The Second Law of Thermodynamics and Thermal Energy Reservoirs

6-1C Water is not a fuel; thus the claim is false.
6-2C Transferring 5 kWh of heat to an electric resistance wire and producing 5 kWh of electricity.
6-3C An electric resistance heater which consumes 5 kWh of electricity and supplies 6 kWh of heat to a room.
6-4C Transferring 5 kWh of heat to an electric resistance wire and producing 6 kWh of electricity.
6-5C No. Heat cannot flow from a low-temperature medium to a higher temperature medium.
6-6C A thermal-energy reservoir is a body that can supply or absorb finite quantities of heat isothermally. Some examples are the oceans, the lakes, and the atmosphere.
6-7C Yes. Because the temperature of the oven remains constant no matter how much heat is transferred to the potatoes.
6-8C The surrounding air in the room that houses the TV set.

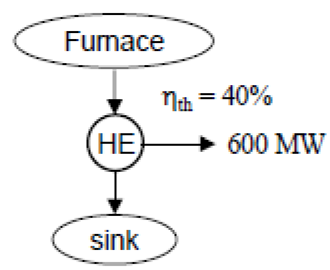
Heat Engines and Thermal Efficiency

6-9C No. Such an engine violates the Kelvin-Planck statement of the second law of thermodynamics.
6-10C Heat engines are cyclic devices that receive heat from a source, convert some of it to work, and reject the rest to a sink.
6-11C Method (b). With the heating element in the water, heat losses to the surrounding air are minimized, and thus the desired heating can be achieved with less electrical energy input.
6-12C No. Because 100% of the work can be converted to heat.
6-13C It is expressed as "No heat engine can exchange heat with a single reservoir, and produce an equivalent amount of work".
6-14C (a) No, (b) Yes. According to the second law, no heat engine can have and efficiency of 100%.
6-15C No. Such an engine violates the Kelvin-Planck statement of the second law of thermodynamics.
6-16C No. The Kelvin-Plank limitation applies only to heat engines; engines that receive heat and convert some of it to work.

6-17

Assumptions **1** The plant operates steadily. **2** Heat losses from the working fluid at the pipes and other components are negligible.
Analysis The rate of heat supply to the power plant is determined from the thermal efficiency relation,

$$\dot{Q}_H = \frac{\dot{W}_{\text{net,out}}}{\eta_{\text{th}}} = \frac{600 \text{ MW}}{0.4} = 1500 \text{ MW}$$



The rate of heat transfer to the river water is determined from the first law η th = 40% relation for a heat engine,

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{\text{net,out}} = 1500 - 600 = \mathbf{900 \text{ MW}}$$

In reality the amount of heat rejected to the river will be **lower** since part of the heat will be lost to the surrounding air from the working fluid as it passes through the pipes and other components.

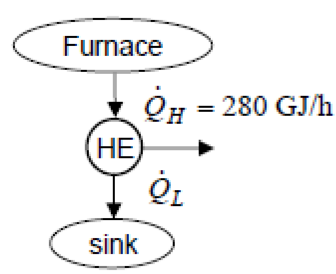
6-18

Assumptions **1** The plant operates steadily. **2** Heat losses from the working fluid at the pipes and other components are taken into consideration.
Analysis (*a*) The total heat rejected by this power plant is

$$\dot{Q}_L = 145 + 8 = 153 \text{ GJ/h}$$

Then the net power output of the plant becomes

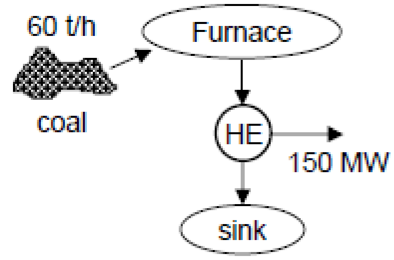
$$\dot{W}_{\text{net,out}} = \dot{Q}_H - \dot{Q}_L = 280 - 153 = 127 \text{ GJ/h} = \mathbf{35.3 \text{ MW}}$$



(*b*) The thermal efficiency of the plant is determined from its definition,

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_H} = \frac{127 \text{ GJ/h}}{280 \text{ GJ/h}} = 0.454 = \mathbf{45.4\%}$$

6-20



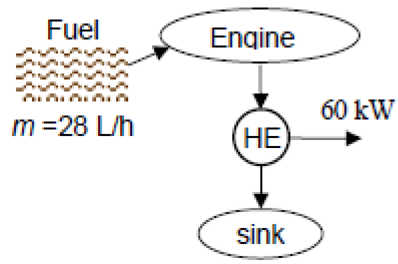
Properties The heating value of coal is given to be 30,000 kJ/kg.
Analysis The rate of heat supply to this power plant is

$$\dot{Q}_H = \dot{m}_{\text{coal}} u_{\text{coal}} = (60{,}000 \text{ kg/h})(30{,}000 \text{ kJ/kg}) = 1.8 \times 10^9 \text{ kJ/h} = 500 \text{ MW}$$

Then the thermal efficiency of the plant becomes

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_H} = \frac{150 \text{ MW}}{500 \text{ MW}} = 0.300 = \mathbf{30.0\%}$$

6-21



Properties The heating value of the fuel is given to be 44,000 kJ/kg.
Analysis The mass consumption rate of the fuel is

$$\dot{m}_{\text{fuel}} = (\rho \dot{V})_{\text{fuel}} = (0.8 \text{ kg/L})(28 \text{ L/h}) = 22.4 \text{ kg/h}$$

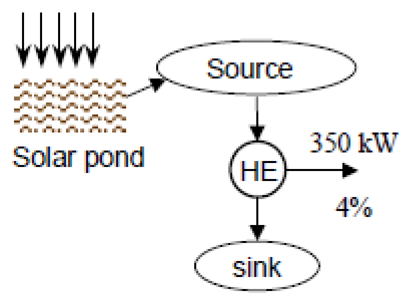
The rate of heat supply to the car is

$$\dot{Q}_H = \dot{m}_{\text{coal}} u_{\text{coal}} = (22.4 \text{ kg/h})(44{,}000 \text{ kJ/kg}) = 985{,}600 \text{ kJ/h} = 273.78 \text{ kW}$$

Then the thermal efficiency of the car becomes

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_H} = \frac{60 \text{ kW}}{273.78 \text{ kW}} = 0.219 = \mathbf{21.9\%}$$

6-22

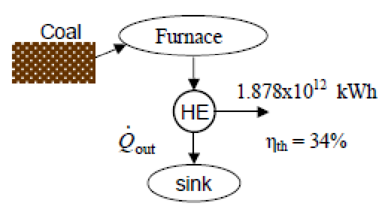


Analysis The rate of solar energy collection or the rate of heat supply to the power plant is determined from the thermal efficiency relation to be

$$\dot{Q}_H = \frac{\dot{W}_{\text{net,out}}}{\eta_{\text{th}}} = \frac{350 \text{ kW}}{0.04} \left(\frac{1 \text{ Btu}}{1.055 \text{ kJ}} \right) \left(\frac{3600 \text{ s}}{1 \text{ h}} \right) = \mathbf{2.986 \times 10^7 \text{ Btu/h}}$$

6-23

Analysis The United States produces about 51 percent of its electricity from coal at a conversion efficiency of about 34 percent. Noting that the conversion efficiency is 34%, the amount of heat rejected by the coal plants per year is



$$\eta_{\text{th}} = \frac{W_{\text{coal}}}{Q_{\text{in}}} = \frac{W_{\text{coal}}}{Q_{\text{out}} + W_{\text{coal}}}$$

$$Q_{\text{out}} = \frac{W_{\text{coal}}}{\eta_{\text{th}}} - W_{\text{coal}} = \frac{1.878 \times 10^{12} \text{ kWh}}{0.34} - 1.878 \times 10^{12} \text{ kWh} = \mathbf{3.646 \times 10^{12} \text{ kWh}}$$

6-28

Analysis (*a*) The rate and the amount of heat inputs to the power plant are

$$\dot{Q}_{in} = \frac{\dot{W}_{net,out}}{\eta_{th}} = \frac{300 \text{ MW}}{0.32} = 937.5 \text{ MW}$$

$$Q_{in} = \dot{Q}_{in}\Delta t = (937.5 \text{ MJ/s})(24 \times 3600 \text{ s}) = 8.1 \times 10^7 \text{ MJ}$$

The amount and rate of coal consumed during this period are

$$m_{coal} = \frac{Q_{in}}{q_{HV}} = \frac{8.1 \times 10^7 \text{ MW}}{28 \text{ MJ/kg}} = \mathbf{2.893 \times 10^6 \text{ kg}}$$

$$\dot{m}_{coal} = \frac{m_{coal}}{\Delta t} = \frac{2.893 \times 10^6 \text{ kg}}{24 \times 3600 \text{ s}} = 33.48 \text{ kg/s}$$

(*b*) Noting that the air-fuel ratio is 12, the rate of air flowing through the furnace is

$$\dot{m}_{air} = (\text{AF})\dot{m}_{coal} = (12 \text{ kg air/kg fuel})(33.48 \text{ kg/s}) = \mathbf{401.8 \text{ kg/s}}$$

Refrigerators and Heat Pumps

6-29C The difference between the two devices is one of purpose. The purpose of a refrigerator is to remove heat from a cold medium whereas the purpose of a heat pump is to supply heat to a warm medium.

6-30C The difference between the two devices is one of purpose. The purpose of a refrigerator is to remove heat from a refrigerated space whereas the purpose of an air-conditioner is remove heat from a living space.

6-31C No. Because the refrigerator consumes work to accomplish this task.

6-32C No. Because the heat pump consumes work to accomplish this task.

6-33C The coefficient of performance of a refrigerator represents the amount of heat removed from the refrigerated space for each unit of work supplied. It can be greater than unity.

6-34C The coefficient of performance of a heat pump represents the amount of heat supplied to the heated space for each unit of work supplied. It can be greater than unity.

6-35C No. The heat pump captures energy from a cold medium and carries it to a warm medium. It does not create it.

6-36C No. The refrigerator captures energy from a cold medium and carries it to a warm medium. It does not create it.

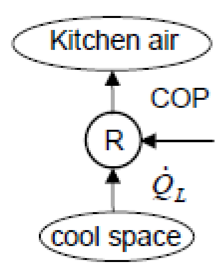
6-37C No device can transfer heat from a cold medium to a warm medium without requiring a heat or work input from the surroundings.

6-38C The violation of one statement leads to the violation of the other one, as shown in Sec. 6-4, and thus we conclude that the two statements are equivalent.

6-39

(*a*) Using the definition of the coefficient of performance, the power input to the refrigerator is determined to be

$$\dot{W}_{net,in} = \frac{\dot{Q}_L}{\text{COP}_R} = \frac{60 \text{ kJ/min}}{1.2} = 50 \text{ kJ/min} = \mathbf{0.83 \text{ kW}}$$



(*b*) The heat transfer rate to the kitchen air is determined from the energy balance,

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{net,in} = 60 + 50 = \mathbf{110 \text{ kJ/min}}$$

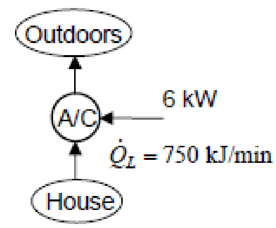
6-40

(*a*) The coefficient of performance of the air-conditioner (or refrigerator) is determined from its definition,

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{\text{net,in}}} = \frac{750 \text{ kJ/min}}{6 \text{ kW}}\left(\frac{1 \text{ kW}}{60 \text{ kJ/min}}\right) = \mathbf{2.08}$$

(*b*) The rate of heat discharge to the outside air is determined from the energy balance,

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{net,in}} = (750 \text{ kJ/min}) + (6 \times 60 \text{ kJ/min}) = \mathbf{1110 \text{ kJ/min}}$$



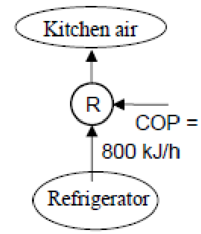
6-41

Since the refrigerator runs one-fourth of the time and removes heat from the food compartment at an average rate of 800 kJ/h, the refrigerator removes heat at a rate of

$$\dot{Q}_L = 4 \times (800 \text{ kJ/h}) = 3200 \text{ kJ/h}$$

when running. Thus the power the refrigerator draws when it is running is

$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_L}{\text{COP}_R} = \frac{3200 \text{ kJ/h}}{2.2} = 1455 \text{ kJ/h} = \mathbf{0.40 \text{ kW}}$$



6-43

The total amount of heat that needs to be removed from the watermelons is

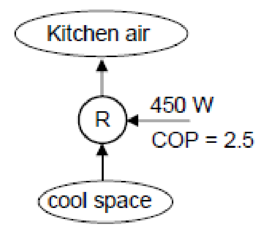
$$Q_L = (mc\Delta T)_{\text{watermelons}} = 5 \times (10 \text{ kg})(4.2 \text{ kJ/kg}\cdot{}^\circ\text{C})(20-8)^\circ\text{C} = 2520 \text{ kJ}$$

The rate at which this refrigerator removes heat is

$$\dot{Q}_L = (\text{COP}_R)(\dot{W}_{\text{net,in}}) = (2.5)(0.45 \text{ kW}) = 1.125 \text{ kW}$$

That is, this refrigerator can remove 1.125 kJ of heat per second. Thus the time required to remove 2520 kJ of heat is

$$\Delta t = \frac{Q_L}{\dot{Q}_L} = \frac{2520 \text{ kJ}}{1.125 \text{ kJ/s}} = 2240 \text{ s} = \mathbf{37.3 \text{ min}}$$



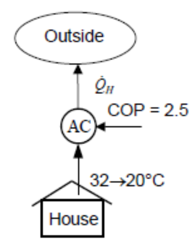
6-44

Air is an ideal gas with constant specific heats at room temperature. The constant volume specific heat of air is given to be $c_V = 0.72$ kJ/kg.° C. Since the house is well-sealed (constant volume), the total amount of heat that needs to be removed from the house is

$$Q_L = (mc_v\Delta T)_{\text{House}} = (800 \text{ kg})(0.72 \text{ kJ/kg}\cdot{}^\circ\text{C})(32-20)^\circ\text{C} = 6912 \text{ kJ}$$

This heat is removed in 15 minutes. Thus the average rate of heat removal from the house is

$$\dot{Q}_L = \frac{Q_L}{\Delta t} = \frac{6912 \text{ kJ}}{15 \times 60 \text{ s}} = 7.68 \text{ kW}$$



Using the definition of the coefficient of performance, the power input to the air-conditioner is determined to be

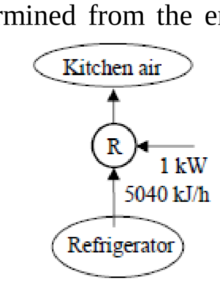
$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_L}{\text{COP}_R} = \frac{7.68 \text{ kW}}{2.5} = \mathbf{3.07 \text{ kW}}$$

6-46

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{\text{net,in}}} = \frac{5040 \text{ kJ/h}}{1 \text{ kW}}\left(\frac{1 \text{ kW}}{3600 \text{ kJ/h}}\right) = \mathbf{1.4}$$

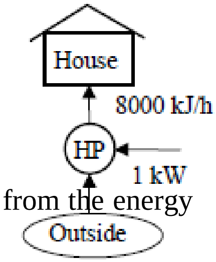
The rate of heat rejection to the surrounding air, per kW of power consumed, is determined from the energy balance,

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{net,in}} = (5040 \text{ kJ/h}) + (1 \times 3600 \text{ kJ/h}) = \mathbf{8640 \text{ kJ/h}}$$



6-47

The coefficient of performance of the refrigerator is determined from its definition,



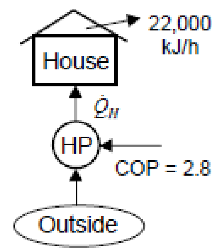
$$\text{COP}_{\text{HP}} = \frac{\dot{Q}_H}{\dot{W}_{\text{net,in}}} = \frac{8000 \text{ kJ/h}}{1 \text{ kW}}\left(\frac{1 \text{ kW}}{3600 \text{ kJ/h}}\right) = \mathbf{2.22}$$

The rate of heat absorption from the surrounding air, per kW of power consumed, is determined from the energy balance,

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{\text{net,in}} = (8{,}000 \text{ kJ/h}) - (1)(3600 \text{ kJ/h}) = \mathbf{4400 \text{ kJ/h}}$$

6-50

Since the heat pump runs one-third of the time and must supply heat to the house at an average rate of 22,000 kJ/h, the heat pump supplies heat at a rate of



$$\dot{Q}_H = 3 \times (22{,}000 \text{ kJ/h}) = 66{,}000 \text{ kJ/h}$$

when running. Thus the power the heat pump draws when it is running is

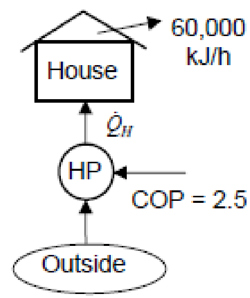
$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_H}{\text{COP}_{\text{HP}}} = \frac{66{,}000 \text{ kJ/h}}{2.8}\left(\frac{1 \text{ kW}}{3600 \text{ kJ/h}}\right) = \mathbf{6.55 \text{ kW}}$$

6-51

The heating load of this heat pump system is the difference between the heat lost to the outdoors and the heat generated in the house from the people, lights, and appliances,

$$\dot{Q}_H = 60{,}000 - 4{,}000 = 56{,}000 \text{ kJ / h}$$

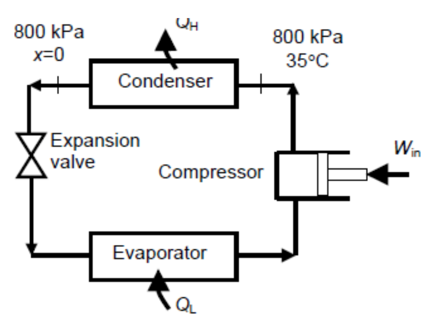
Using the definition of COP, the power input to the heat pump is determined to be



$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_H}{\text{COP}_{\text{HP}}} = \frac{56{,}000 \text{ kJ/h}}{2.5}\left(\frac{1 \text{ kW}}{3600 \text{ kJ/h}}\right) = \mathbf{6.22 \text{ kW}}$$

6-54

The enthalpies of R-134a at the condenser inlet and exit are



$$\left.\begin{array}{l} P_1 = 800 \text{ kPa} \\ T_1 = 35°\text{C} \end{array}\right\} h_1 = 271.22 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 800 \text{ kPa} \\ x_2 = 0 \end{array}\right\} h_2 = 95.47 \text{ kJ/kg}$$

(*a*) An energy balance on the condenser gives the heat rejected in the condenser

$$\dot{Q}_H = \dot{m}(h_1 - h_2) = (0.018 \text{ kg/s})(271.22 - 95.47) \text{ kJ/kg} = 3.164 \text{ kW}$$

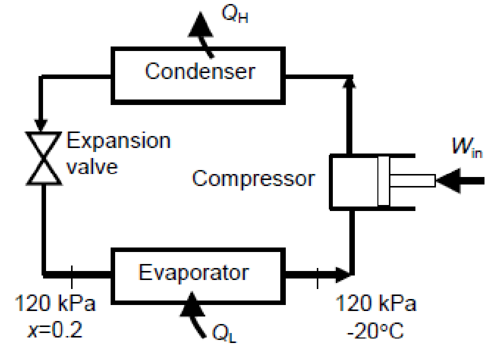
The COP of the heat pump is

$$\text{COP} = \frac{\dot{Q}_H}{\dot{W}_{\text{in}}} = \frac{3.164 \text{ kW}}{1.2 \text{ kW}} = \mathbf{2.64}$$

(*b*) The rate of heat absorbed from the outside air

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{\text{in}} = 3.164 - 1.2 = \mathbf{1.96 \text{ kW}}$$

6-55



The properties of R-134a at the evaporator inlet and exit states are

$$\left.\begin{array}{l} P_1 = 120 \text{ kPa} \\ x_1 = 0.2 \end{array}\right\} h_1 = 65.38 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 120 \text{ kPa} \\ T_2 = -20°\text{C} \end{array}\right\} h_2 = 238.84 \text{ kJ/kg}$$

(*a*) The refrigeration load is

$$\dot{Q}_L = (\text{COP})\dot{W}_{\text{in}} = (1.2)(0.45 \text{ kW}) = 0.54 \text{ kW}$$

The mass flow rate of the refrigerant is determined from

$$\dot{m}_R = \frac{\dot{Q}_L}{h_2 - h_1} = \frac{0.54 \text{ kW}}{(238.84 - 65.38) \text{ kJ/kg}} = \mathbf{0.0031 \text{ kg/s}}$$

(*b*) The rate of heat rejected from the refrigerator is

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{in}} = 0.54 + 0.45 = \mathbf{0.99 \text{ kW}}$$

Reversible and Irreversible Processes

6-58C No. Because it involves heat transfer through a finite temperature difference.

6-59C Because reversible processes can be approached in reality, and they form the limiting cases. Work producing devices that operate on reversible processes deliver the most work, and work consuming devices that operate on reversible processes consume the least work.

6-60C When the compression process is non-quasiequilibrium, the molecules before the piston face cannot escape fast enough, forming a high pressure region in front of the piston. It takes more work to move the piston against this high pressure region.

6-61C When an expansion process is non-quasiequilibrium, the molecules before the piston face cannot follow the piston fast enough, forming a low pressure region behind the piston. The lower pressure that pushes the piston produces less work.

6-62C The irreversibilities that occur within the system boundaries are **internal** irreversibilities; those which occur outside the system boundaries are **external** irreversibilities.

6-63C A reversible expansion or compression process cannot involve unrestrained expansion or sudden compression, and thus it is quasi-equilibrium. A quasi-equilibrium expansion or compression process, on the other hand, may involve external irreversibilities (such as heat transfer through a finite temperature difference), and thus is not necessarily reversible.

The Carnot Cycle and Carnot's Principle

6-64C The four processes that make up the Carnot cycle are isothermal expansion, reversible adiabatic expansion, isothermal compression, and reversible adiabatic compression.

6-65C They are (1) the thermal efficiency of an irreversible heat engine is lower than the efficiency of a reversible heat engine operating between the same two reservoirs, and (2) the thermal efficiency of all the reversible heat engines operating between the same two reservoirs are equal.

6-66C False. The second Carnot principle states that no heat engine cycle can have a higher thermal efficiency than the Carnot cycle operating between the same temperature limits.

6-67C Yes. The second Carnot principle states that all reversible heat engine cycles operating between the same temperature limits have the same thermal efficiency.

6-68C (a) No, (b) No. They would violate the Carnot principle.

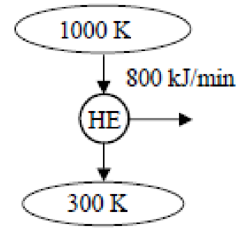
Carnot Heat Engines

6-69C No.

6-70C The one that has a source temperature of 600°C. This is true because the higher the temperature at which heat is supplied to the working fluid of a heat engine, the higher the thermal efficiency.

6-71

(a) The thermal efficiency of a Carnot heat engine depends on the source and the sink temperatures only, and is determined from



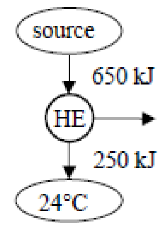
$$\eta_{\text{th,C}} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\text{ K}}{1000\text{ K}} = 0.70 \text{ or } \mathbf{70\%}$$

(b) The power output of this heat engine is determined from the definition of thermal efficiency,

$$\dot{W}_{\text{net,out}} = \eta_{\text{th}}\dot{Q}_H = (0.70)(800\text{ kJ/min}) = 560\text{ kJ/min} = \mathbf{9.33\ kW}$$

6-72

(a) For reversible cyclic devices we have $\left(\frac{Q_H}{Q_L}\right)_{\text{rev}} = \left(\frac{T_H}{T_L}\right)$



Thus the temperature of the source TH must be

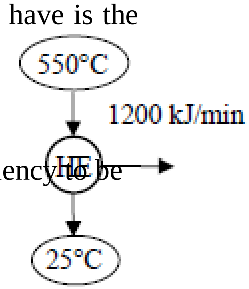
$$T_H = \left(\frac{Q_H}{Q_L}\right)_{\text{rev}} T_L = \left(\frac{650\text{ kJ}}{250\text{ kJ}}\right)(297\text{ K}) = \mathbf{772.2\ K}$$

(*b*) The thermal efficiency of a Carnot heat engine depends on the source and the sink temperatures only, and is determined from

$$\eta_{\text{th,C}} = 1 - \frac{T_L}{T_H} = 1 - \frac{297\text{ K}}{772.2\text{ K}} = 0.615 \text{ or } \mathbf{61.5\%}$$

6-73

The highest thermal efficiency a heat engine operating between two specified temperature limits can have is the Carnot efficiency, which is determined from



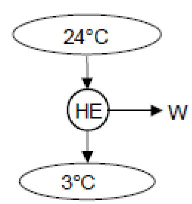
$$\eta_{\text{th,max}} = \eta_{\text{th,C}} = 1 - \frac{T_L}{T_H} = 1 - \frac{298\text{ K}}{823\text{ K}} = 0.638 \text{ or } 63.8\%$$

Then the maximum power output of this heat engine is determined from the definition of thermal efficiency to be

$$\dot{W}_{\text{net,out}} = \eta_{\text{th}}\dot{Q}_H = (0.638)(1200\text{ kJ/min}) = 765.6\text{ kJ/min} = \mathbf{12.8\ kW}$$

6-76

The highest thermal efficiency a heat engine operating between two specified temperature limits can have is the Carnot efficiency, which is determined from

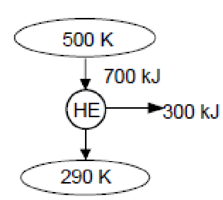


$$\eta_{\text{th,max}} = \eta_{\text{th,C}} = 1 - \frac{T_L}{T_H} = 1 - \frac{276\text{ K}}{297\text{ K}} = 0.071 \quad \text{or} \quad \mathbf{7.1\%}$$

6-77

$$\eta_{\text{th,max}} = \eta_{\text{th,C}} = 1 - \frac{T_L}{T_H} = 1 - \frac{20+273\text{ K}}{140+273\text{ K}} = 0.291 \text{ or } \mathbf{29.1\%}$$

678



$$\eta_{\text{th,max}} = \eta_{\text{th,C}} = 1 - \frac{T_L}{T_H} = 1 - \frac{290\text{ K}}{500\text{ K}} = 0.42 \text{ or } \mathbf{42\%}$$

The actual thermal efficiency of the heat engine in question is

$$\eta_{\text{th}} = \frac{W_{net}}{Q_H} = \frac{300\text{ kJ}}{700\text{ kJ}} = 0.429 \text{ or } \mathbf{42.9\%}$$

which is greater than the maximum possible thermal efficiency. Therefore, this heat engine is a PMM2 and the claim is **false**.

Carnot Refrigerators and Heat Pumps

6-81C By increasing TL or by decreasing TH.

6-82C It is the COP that a Carnot refrigerator would have, $\text{COP}_\text{R} = \frac{1}{T_H/T_L - 1}$.

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6-83C No. At best (when everything is reversible), the increase in the work produced will be equal to the work consumed by the refrigerator. In reality, the work consumed by the refrigerator will always be greater than the additional work produced, resulting in a decrease in the thermal efficiency of the power plant.

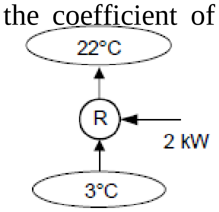
6-84C No. At best (when everything is reversible), the increase in the work produced will be equal to the work consumed by the refrigerator. In reality, the work consumed by the refrigerator will always be greater than the additional work produced, resulting in a decrease in the thermal efficiency of the power plant.

6-85C Bad idea. At best (when everything is reversible), the increase in the work produced will be equal to the work consumed by the heat pump. In reality, the work consumed by the heat pump will always be greater than the additional work produced, resulting in a decrease in the thermal efficiency of the power plant.

6-86 The coefficient of performance of a Carnot refrigerator depends on the temperature limits in the cycle only, and is determined from

$$\text{COP}_{\text{R,C}} = \frac{1}{(T_H/T_L)-1} = \frac{1}{(22+273\text{K})/(3+273\text{K})-1} = 14.5$$

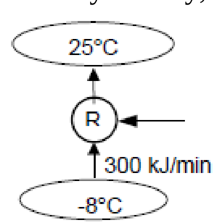
The rate of heat removal from the refrigerated space is determined from the definition of the coefficient of performance of a refrigerator,



$$\dot{Q}_L = \text{COP}_\text{R}\dot{W}_{\text{net,in}} = (14.5)(2\text{ kW}) = 29.0\text{ kW} = \mathbf{1740\ \ kJ/min}$$

6-87

The power input to a refrigerator will be a minimum when the refrigerator operates in a reversible manner. The coefficient of performance of a reversible refrigerator depends on the temperature limits in the cycle only, and is determined from



$$COP_{\text{R,rev}} = \frac{1}{(T_H/T_L)-1} = \frac{1}{(25+273\text{ K})/(-8+273\text{ K})-1} = 8.03$$

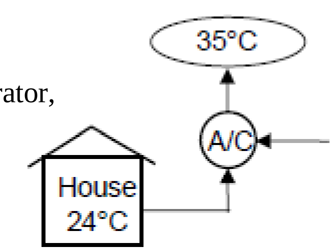
$$\dot{W}_{\text{net,in,min}} = \frac{\dot{Q}_L}{COP_{\text{R,max}}} = \frac{300\text{ kJ/min}}{8.03} = 37.36\text{ kJ/min} = \mathbf{0.623\ kW}$$

6-88

The COP of a Carnot air conditioner (or Carnot refrigerator) depends on the temperature limits in the cycle only, and is determined from

$$\text{COP}_{\text{R,C}} = \frac{1}{(T_H/T_L)-1} = \frac{1}{(35+273\text{ K})/(24+273\text{ K})-1} = 27.0$$

The power input to this refrigerator is determined from the definition of the COP of a refrigerator,

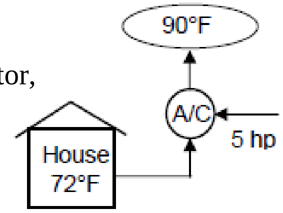


$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_L}{\text{COP}_{\text{R,max}}} = \frac{750\text{ kJ/min}}{27.0} = 27.8\text{ kJ/min} = \mathbf{0.463\ kW}$$

6-89

The rate of heat removal from a house will be a maximum when the air-conditioning system operates in a reversible manner.

$$COP_{R,rev} = \frac{1}{(T_H/T_L)-1} = \frac{1}{(90+460\text{ R})/(72+460\text{ R})-1} = 29.6$$



The rate of heat removal from the house is determined from the definition of the COP of a refrigerator,

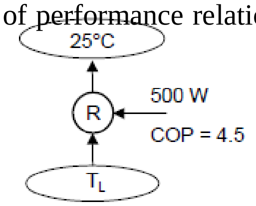
$$\dot{Q}_L = \text{COP}_\text{R}\dot{W}_\text{net,in} = (29.6)(5\text{ hp})\left(\frac{42.41\text{ Btu/min}}{1\text{ hp}}\right) = \mathbf{6277\ \ Btu/min}$$

6-90

(*a*) The rate of heat removal from the refrigerated space is determined from the definition of the COP of a refrigerator,

$$\dot{Q}_L = \text{COP}_\text{R}\dot{W}_\text{net,in} = (4.5)(0.5\text{ kW}) = 2.25\text{ kW} = \mathbf{135\ kJ/min}$$

(*b*) The temperature of the refrigerated space *TL* is determined from the coefficient of performance relation for a Carnot refrigerator,



$$\text{COP}_\text{R,rev} = \frac{1}{(T_H/T_L)-1} \longrightarrow 4.5 = \frac{1}{(25+273\text{ K})/T_L - 1}$$

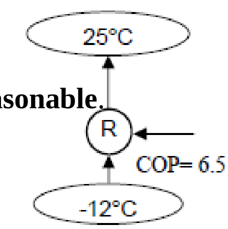
It yields $\quad T_L = 243.8\text{ K} = \mathbf{-29.2°C}$

6-91

The highest coefficient of performance a refrigerator can have when removing heat from a cool medium at -12°C to a warmer medium at 25°C is

$$\text{COP}_\text{R,max} = \text{COP}_\text{R,rev} = \frac{1}{(T_H/T_L)-1} = \frac{1}{(25+273\text{ K})/(-12+273\text{ K})-1} = 7.1$$

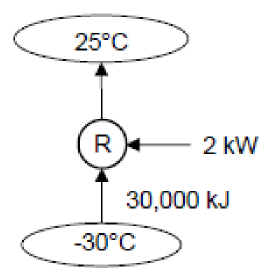
The COP claimed by the inventor is 6.5, which is below this maximum value, thus the claim is **reasonable**. However, it is not probable.



6-92

The highest coefficient of performance a refrigerator can have when removing heat from a cool medium at -30°C to a warmer medium at 25°C is

$$\text{COP}_\text{R,max} = \text{COP}_\text{R,rev} = \frac{1}{(T_H/T_L)-1} = \frac{1}{(25+273\text{ K})/(-30+273\text{ K})-1} = 4.42$$



The work consumed by the actual refrigerator during this experiment is

$$W_\text{net,in} = \dot{W}_\text{net,in}\Delta t = (2\text{ kJ/s})(20\times 60\text{ s}) = 2400\text{ kJ}$$

Then the coefficient of performance of this refrigerator becomes

$$\text{COP}_\text{R} = \frac{Q_L}{W_\text{net,in}} = \frac{30{,}000\text{kJ}}{2400\text{kJ}} = 12.5$$

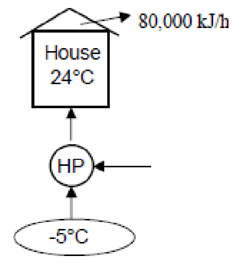
which is above the maximum value. Therefore, these measurements are **not reasonable**.

6-94

The power input to a heat pump will be a minimum when the heat pump operates in a reversible manner. The COP of a reversible heat pump depends on the temperature limits in the cycle only, and is determined from The required power input to this reversible heat pump is determined from the definition of the coefficient of performance to be

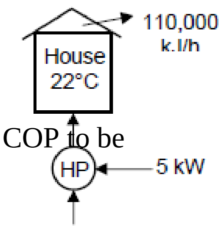
$$\mathrm{COP}_{\mathrm{HP,rev}} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(-5+273\ \mathrm{K})/(24+273\ \mathrm{K})} = 10.2$$

$$\dot{W}_{\mathrm{net,in,min}} = \frac{\dot{Q}_H}{\mathrm{COP}_{\mathrm{HP}}} = \frac{80{,}000\ \mathrm{kJ/h}}{10.2}\left(\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}\right) = \mathbf{2.18\ kW}$$



which is the *minimum* power input required.

6-95



$$\mathrm{COP}_{\mathrm{HP,rev}} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(2+273\ \mathrm{K})/(22+273\ \mathrm{K})} = 14.75$$

The required power input to this reversible heat pump is determined from the definition of the COP to be

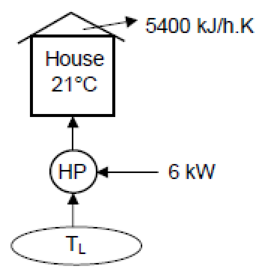
$$\dot{W}_{\mathrm{net,in,min}} = \frac{\dot{Q}_H}{\mathrm{COP}_{\mathrm{HP}}} = \frac{110{,}000\ \mathrm{kJ/h}}{14.75}\left(\frac{1\ \mathrm{h}}{3600\ \mathrm{s}}\right) = \mathbf{2.07\ kW}$$

This heat pump is **powerful enough** since 5 kW > 2.07 kW.

6-96

Denoting the outdoor temperature by TL, the heating load of this house can be expressed as

$$\dot{Q}_H = (5400\ \mathrm{kJ/h\cdot K})(294 - T_L) = (1.5\ \mathrm{kW/K})(294 - T_L)\mathrm{K}$$



$$\mathrm{COP}_{\mathrm{HP}} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-T_L/(294\ \mathrm{K})}$$

$$\mathrm{COP}_{\mathrm{HP}} = \frac{\dot{Q}_H}{\dot{W}_{\mathrm{net,in}}} = \frac{(1.5\ \mathrm{kW/K})(294-T_L)\mathrm{K}}{6\ \mathrm{kW}}$$

Equating the two relations above and solving for *TL*, we obtain *TL* = 259.7 K = **-13.3°C**

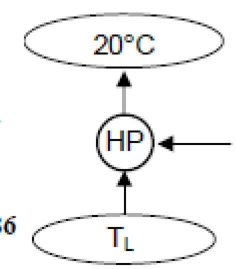
6-97

The coefficient of performance of a heat pump will be a maximum when the heat pump operates in a reversible manner.

$$COP_{HP,rev} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(10+273\mathrm{K})/(20+273\mathrm{K})} = \mathbf{29.3}$$

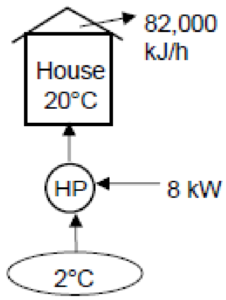
$$COP_{HP,rev} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(-5+273\mathrm{K})/(20+273\mathrm{K})} = \mathbf{11.7}$$

$$COP_{HP,rev} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(-30+273\mathrm{K})/(20+273\mathrm{K})} = \mathbf{5.86}$$



6-99

$$\mathrm{COP}_{\mathrm{HP,rev}} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(2+273\ \mathrm{K})/(20+273\ \mathrm{K})} = 16.3$$



The amount of heat the house lost that day is

$$Q_H = \dot{Q}_H(1\ \mathrm{day}) = (82{,}000\ \mathrm{kJ/h})(24\ \mathrm{h}) = 1{,}968{,}000\ \mathrm{kJ}$$

Then the required work input to this Carnot heat pump is determined from the definition of the coefficient of performance to be

$$W_{\mathrm{net,in}} = \frac{Q_H}{\mathrm{COP}_{\mathrm{HP}}} = \frac{1{,}968{,}000\ \mathrm{kJ}}{16.3} = 120{,}736\ \mathrm{kJ}$$

Thus the length of time the heat pump ran that day is

$$\Delta t = \frac{W_{\mathrm{net,in}}}{\dot{W}_{\mathrm{net,in}}} = \frac{120{,}736\ \mathrm{kJ}}{8\ \mathrm{kJ/s}} = 15{,}092\ \mathrm{s} = \mathbf{4.19\ h}$$

(*b*) The total heating cost that day is

$$\mathrm{Cost} = W \times \mathrm{price} = (\dot{W}_{\mathrm{net,in}} \times \Delta t)(\mathrm{price}) = (8\ \mathrm{kW})(4.19\ \mathrm{h})(0.085\ \$/\mathrm{kWh}) = \mathbf{\$2.85}$$

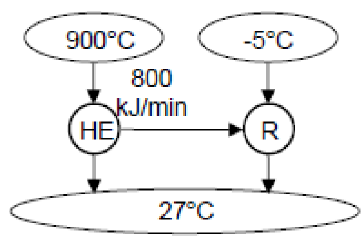
(*c*) If resistance heating were used, the entire heating load for that day would have to be met by electrical energy. Therefore, the heating system would consume 1,968,000 kJ of electricity that would cost

$$\text{New Cost} = Q_H \times \mathrm{price} = (1{,}968{,}000\mathrm{kJ})\left(\frac{1\ \mathrm{kWh}}{3600\ \mathrm{kJ}}\right)(0.085\ \$/\mathrm{kWh}) = \mathbf{\$46.47}$$

6-100

Analysis (a) The highest thermal efficiency a heat engine operating between two specified temperature limits can have is the Carnot efficiency, which is determined from

$$\eta_{\mathrm{th,max}} = \eta_{\mathrm{th,C}} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\ \mathrm{K}}{1173\ \mathrm{K}} = 0.744$$



Then the maximum power output of this heat engine is determined from the definition of thermal efficiency to be

$$\dot{W}_{\mathrm{net,out}} = \eta_{\mathrm{th}}\dot{Q}_H = (0.744)(800\ \mathrm{kJ/min}) = 595.2\ \mathrm{kJ/min}$$

which is also the power input to the refrigerator, $\dot{W}_{\mathrm{net,in}}$.

The rate of heat removal from the refrigerated space will be a maximum if a Carnot refrigerator is used. The COP of the Carnot refrigerator is

$$\mathrm{COP}_{\mathrm{R,rev}} = \frac{1}{(T_H/T_L)-1} = \frac{1}{(27+273\ \mathrm{K})/(-5+273\ \mathrm{K})-1} = 8.37$$

Then the rate of heat removal from the refrigerated space becomes

$$\dot{Q}_{L,\mathrm{R}} = (\mathrm{COP}_{\mathrm{R,rev}})(\dot{W}_{\mathrm{net,in}}) = (8.37)(595.2\ \mathrm{kJ/min}) = \mathbf{4982\ kJ/min}$$

(b) The total rate of heat rejection to the ambient air is the sum of the heat rejected by the heat engine ($\dot{Q}_{L,\mathrm{HE}}$) and the heat discarded by the refrigerator ($\dot{Q}_{H,\mathrm{R}}$),

$$\dot{Q}_{L,\mathrm{HE}} = \dot{Q}_{H,\mathrm{HE}} - \dot{W}_{\mathrm{net,out}} = 800 - 595.2 = 204.8\ \mathrm{kJ/min}$$

$$\dot{Q}_{H,\mathrm{R}} = \dot{Q}_{L,\mathrm{R}} + \dot{W}_{\mathrm{net,in}} = 4982 + 595.2 = 5577.2\ \mathrm{kJ/min}$$

and

$$\dot{Q}_{\mathrm{ambient}} = \dot{Q}_{L,\mathrm{HE}} + \dot{Q}_{H,\mathrm{R}} = 204.8 + 5577.2 = \mathbf{5782\ kJ/min}$$