a and Eq. 20-3. Equate these two expressions to solve for the work required.

$$e = 1 - \frac{T_L}{T_H} = ; e = \frac{W}{Q_H} \rightarrow 1 - \frac{T_L}{T_H} = \frac{W}{Q_H} \rightarrow W = Q_H \left(1 - \frac{T_L}{T_H} \right)$$

$$(a) W = Q_H \left(1 - \frac{T_L}{T_H} \right) = (3100 \text{ J}) \left(1 - \frac{0 + 273}{22 + 273} \right) = 231.2 \text{ J} \approx \boxed{230 \text{ J}}$$

$$(b) W = Q_H \left(1 - \frac{T_L}{T_H} \right) = (3100 \text{ J}) \left(1 - \frac{-15 + 273}{22 + 273} \right) = 388.8 \text{ J} \approx \boxed{390 \text{ J}}$$

31. The coefficient of performance is the heat removed from the low-temperature area divided by the work done to remove the heat. In this case, the heat removed is the latent heat released by the freezing ice, and the work done is 1.2 kW times the elapsed time. The mass of water frozen is its density times its volume.

$$\text{COP} = \frac{Q_L}{W} = \frac{mL_f}{W} = \frac{\rho V L_f}{Pt} \rightarrow$$

$$V = \frac{(\text{COP}) Pt}{\rho L_f} = \frac{(7.0)(1200 \text{ W})(3600 \text{ s})}{(1.0 \times 10^3 \text{ kg/m}^3)(3.33 \times 10^5 \text{ J/kg})} = 0.0908 \text{ m}^3 \approx \boxed{91 \text{ L}}$$