Chapter 6
THE SECOND LAW OF THERMODYNAMICS

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.

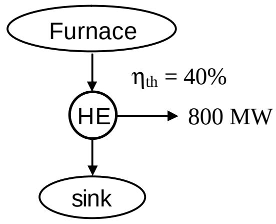
6-16C No. The Kelvin-Plank limitation applies only to heat engines; engines that receive heat and convert some of it to work.

6-17 The power output and thermal efficiency of a power plant are given. The rate of heat rejection is to be determined, and the result is to be compared to the actual case in practice.

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,

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



The rate of heat transfer to the river water is determined from the first law relation for a heat engine,

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

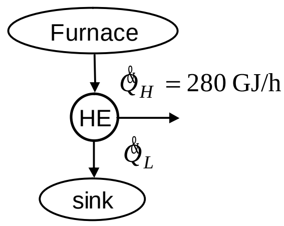
In reality the amount of heat rejected to the river will be **lower** since part of the heat will be lost to the surrounding air from the working fluid as it passes through the pipes and other components.

6-18 The rates of heat supply and heat rejection of a power plant are given. The power output and the thermal efficiency of this power plant are to be determined.

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

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

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

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

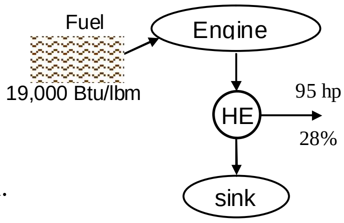
6-19E The power output and thermal efficiency of a car engine are given. The rate of fuel consumption is to be determined.

Assumptions The car operates steadily.

Properties The heating value of the fuel is given to be 19,000 Btu/lbm.

Analysis This car engine is converting 28% of the chemical energy released during the combustion process into work. The amount of energy input required to produce a power output of 95 hp is determined from the definition of thermal efficiency to be

$$\dot{Q}_H = \frac{\dot{W}_{net,out}}{\eta_{th}} = \frac{95\text{hp}}{0.28}\left(\frac{2545\text{Btu/h}}{1\text{hp}}\right) = 863{,}482\text{Btu/h}$$



To supply energy at this rate, the engine must burn fuel at a rate of

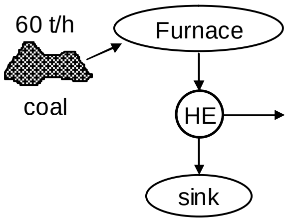
$$\dot{m} = \frac{863{,}482\text{Btu/h}}{19{,}000\text{Btu/lbm}} = \mathbf{45.4lbm/h}$$

since 19,000 Btu of thermal energy is released for each lbm of fuel burned.

6-20 The power output and fuel consumption rate of a power plant are given. The overall efficiency is to be determined.

Assumptions The plant operates steadily.

Properties The heating value of coal is given to be 30,000 kJ/kg.



Analysis The rate of energy supply (in chemical form) to this power plant is

$$\dot{Q}_H = \dot{m}_{coal} u_{coal} = (60{,}000 \text{ kg/h})(30{,}000 \text{ kJ/kg}) = 1.8\times10^9 \text{ kJ/h} = 500 \text{ MW}$$

Then the overall efficiency of the plant becomes

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

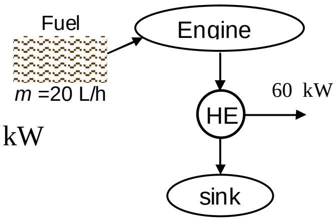
6-21 The power output and fuel consumption rate of a car engine are given. The efficiency of the engine is to be determined.

Assumptions The car operates steadily.

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

Analysis The mass consumption rate of the fuel is

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



The rate of energy supply (in chemical form) to the car is

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

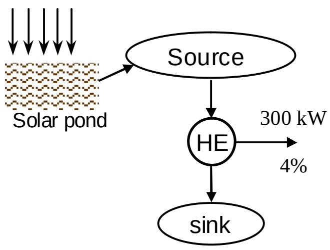
Then the overall efficiency of the car becomes

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

6-22E The power output and thermal efficiency of a solar pond power plant are given. The rate of solar energy collection is to be determined.

Assumptions The plant operates steadily.

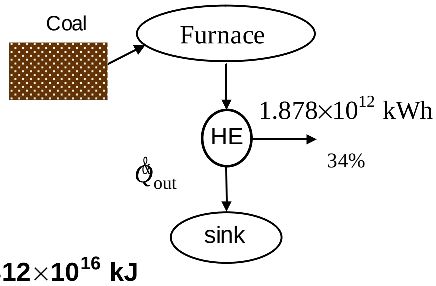
Analysis The rate of solar energy collection or the rate of heat supply to the power plant is determined from the thermal efficiency relation to be



$$\dot{Q}_H = \frac{\dot{W}_{net,out}}{\eta_{th}} = \frac{200 \text{ kW}}{0.04}\left(\frac{1 \text{ Btu}}{1.055 \text{ kJ}}\right)\left(\frac{3600 \text{ s}}{1 \text{ h}}\right) = 1.7 \times \mathbf{10^7 \text{ Btu/h}}$$

6-23 In 2001, the United States produced 1.878×10^{12} kWh of electricity from coal-fired power pants. For an average thermal efficiency of 34%, the amount of heat rejected that year by the coal-fired power plants is to be determined.

Assumptions All the losses appear as thermal energy in the environment.



Analysis The rate of heat rejection can be expressed as

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{coal}}}{\dot{Q}_{\text{in}}} = \frac{\dot{W}_{\text{coal}}}{\dot{Q}_{\text{out}} + \dot{W}_{\text{coal}}} \rightarrow \dot{Q}_{\text{out}} = \frac{\dot{W}_{\text{coal}}}{\eta_{\text{th}}} - \dot{W}_{\text{coal}}$$

Substituting,

$$\dot{Q}_{\text{out}} = \frac{\dot{W}_{\text{coal}}}{\eta_{\text{th}}} - \dot{W}_{\text{coal}} = \frac{1.878\times10^{12}}{0.34} - 1.878\times10^{12} = 3.646\times10^{12}\ \text{kWh} = \mathbf{1.312\times10^{16}\ kJ}$$

since 1 kWh = 3600 kJ.

6-24 The projected power needs of the United States is to be met by building inexpensive but inefficient coal plants or by building expensive but efficient IGCC plants. The price of coal that will enable the IGCC plants to recover their cost difference from fuel savings in 5 years is to be determined.

Assumptions **1** Power is generated continuously by either plant at full capacity. **2** The time value of money (interest, inflation, etc.) is not considered.

Properties The heating value of the coal is given to be 28×10^6 kJ/ton.

Analysis For a power generation capacity of 150,000 MW, the construction costs of coal and IGCC plants and their difference are

$$\text{Construction cost}_{\text{coal}} = (150{,}000{,}000\text{ kW})(\$1300/\text{kW}) = \$195\times10^9$$

$$\text{Construction cost}_{\text{IGCC}} = (150{,}000{,}000\text{ kW})(\$1500/\text{kW}) = \$225\times10^9$$

$$\text{Construction cost difference} = \$225\times10^9 - \$195\times10^9 = \$30\times10^9$$

The amount of electricity produced by either plant in 5 years is

$$W_e = \dot{W}\Delta t = (150{,}000{,}000\text{ kW})(5\times365\times24\text{ h}) = 6.570\times10^{12}\text{ kWh}$$

The amount of fuel needed to generate a specified amount of power can be determined from

$$\eta = \frac{W_e}{Q_{\text{in}}} \rightarrow Q_{\text{in}} = \frac{W_e}{\eta} \quad\text{or}\quad m_{\text{fuel}} = \frac{Q_{\text{in}}}{\text{Heating value}} = \frac{W_e}{\eta(\text{Heating value})}$$

Then the amount of coal needed to generate this much electricity by each plant and their difference are

$$m_{\text{coal, coal plant}} = \frac{W_e}{\eta(\text{Heating value})} = \frac{6.570\times10^{12}\text{ kWh}}{(0.34)(28\times10^6\text{ kJ/ton})}\left(\frac{3600\text{ kJ}}{1\text{ kWh}}\right) = 2.484\times10^9\text{ tons}$$

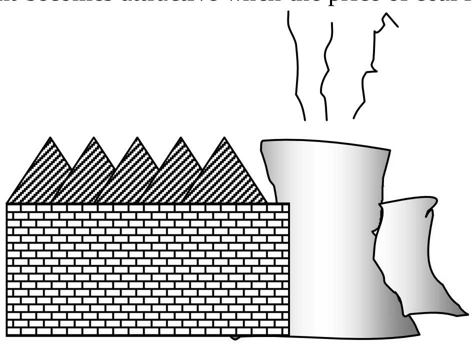
$$m_{\text{coal, IGCC plant}} = \frac{W_e}{\eta(\text{Heating value})} = \frac{6.570\times10^{12}\text{ kWh}}{(0.45)(28\times10^6\text{ kJ/ton})}\left(\frac{3600\text{ kJ}}{1\text{ kWh}}\right) = 1.877\times10^9\text{ tons}$$

$$\Delta m_{\text{coal}} = m_{\text{coal, coal plant}} - m_{\text{coal, IGCC plant}} = 2.484\times10^9 - 1.877\times10^9 = 0.607\times10^9\text{ tons}$$

For Δm_{coal} to pay for the construction cost difference of $30 billion, the price of coal should be

$$\text{Unit cost of coal} = \frac{\text{Construction cost difference}}{\Delta m_{\text{coal}}} = \frac{\$30\times10^9}{0.607\times10^9\text{ tons}} = \mathbf{\$49.4/ton}$$

Therefore, the IGCC plant becomes attractive when the price of coal is above $49.4 per ton.



6-25 Problem 6-24 is reconsidered. The price of coal is to be investigated for varying simple payback periods, plant construction costs, and operating efficiency.

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"Knowns:"
HeatingValue = 28E+6 "[kJ/ton]"
W_dot = 150E+6 "[kW]"
{PayBackPeriod = 5"[years]"
eta_coal = 0.34
eta_IGCC = 0.45
CostPerkW_Coal = 1300"[dollars/kW]"
CostPerkW_IGCC=1500"[dollars/kW]"}

"Analysis:"
"For a power generation capacity of 150,000 MW, the construction costs of coal
and IGCC plants and their difference are"
ConstructionCost_coal = W_dot *CostPerkW_Coal "[dollars]"
ConstructionCost_IGCC= W_dot *CostPerkW_IGCC "[dollars]"
ConstructionCost_diff = ConstructionCost_IGCC - ConstructionCost_coal "[dollars]"

"The amount of electricity produced by either plant in 5 years is "
W_ele = W_dot*PayBackPeriod*convert(year,h)  "[kWh]"

"The amount of fuel needed to generate a specified amount of power can be determined
from the plant efficiency and the heating value of coal."
"Then the amount of coal needed to generate this much electricity by each plant and their
difference are"
    "Coal Plant:"
        eta_coal = W_ele/Q_in_coal
        Q_in_coal = m_fuel_CoalPlant*HeatingValue*convert(kJ,kWh)
    "IGCC Plant:"
        eta_IGCC = W_ele/Q_in_IGCC
        Q_in_IGCC = m_fuel_IGCCPlant*HeatingValue*convert(kJ,kWh)

    DELTAm_coal = m_fuel_CoalPlant - m_fuel_IGCCPlant "[tons]"
"For  to pay for the construction cost difference of $30 billion, the price of coal should be"
UnitCost_coal = ConstructionCost_diff /DELTAm_coal "[dollars/ton]"
"Therefore, the IGCC plant becomes attractive when the price of coal is above $49.4 per
ton."
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SOLUTION

Variables in Main
ConstructionCost_coal=1.950E+11 [dollars]
ConstructionCost_diff=3.000E+10 [dollars]
ConstructionCost_IGCC=2.250E+11 [dollars]
CostPerkW_Coal=1300 [dollars/kW]
CostPerkW_IGCC=1500 [dollars/kW]
DELTAm_coal=6.073E+08 [tons]
eta_coal=0.34
eta_IGCC=0.45
HeatingValue=2.800E+07 [kJ/ton]
m_fuel_CoalPlant=2.484E+09 [tons]
m_fuel_IGCCPlant=1.877E+09 [tons]
PayBackPeriod=5 [years]
Q_in_coal=1.932E+13 [kWh]
Q_in_IGCC=1.460E+13 [kWh]
UnitCost_coal=49.4 [dollars/ton]
W_dot=1.500E+08 [kW]
W_ele=6.570E+12 [kWh]

6-26 The projected power needs of the United States is to be met by building inexpensive but inefficient coal plants or by building expensive but efficient IGCC plants. The price of coal that will enable the IGCC plants to recover their cost difference from fuel savings in 3 years is to be determined.

Assumptions **1** Power is generated continuously by either plant at full capacity. **2** The time value of money (interest, inflation, etc.) is not considered.

Properties The heating value of the coal is given to be 28×10^6 kJ/ton.

Analysis For a power generation capacity of 150,000 MW, the construction costs of coal and IGCC plants and their difference are

$$\text{Construction cost}_{\text{coal}} = (150{,}000{,}000\text{ kW})(\$1300/\text{kW}) = \$195\times10^9$$

$$\text{Construction cost}_{\text{IGCC}} = (150{,}000{,}000\text{ kW})(\$1500/\text{kW}) = \$225\times10^9$$

$$\text{Construction cost difference} = \$225\times10^9 - \$195\times10^9 = \$30\times10^9$$

The amount of electricity produced by either plant in 3 years is

$$W_e = \dot{W}\Delta t = (150{,}000{,}000\text{ kW})(3\times365\times24\text{ h}) = 3.942\times10^{12}\text{ kWh}$$

The amount of fuel needed to generate a specified amount of power can be determined from

$$\eta = \frac{W_e}{Q_{\text{in}}} \rightarrow Q_{\text{in}} = \frac{W_e}{\eta} \quad \text{or} \quad m_{\text{fuel}} = \frac{Q_{\text{in}}}{\text{Heating value}} = \frac{W_e}{\eta(\text{Heating value})}$$

Then the amount of coal needed to generate this much electricity by each plant and their difference are

$$m_{\text{coal, coal plant}} = \frac{W_e}{\eta(\text{Heating value})} = \frac{3.942\times10^{12}\text{ kWh}}{(0.34)(28\times10^6\text{ kJ/ton})}\left(\frac{3600\text{ kJ}}{1\text{ kWh}}\right) = 1.491\times10^9\text{ tons}$$

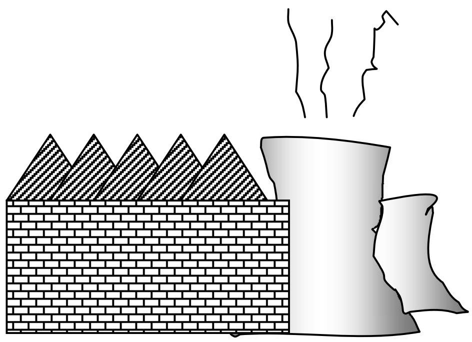
$$m_{\text{coal, IGCC plant}} = \frac{W_e}{\eta(\text{Heating value})} = \frac{3.942\times10^{12}\text{ kWh}}{(0.45)(28\times10^6\text{ kJ/ton})}\left(\frac{3600\text{ kJ}}{1\text{ kWh}}\right) = 1.126\times10^9\text{ tons}$$

$$\Delta m_{\text{coal}} = m_{\text{coal, coal plant}} - m_{\text{coal, IGCC plant}} = 1.491\times10^9 - 1.126\times10^9 = 0.365\times10^9\text{ tons}$$

For Δm_{coal} to pay for the construction cost difference of \$30 billion, the price of coal should be

$$\text{Unit cost of coal} = \frac{\text{Construction cost difference}}{\Delta m_{\text{coal}}} = \frac{\$30\times10^9}{0.365\times10^9\text{ tons}} = \mathbf{\$82.2/ton}$$

Therefore, the IGCC plant becomes attractive when the price of coal is above \$82.2 per ton.



6-27 A wind turbine is rotating at 20 rpm under steady winds of 30 km/h. The power produced, the tip speed of the blade, and the revenue generated by the wind turbine per year are to be determined. √

Assumptions **1** Steady operating conditions exist. **2** The wind turbine operates continuously during the entire year at the specified conditions.

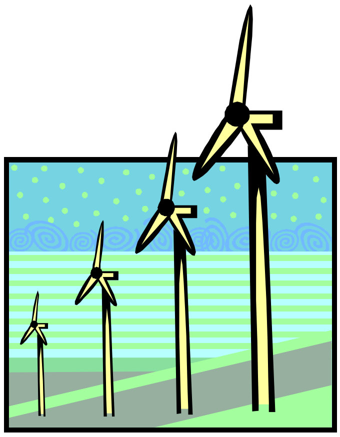
Properties The density of air is given to be $\rho = 1.20$ kg/m^3.

Analysis (*a*) The blade span area and the mass flow rate of air through the turbine are

$$A = \pi D^2/4 = \pi(80\text{ m})^2/4 = 5027\text{ m}^2$$

$$\mathbf{V} = (30\text{ km/h})\left(\frac{1000\text{ m}}{1\text{ km}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 8.333\text{ m/s}$$

$$\dot{m} = \rho A\mathbf{V} = (1.2\text{ kg/m}^3)(5027\text{ m}^2)(8.333\text{ m/s}) = 50{,}270\text{ kg/s}$$



Noting that the kinetic energy of a unit mass is $\mathbf{V}^2/2$ and the wind turbine captures
35% of this energy, the power generated by this wind turbine becomes

$$\dot{W} = \eta\left(\frac{1}{2}\dot{m}\mathbf{V}^2\right) = (0.35)\frac{1}{2}(50{,}270\text{ kg/s})(8.333\text{ m/s})^2\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{610.9\text{ kW}}$$

(*b*) Noting that the tip of blade travels a distance of πD per revolution, the tip velocity of the turbine blade for an rpm of $\dot{n}$ becomes

$$\mathbf{V}_{\text{tip}} = \pi D\dot{n} = \pi(80\text{ m})(20/\text{min}) = 5027\text{ m/min} = 83.8\text{ m/s} = \mathbf{302\text{ km/h}}$$

(*c*) The amount of electricity produced and the revenue generated per year are

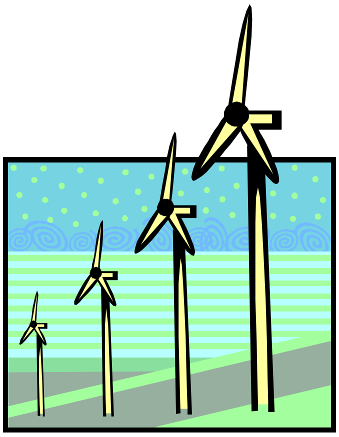
$$\text{Electricity produced} = \dot{W}\Delta t = (610.9\text{ kW})(365\times 24\text{ h/year})$$
$$= 5.351\times 10^6\text{ kWh/year}$$

$$\text{Revenue generated} = (\text{Electricity produced})(\text{Unit price}) = (5.351\times 10^6\text{ kWh/year})(\$0.06/\text{kWh})$$
$$= \mathbf{\$321{,}100/year}$$

6-28 A wind turbine is rotating at 20 rpm under steady winds of 25 km/h. The power produced, the tip speed of the blade, and the revenue generated by the wind turbine per year are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The wind turbine operates continuously during the entire year at the specified conditions.

Properties The density of air is given to be $\rho = 1.20$ kg/m^3.



Analysis (*a*) The blade span area and the mass flow rate of air through the turbine are

$$A = \pi D^2/4 = \pi(80\text{ m})^2/4 = 5027\text{ m}^2$$

$$\mathbf{V} = (25\text{ km/h})\left(\frac{1000\text{ m}}{1\text{ km}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right) = 6.944\text{ m/s}$$

$$\dot{m} = \rho A\mathbf{V} = (1.2\text{ kg/m}^3)(5027\text{ m}^2)(6.944\text{ m/s}) = 41{,}890\text{ kg/s}$$

Noting that the kinetic energy of a unit mass is $\mathbf{V}^2/2$ and the wind turbine captures 35% of this energy, the power generated by this wind turbine becomes

$$\dot{W} = \eta\left(\frac{1}{2}\dot{m}\mathbf{V}^2\right) = (0.35)\frac{1}{2}(41{,}890\text{ kg/s})(6.944\text{ m/s})^2\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{353.5\text{ kW}}$$

(*b*) Noting that the tip of blade travels a distance of πD per revolution, the tip velocity of the turbine blade for an rpm of $\dot{n}$ becomes

$$\mathbf{V}_{\text{tip}} = \pi D\dot{n} = \pi(80\text{ m})(20/\text{min}) = 5027\text{ m/min} = 83.8\text{ m/s} = \mathbf{302\text{ km/h}}$$

(*c*) The amount of electricity produced and the revenue generated per year are

$$\begin{aligned}\text{Electricity produced} &= \dot{W}\Delta t = (353.5\text{ kW})(365\times 24\text{ h/year})\\ &= 3.097\times 10^6\text{ kWh/year}\end{aligned}$$

$$\begin{aligned}\text{Revenue generated} &= (\text{Electricity produced})(\text{Unit price}) = (3.097\times 10^6\text{ kWh/year})(\$0.06/\text{kWh})\\ &= \mathbf{\$185{,}780/year}\end{aligned}$$

6-29E An OTEC power plant operates between the temperature limits of 86°F and 41°F. The cooling water experiences a temperature rise of 6°F in the condenser. The amount of power that can be generated by this OTEC plans is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Water is an incompressible substance with constant properties.

Properties The density and specific heat of water are ρ = 64.0 lbm/ft^3 and C = 1.0 Btu/lbm.°F, respectively.

Analysis The mass flow rate of the cooling water is

$$\dot{m}_{\text{water}} = \rho \dot{V}_{\text{water}} = (64.0\ \text{lbm/ft}^3)(13{,}300\ \text{gal/min})\left[\frac{1\ \text{ft}^3}{7.4804\ \text{gal}}\right] = 113{,}790\ \text{lbm/min} = 1897\ \text{lbm/s}$$

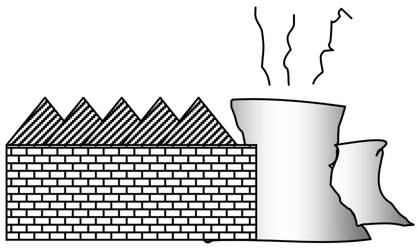
The rate of heat rejection to the cooling water is

$$\dot{Q}_{\text{out}} = \dot{m}_{\text{water}} C(T_{\text{out}} - T_{\text{in}}) = (1897\ \text{lbm/s})(1.0\ \text{Btu/lbm.°F})(6\text{°F}) = 11{,}380\ \text{Btu/s}$$

Noting that the thermal efficiency of this plant is 2.5%, the power generation is determined to be

$$\eta = \frac{\dot{W}}{\dot{Q}_{\text{in}}} = \frac{\dot{W}}{\dot{W} + \dot{Q}_{\text{out}}} \quad \rightarrow\ 0.025 = \frac{\dot{W}}{\dot{W} + (11{,}380\ \text{Btu/s})} \quad \rightarrow \quad \dot{W} = 292\ \text{Btu/s} = \mathbf{308\ kW}$$

since 1 kW = 0.9478 Btu/s.



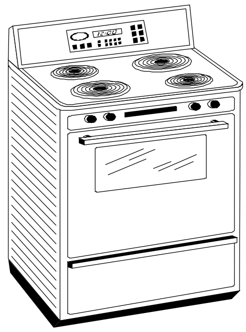
Energy Conversion Efficiencies

6-30 A hooded electric open burner and a gas burner are considered. The amount of the electrical energy used directly for cooking and the cost of energy per "utilized" kWh are to be determined. √

Analysis The efficiency of the electric heater is given to be 78 percent. Therefore, a burner that consumes 3-kW of electrical energy will supply

$\eta_{gas} = 38\%$

$\eta_{electric} = 73\%$



$$\dot{Q}_{utilized} = (\text{Energy input}) \times (\text{Efficiency}) = (3\text{ kW})(0.73) = \mathbf{2.19\ kW}$$

of useful energy. The unit cost of utilized energy is inversely proportional to the efficiency, and is determined from

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$0.07/\text{kWh}}{0.73} = \mathbf{\$0.096/kWh}$$

Noting that the efficiency of a gas burner is 38 percent, the energy input to a gas burner that supplies utilized energy at the same rate (2.19 kW) is

$$\dot{Q}_{input,\ gas} = \frac{\dot{Q}_{utilized}}{\text{Efficiency}} = \frac{2.19\text{ kW}}{0.38} = \mathbf{5.76\ kW}\ \ (= 19{,}660\text{ Btu/h})$$

since 1 kW = 3412 Btu/h. Therefore, a gas burner should have a rating of at least 19,660 Btu/h to perform as well as the electric unit.

Noting that 1 therm = 29.3 kWh, the unit cost of utilized energy in the case of gas burner is determined the same way to be

$$\text{Cost of utilized energy} = \frac{\text{Cost of energy input}}{\text{Efficiency}} = \frac{\$0.60/(29.3\text{ kWh})}{0.38} = \mathbf{\$0.054/kWh}$$

which is about one-quarter of the unit cost of utilized electricity.

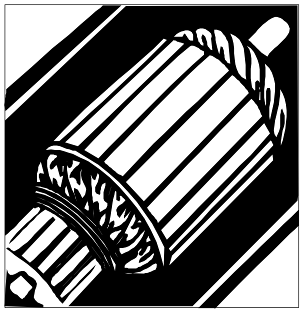
6-31 A worn out standard motor is replaced by a high efficiency one. The reduction in the internal heat gain due to the higher efficiency under full load conditions is to be determined.

Assumptions **1** The motor and the equipment driven by the motor are in the same room. **2** The motor operates at full load so that $f_{\text{load}} = 1$.

Analysis The heat generated by a motor is due to its inefficiency, and the difference between the heat generated by two motors that deliver the same shaft power is simply the difference between the electric power drawn by the motors,

$$\dot{W}_{\text{in, electric, standard}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}} = (75 \times 746 \text{ W})/0.91 = 61{,}484 \text{ W}$$

$$\dot{W}_{\text{in, electric, efficient}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}} = (75 \times 746 \text{ W})/0.954 = 58{,}648 \text{ W}$$



Then the reduction in heat generation becomes

$$\dot{Q}_{\text{reduction}} = \dot{W}_{\text{in, electric, standard}} - \dot{W}_{\text{in, electric, efficient}} = 61{,}484 - 58{,}648 = \mathbf{2836 \text{ W}}$$

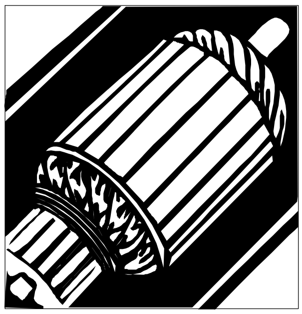
6-32 An electric car is powered by an electric motor mounted in the engine compartment. The rate of heat supply by the motor to the engine compartment at full load conditions is to be determined.

Assumptions The motor operates at full load so that the load factor is 1.

Analysis The heat generated by a motor is due to its inefficiency, and is equal to the difference between the electrical energy it consumes and the shaft power it delivers,

$$\dot{W}_{\text{in, electric}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}} = (75 \text{ hp})/0.91 = 82.42 \text{ hp}$$

$$\dot{Q}_{\text{generation}} = \dot{W}_{\text{in, electric}} - \dot{W}_{\text{shaft out}} = 82.42 - 75 = 7.42 \text{ hp} = \mathbf{5.54 \text{ kW}}$$



since 1 hp = 0.746 kW.

Discussion Note that the electrical energy not converted to mechanical power is converted to heat.

6-33 A worn out standard motor is to be replaced by a high efficiency one. The amount of electrical energy and money savings as a result of installing the high efficiency motor instead of the standard one as well as the simple payback period are to be determined.

Assumptions The load factor of the motor remains constant at 0.75.

Analysis The electric power drawn by each motor and their difference can be expressed as

$$\dot{W}_{\text{electric in, standard}} = \dot{W}_{\text{shaft}} / \eta_{\text{standard}} = (\text{Power rating})(\text{Load factor}) / \eta_{\text{standard}}$$

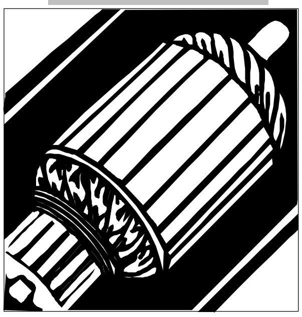
$$\dot{W}_{\text{electric in, efficient}} = \dot{W}_{\text{shaft}} / \eta_{\text{efficient}} = (\text{Power rating})(\text{Load factor}) / \eta_{\text{efficient}}$$

$$\begin{aligned}\text{Power savings} &= \dot{W}_{\text{electric in, standard}} - \dot{W}_{\text{electric in, efficient}} \\ &= (\text{Power rating})(\text{Load factor})[1/\eta_{\text{standard}} - 1/\eta_{\text{efficient}}]\end{aligned}$$

where η_{standard} is the efficiency of the standard motor, and $\eta_{\text{efficient}}$ is the efficiency of the comparable high efficiency motor. Then the annual energy and cost savings associated with the installation of the high efficiency motor are determined to be

$\eta_{\text{old}} = 91.0\%$

$\eta_{\text{new}} = 95.4\%$



Energy Savings = (Power savings)(Operating Hours)
= (Power Rating)(Operating Hours)(Load Factor)($1/\eta_{\text{standard}} - 1/\eta_{\text{efficient}}$)
= (75 hp)(0.746 kW/hp)(4,368 hours/year)(0.75)(1/0.91 - 1/0.954)
= **9,290 kWh/year**

Cost Savings = (Energy savings)(Unit cost of energy)
= (9,290 kWh/year)($0.08/kWh)
= **$743/year**

The implementation cost of this measure consists of the excess cost the high efficiency motor over the standard one. That is,

Implementation Cost = Cost differential = $5,520 - $5,449 = $71

This gives a simple payback period of

$$\text{Simple payback period} = \frac{\text{Implementation cost}}{\text{Annual cost savings}} = \frac{\$71}{\$743/\text{ year}} = \mathbf{0.096\ year}\ (\text{or } 1.1 \text{ months})$$

Therefore, the high-efficiency motor will pay for its cost differential in about one month.

6-34E The combustion efficiency of a furnace is raised from 0.7 to 0.8 by tuning it up. The annual energy and cost savings as a result of tuning up the boiler are to be determined. √

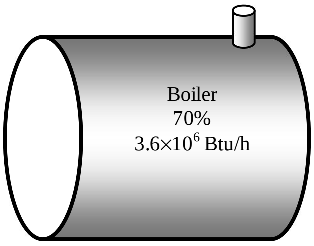
Assumptions The boiler operates at full load while operating.

Analysis The heat output of boiler is related to the fuel energy input to the boiler by

Boiler output = (Boiler input)(Combustion efficiency) or $\dot{Q}_{\text{out}} = \dot{Q}_{\text{in}}\eta_{\text{furnace}}$

The current rate of heat input to the boiler is given to be $\dot{Q}_{\text{in, current}} = 3.6\times10^6$ Btu/h .
Then the rate of useful heat output of the boiler becomes

$$\dot{Q}_{\text{out}} = (\dot{Q}_{\text{in}}\eta_{\text{furnace}})_{\text{current}} = (3.6\times10^6 \text{ Btu/h})(0.7) = 2.52\times10^6 \text{ Btu/h}$$



The boiler must supply useful heat at the same rate after the tune up. Therefore, the rate of heat input to the boiler after the tune up and the rate of energy savings become

$$\dot{Q}_{\text{in, new}} = \dot{Q}_{\text{out}} / \eta_{\text{furnace, new}} = (2.52\times10^6 \text{ Btu/h})/0.8 = 3.15\times10^6 \text{ Btu/h}$$
$$\dot{Q}_{\text{in, saved}} = \dot{Q}_{\text{in, current}} - \dot{Q}_{\text{in, new}} = 3.6\times10^6 - 3.15\times10^6 = 0.45\times10^6 \text{ Btu/h}$$

Then the annual energy and cost savings associated with tuning up the boiler become

Energy Savings $= \dot{Q}_{\text{in, saved}}$ (Operation hours)
= $(0.45\times10^6$ Btu/h)(1500 h/year) = $\mathbf{675\times10^6}$ **Btu/yr**

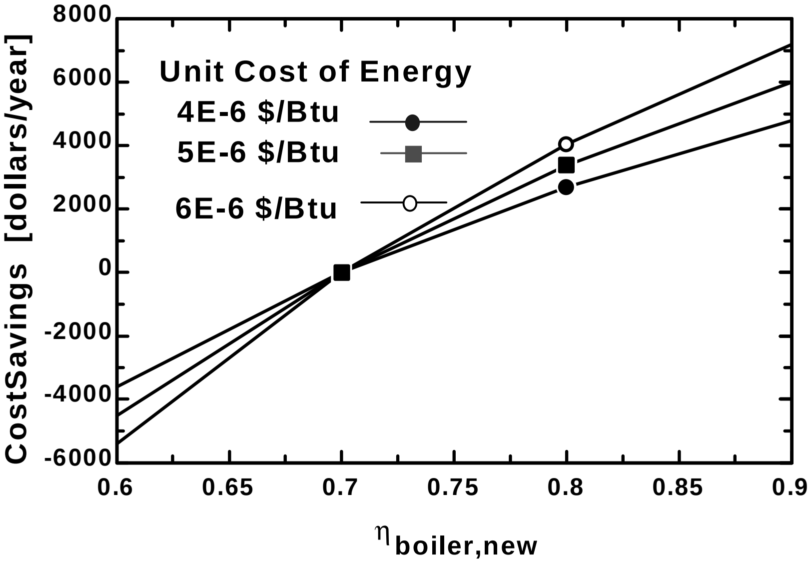
Cost Savings = (Energy Savings)(Unit cost of energy)
= $(675\times10^6$ Btu/yr)($4.35 per 10^6 Btu) = **$2936/year**

Discussion Notice that tuning up the boiler will save $2936 a year, which is a significant amount. The implementation cost of this measure is negligible if the adjustment can be made by in-house personnel. Otherwise it is worthwhile to have an authorized representative of the boiler manufacturer to service the boiler twice a year.

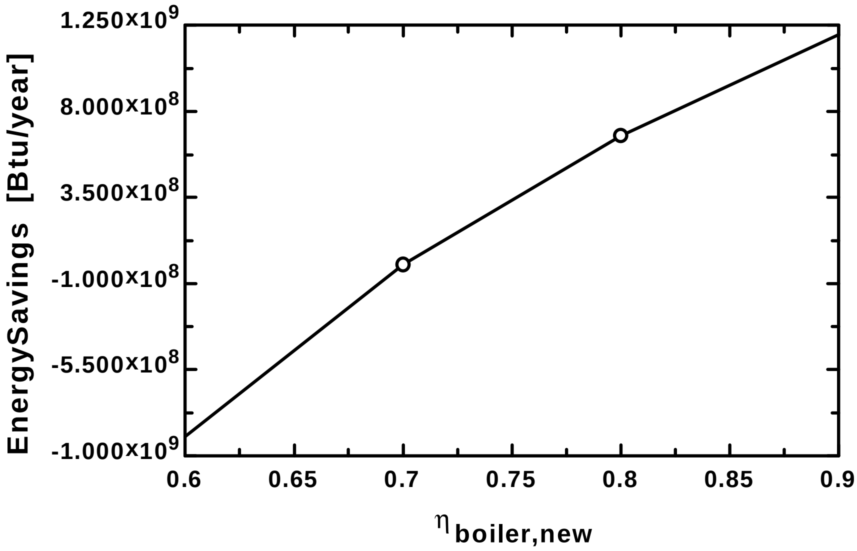
6-35E Problem 6-34E is reconsidered. The effects of the unit cost of energy and combustion efficiency on the annual energy used and the cost savings as the efficiency varies from 0.6 to 0.9 and the unit cost varies from $4 to $6 per million Btu are the investigated. The annual energy saved and the cost savings are to be plotted against the efficiency for unit costs of $4, $5, and $6 per million Btu.

```
"Knowns:"
eta_boiler_current = 0.7
eta_boiler_new = 0.8
Q_dot_in_current = 3.6E+6 "[Btu/h]"
DELTAt = 1500 "[h/year]"
UnitCost_energy = 5E-6 "[dollars/Btu]"
"Analysis: The heat output of boiler is related to the fuel energy input to the boiler by
    Boiler output = (Boiler input)(Combustion efficiency)
Then the rate of useful heat output of the boiler becomes"

Q_dot_out=Q_dot_in_current*eta_boiler_current "[Btu/h]"
"The boiler must supply useful heat at the same rate after the tune up.
Therefore, the rate of heat input to the boiler after the tune up
and the rate of energy savings become "

Q_dot_in_new=Q_dot_out/eta_boiler_new "[Btu/h]"
Q_dot_in_saved=Q_dot_in_current - Q_dot_in_new "[Btu/h]"

"Then the  annual energy and cost savings associated with tuning up the boiler become"

    EnergySavings   =Q_dot_in_saved*DELTAt "[Btu/year]"
    CostSavings = EnergySavings*UnitCost_energy "[dollars/year]"
"Discussion Notice that tuning up the boiler will save $2936 a year, which is a
significant amount. The implementation cost of this measure is negligible if the
adjustment can be made by in-house personnel. Otherwise it is worthwhile to have
an authorized representative of the boiler manufacturer to service the boiler twice a year. "
```

CostSavings [dollars/year]	EnergySavings [Btu/year]	$\eta_{boiler,new}$
-4500	-9.000E+08	0.6
0	0	0.7
3375	6.750E+08	0.8
6000	1.200E+09	0.9



Unit Cost of Energy
4E-6 $/Btu
5E-6 $/Btu
6E-6 $/Btu
CostSavings [dollars/year]
8000
6000
4000
2000
0
-2000
-4000
-6000
0.6
0.65
0.7
0.75
0.8
0.85
0.9
η boiler,new

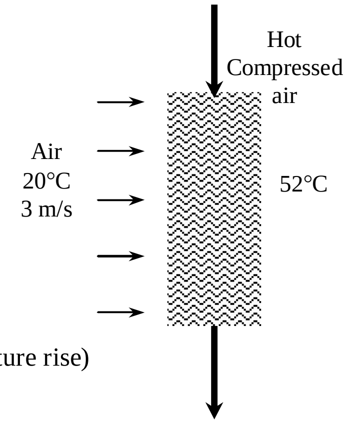


EnergySavings [Btu/year]
1.250x10^9
8.000x10^8
3.500x10^8
-1.000x10^8
-5.500x10^8
-1.000x10^9
0.6
0.65
0.7
0.75
0.8
0.85
0.9
η boiler,new

6-36 The gas space heating of a facility is to be supplemented by air heated in a liquid-to-air heat exchanger of a compressor. The amount of money that will be saved by diverting the compressor waste heat into the facility during the heating season is to be determined.

Assumptions The atmospheric pressure at that location is 1 atm.

Analysis The mass flow rate of air through the liquid-to-air heat exchanger is



Mass flow rate of air = (Density of air)(Average velocity)(Flow area)
= (1.21 kg/m^3)(3 m/s)(1.0 m^2)
= 3.63 kg/s = 13,068 kg/h

Noting that the exit temperature of air is 52°C, the rate at which heat can be recovered (or the rate at which heat is transferred to air) is

Rate of Heat Recovery = (Mass flow rate of air)(Specific heat of air)(Temperature rise)
= (13,068 kg/h)(1.0 kJ/kg.°C)(52 – 20)°C
= 418,176 kJ/h

The number of operating hours of this compressor during the heating season is

Operating hours = (20 hours/day)(5 days/week)(26 weeks/year) = 2600 hours/year

Then the annual energy and cost savings become

Energy Savings = (Rate of Heat Recovery)(Annual Operating Hours)/Efficiency
= (418,176 kJ/h)(2600 h/year)/0.8
= 1,359,100,000 kJ/year
= 12,882 therms/year

Cost Savings = (Energy savings)(Unit cost of energy saved)
= (12,882 therms/year)($0.50/therm)
= $6441/year

Discussion Notice that utilizing the waste heat from the compressor will save $6441 per year from the heating costs. The implementation of this measure requires the installation of an ordinary sheet metal duct from the outlet of the heat exchanger into the building. The installation cost associated with this measure is relatively low. Several manufacturing facilities already have this conservation system in place. A damper is used to direct the air into the building in winter and to the ambient in summer. Combined compressor/heat-recovery systems are available in the market for both air-cooled (greater than 50 hp) and water cooled (greater than 125 hp) systems.

6-37 Several people are working out in an exercise room. The rate of heat gain from people and the equipment is to be determined.

Assumptions The average rate of heat dissipated by people in an exercise room is 525 W.

Analysis The 8 weight lifting machines do not have any motors, and thus they do not contribute to the internal heat gain directly. The usage factors of the motors of the treadmills are taken to be unity since they are used constantly during peak periods. Noting that 1 hp = 746 W, the total heat generated by the motors is

$$\begin{aligned}\dot{Q}_{\text{motors}} &= (\text{No. of motors}) \times \dot{W}_{\text{motor}} \times f_{\text{load}} \times f_{\text{usage}} / \eta_{\text{motor}} \\ &= 4 \times (2.5 \times 746\text{ W}) \times 0.70 \times 1.0/0.77 = 6782\text{ W}\end{aligned}$$

The heat gain from 14 people is

$$\dot{Q}_{\text{people}} = (\text{No. of people}) \times \dot{Q}_{\text{person}} = 14 \times (525\text{ W}) = 7350\text{ W}$$

Then the total rate of heat gain of the exercise room during peak period becomes

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{motors}} + \dot{Q}_{\text{people}} = 6782 + 7350 = \mathbf{14{,}132\ W}$$

6-38 A classroom has a specified number of students, instructors, and fluorescent light bulbs. The rate of internal heat generation in this classroom is to be determined.

Assumptions **1** There is a mix of men, women, and children in the classroom. **2** The amount of light (and thus energy) leaving the room through the windows is negligible.

Properties The average rate of heat generation from people seated in a room/office is given to be 100 W.

Analysis The amount of heat dissipated by the lamps is equal to the amount of electrical energy consumed by the lamps, including the 10% additional electricity consumed by the ballasts. Therefore,

$$\dot{Q}_{\text{lighting}} = (\text{Energy consumed per lamp}) \times (\text{No. of lamps})$$
$$= (40\text{ W})(1.1)(18) = 792\text{ W}$$
$$\dot{Q}_{\text{people}} = (\text{No. of people}) \times \dot{Q}_{\text{person}} = 56 \times (100\text{ W}) = 5600\text{ W}$$

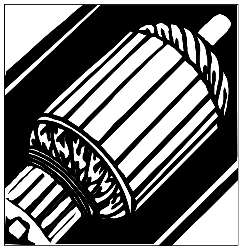
Then the total rate of heat gain (or the internal heat load) of the classroom from the lights and people become

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{lighting}} + \dot{Q}_{\text{people}} = 792 + 5600 = \mathbf{6392\ W}$$

6-39 A room is cooled by circulating chilled water through a heat exchanger, and the air is circulated through the heat exchanger by a fan. The contribution of the fan-motor assembly to the cooling load of the room is to be determined.

Assumptions The fan motor operates at full load so that $f_{\text{load}} = 1$.

Analysis The entire electrical energy consumed by the motor, including the shaft power delivered to the fan, is eventually dissipated as heat. Therefore, the contribution of the fan-motor assembly to the cooling load of the room is equal to the electrical energy it consumes,



$$\dot{Q}_{\text{internal generation}} = \dot{W}_{\text{in, electric}} = \dot{W}_{\text{shaft}} / \eta_{\text{motor}}$$
$$= (0.25\text{ hp})/0.54 = 0.463\text{ hp} = \mathbf{345\ W}$$

since 1 hp = 746 W.

Refrigerators and Heat Pumps

6-40C 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.

6-41C 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.

6-42C No. Because the refrigerator consumes work to accomplish this task.

6-43C No. Because the heat pump consumes work to accomplish this task.

6-44C 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.

6-45C 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.

6-46C No. The heat pump captures energy from a cold medium and carries it to a warm medium. It does not create it.

6-47C No. The refrigerator captures energy from a cold medium and carries it to a warm medium. It does not create it.

6-48C No device can transfer heat from a cold medium to a warm medium without requiring a heat or work input from the surroundings.

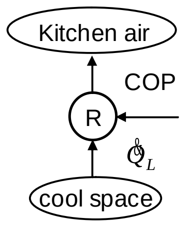
6-49C The violation of one statement leads to the violation of the other one, as shown in Sec. 6-4, and thus we conclude that the two statements are equivalent.

6-50 The COP and the refrigeration rate of a refrigerator are given. The power consumption and the rate of heat rejection are to be determined.

Assumptions The refrigerator operates steadily.

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

$$\dot{W}_{net,in} = \frac{\dot{Q}_L}{COP_R} = \frac{60 \text{ kJ/min}}{1.5} = 40 \text{ kJ/min} = \mathbf{0.67\ kW}$$



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

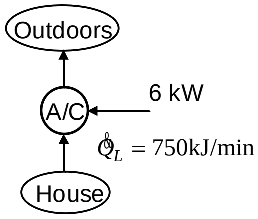
$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{net,in} = 60 + 40 = \mathbf{100\ kJ/min}$$

6-51 The power consumption and the cooling rate of an air conditioner are given. The COP and the rate of heat rejection are to be determined.

Assumptions The air conditioner operates steadily.

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

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



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

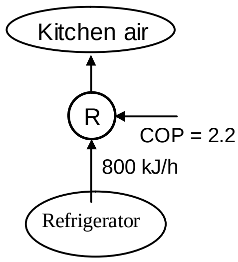
$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{net,in} = (750 \text{ kJ/min}) + (6)(60 \text{ kJ/min}) = \mathbf{1110 \text{ kJ/min}}$$

6-52 The COP and the refrigeration rate of a refrigerator are given. The power consumption of the refrigerator is to be determined.

Assumptions The refrigerator operates steadily.

Analysis 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

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



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

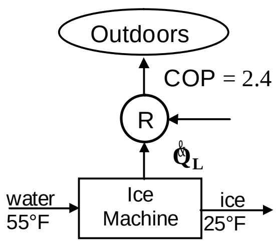
$$\dot{W}_{net,in} = \frac{\dot{Q}_L}{COP_R} = \frac{3200 \text{kJ/h}}{2.2} = 1455 \text{ kJ/h} = \mathbf{0.40 \text{ kW}}$$

6-53E The COP and the refrigeration rate of an ice machine are given. The power consumption is to be determined.

Assumptions The ice machine operates steadily.

Analysis The cooling load of this ice machine is

$$\dot{Q}_L = \dot{m}q_L = (20 \text{lbm/h})(169 \text{Btu/lbm}) = 3380 \text{Btu/h}$$



Using the definition of the coefficient of performance, the power input to the ice machine system is determined to be

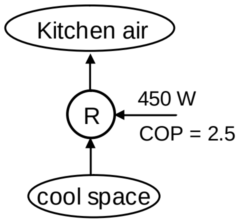
$$\dot{W}_{net,in} = \frac{\dot{Q}_L}{COP_R} = \frac{3380 \text{Btu/h}}{2.4}\left(\frac{1 \text{hp}}{2545 \text{Btu/h}}\right) = \mathbf{0.553 hp}$$

6-54 The COP and the power consumption of a refrigerator are given. The time it will take to cool 5 watermelons is to be determined.

Assumptions **1** The refrigerator operates steadily. **2** The heat gain of the refrigerator through its walls, door, etc. is negligible. **3** The watermelons are the only items in the refrigerator to be cooled.

Properties The specific heat of watermelons is given to be C = 4.2 kJ/kg.°C.

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



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

The rate at which this refrigerator removes heat is

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

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

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

This answer is optimistic since the refrigerated space will gain some heat during this process from the surrounding air, which will increase the work load. Thus, in reality, it will take longer to cool the watermelons.

6-55 [*Also solved by EES on enclosed CD*] An air conditioner with a known COP cools a house to desired temperature in 15 min. The power consumption of the air conditioner is to be determined.

Assumptions **1** The air conditioner operates steadily. **2** The house is well-sealed so that no air leaks in or out during cooling. **3** Air is an ideal gas with constant specific heats at room temperature.

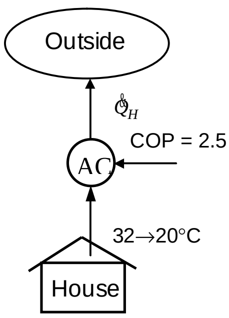
Properties The constant volume specific heat of air is given to be C_v = 0.72 kJ/kg.°C.

Analysis Since the house is well-sealed (constant volume), the total amount of heat that needs to be removed from the house is

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

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

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

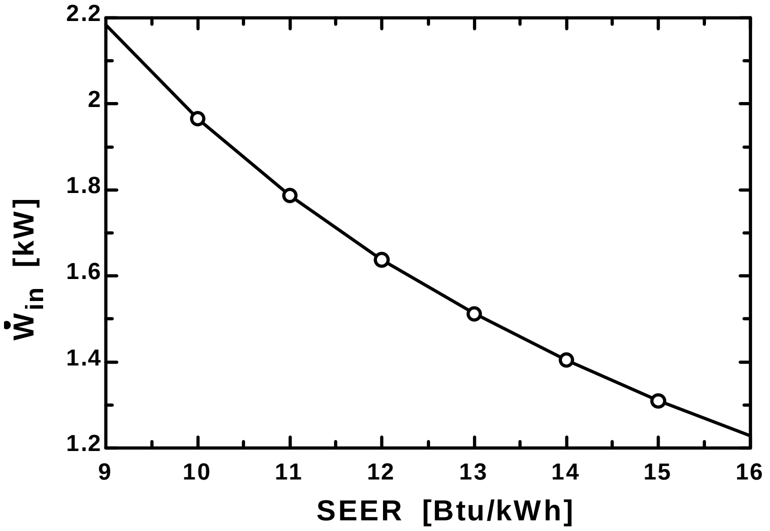
6-56 Problem 6-55 is reconsidered. The rate of power drawn by the air conditioner required to cool the house as a function for air conditioner SEER ratings in the range 9 to 16 is to be investigated. Representative costs of air conditioning units in the SEER rating range are to be included.

"Input Data"
T_1=32"C"
T_2=20"C"
C_v = 0.72"kJ/kg-C"
m_house=800"kg"
DELTAtime=20 "min"
{SEER=9"[Btu/kWh]"}
COP=SEER/3.412

"Assuming no work done on the house and no heat energy added to the house
in the time period with no change in KE and PE, the first law applied to the house is:"
E_dot_in - E_dot_out = DELTAE_dot "kJ/min"
E_dot_in = 0
E_dot_out = Q_dot_L "kJ/min"
DELTAE_dot = m_house*DELTAu_house/DELTAtime "kJ/min"
DELTAu_house = C_v*(T_2-T_1) "kJ/kg"

"Using the definition of the coefficient of performance of the A/C:"
W_dot_in = Q_dot_L/COP "kJ/min"*convert('kJ/min','kW') "kW"
Q_dot_H= W_dot_in*convert('KW','kJ/min') + Q_dot_L "kJ/min"

SEER [Btu/kWh]	W_{in} [kW]
9	2.184
10	1.965
11	1.787
12	1.638
13	1.512
14	1.404
15	1.31
16	1.228

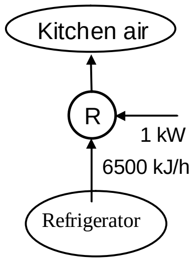


6-57 The heat removal rate of a refrigerator per kW of power it consumes is given. The COP and the rate of heat rejection are to be determined.

Assumptions The refrigerator operates steadily.

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

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{6500\ \text{kJ/h}}{1\ \text{kW}}\left(\frac{1\ \text{kW}}{3600\ \text{kJ/h}}\right) = \mathbf{1.81}$$



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

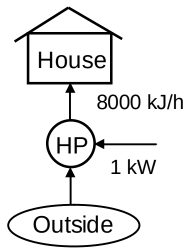
$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{net,in} = (6500\ \text{kJ/h}) + (1)(3600\ \text{kJ/h}) = \mathbf{10{,}100\ kJ/h}$$

6-58 The rate of heat supply of a heat pump per kW of power it consumes is given. The COP and the rate of heat absorption from the cold environment are to be determined.

Assumptions The heat pump operates steadily.

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

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



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

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

6-59 A house is heated by resistance heaters, and the amount of electricity consumed during a winter month is given. The amount of money that would be saved if this house were heated by a heat pump with a known COP is to be determined.

Assumptions The heat pump operates steadily.

Analysis The amount of heat the resistance heaters supply to the house is equal to he amount of electricity they consume. Therefore, to achieve the same heating effect, the house must be supplied with 1200 kWh of energy. A heat pump that supplied this much heat will consume electrical power in the amount of

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{1200\ \text{kWh}}{2.4} = 500\ \text{kWh}$$

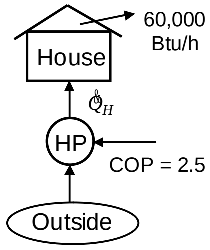
which represent a savings of 1200 – 500 = 700 kWh. Thus the homeowner would have saved

(700 kWh)(0.085 \$/kWh) = **\$59.50**

6-60E The rate of heat supply and the COP of a heat pump are given. The power consumption and the rate of heat absorption from the outside air are to be determined.

Assumptions The heat pump operates steadily.

Analysis (*a*) The power consumed by this heat pump can be determined from the definition of the coefficient of performance of a heat pump to be



$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{60{,}000\text{Btu/h}}{2.5} = 24{,}000\text{Btu/h} = \mathbf{9.43hp}$$

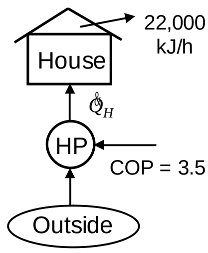
(*b*) The rate of heat transfer from the outdoor air is determined from the conservation of energy principle,

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{net,in} = (60{,}000 - 24{,}000\text{Btu/h}) = \mathbf{36{,}000\ Btu/h}$$

6-61 The rate of heat loss from a house and the COP of the heat pump are given. The power consumption of the heat pump when it is running is to be determined.

Assumptions The heat pump operates one-third of the time.

Analysis Since the heat pump runs one-third of the time and must supply heat to the house at an average rate of 15,000 kJ/h, the heat pump supplies heat at a rate of



$$\dot{Q}_H = 3(22{,}000\text{kJ/h}) = 66.000\ \text{kJ/h}$$

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

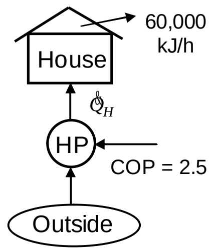
$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{66{,}000\ \text{kJ/h}}{3.5}\left(\frac{1\ \text{kW}}{3600\ \text{kJ/h}}\right) = \mathbf{5.23\ \ kW}$$

6-62 The rate of heat loss, the rate of internal heat gain, and the COP of a heat pump are given. The power input to the heat pump is to be determined.

Assumptions The heat pump operates steadily.

Analysis 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

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

6-63 An office that is being cooled adequately by a 12,000 Btu/h window air-conditioner is converted to a computer room. The number of additional air-conditioners that need to be installed is to be determined.

Assumptions **1** The computer are operated by 4 adult men. **2** The computers consume 40 percent of their rated power at any given time.

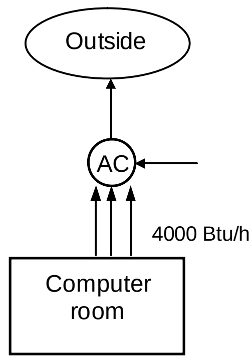
Properties The average rate of heat generation from a person seated in a room/office is 100 W (given).

Analysis The amount of heat dissipated by the computers is equal to the amount of electrical energy they consume. Therefore,

$$\dot{Q}_{\text{computers}} = (\text{Rated power}) \times (\text{Usage factor}) = (3.5 \text{ kW})(0.4) = 1.4 \text{ kW}$$

$$\dot{Q}_{\text{people}} = (\text{No. of people}) \times \dot{Q}_{\text{person}} = 4 \times (100 \text{ W}) = 400 \text{ W}$$

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{computers}} + \dot{Q}_{\text{people}} = 1400 + 400 = 1800 \text{ W} = 6142 \text{ Btu/h}$$



since 1 W = 3.412 Btu/h. Then noting that each available air conditioner provides 4,000 Btu/h cooling, the number of air-conditioners needed becomes

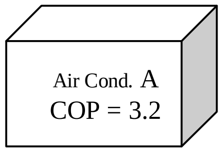
$$\text{No. of air conditioners} = \frac{\text{Cooling load}}{\text{Cooling capacity of A/C}} = \frac{6142 \text{ Btu/h}}{4000 \text{ Btu/h}}$$
$$= 1.5 \approx \mathbf{2 \ Air \ conditioners}$$

6-64 A decision is to be made between a cheaper but inefficient air-conditioner and an expensive but efficient air-conditioner for a building. The better buy is to be determined.

Assumptions The two air conditioners are comparable in all aspects other than the initial cost and the efficiency.

Analysis The unit that will cost less during its lifetime is a better buy. The total cost of a system during its lifetime (the initial, operation, maintenance, etc.) can be determined by performing a life cycle cost analysis. A simpler alternative is to determine the simple payback period. The energy and cost savings of the more efficient air conditioner in this case is

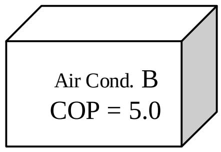
$$\begin{aligned}\text{Energy savings} &= (\text{Annual energy usage of A}) - (\text{Annual energy usage of B})\\ &= (\text{Annual cooling load})(1/\text{COP}_\text{A} - 1/\text{COP}_\text{B})\\ &= (120{,}000\ \text{kWh/year})(1/3.2 - 1/5.0)\\ &= 13{,}500\ \text{kWh/year}\end{aligned}$$



$$\begin{aligned}\text{Cost savings} &= (\text{Energy savings})(\text{Unit cost of energy})\\ &= (13{,}500\ \text{kWh/year})(\$0.10/\text{kWh}) = \mathbf{\$1350/year}\end{aligned}$$

The installation cost difference between the two air-conditioners is

Cost difference = Cost of B – cost of A = 7000 – 5500 = $1500



Therefore, the more efficient air-conditioner B will pay for the $1500 cost differential in this case in about 1 year.

Discussion A cost conscious consumer will have no difficulty in deciding that the more expensive but more efficient air-conditioner B is clearly the better buy in this case since air conditioners last at least 15 years. But the decision would not be so easy if the unit cost of electricity at that location was much less than $0.10/kWh, or if the annual air-conditioning load of the house was much less than 120,000 kWh.

Perpetual-Motion Machines

6-65C This device creates energy, and thus it is a PMM1.

6-66C This device creates energy, and thus it is a PMM1.

Reversible and Irreversible Processes

6-67C No. Because it involves heat transfer through a finite temperature difference.

6-68C 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.

6-69C 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.

6-70C 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.

6-71C The irreversibilities that occur within the system boundaries are **internal** irreversibilities; those which occur outside the system boundaries are **external** irreversibilities.

6-72C 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

6-73C The four processes that make up the Carnot cycle are isothermal expansion, reversible adiabatic expansion, isothermal compression, and reversible adiabatic compression.

6-74C 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.

6-75C 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.

6-76C Yes. The second Carnot principle states that all reversible heat engine cycles operating between the same temperature limits have the thermal efficiency.

6-77C (a) No, (b) No. They would violate the Carnot principle.

Carnot Heat Engines

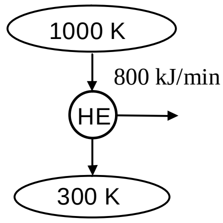
6-78C No.

6-79C 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.

6-80 The source and sink temperatures of a Carnot heat engine and the rate of heat supply are given. The thermal efficiency and the power output are to be determined.

Assumptions The Carnot heat engine operates steadily.

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



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

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

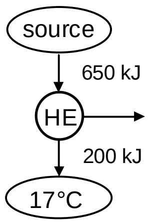
$$\dot{W}_{net,out} = \eta_{th}\dot{Q}_H = (0.70)(800\text{kJ/min}) = 560\text{kJ/min} = \mathbf{9.33kW}$$

6-81 The sink temperature of a Carnot heat engine and the rates of heat supply and heat rejection are given. The source temperature and the thermal efficiency of the engine are to be determined.

Assumptions The Carnot heat engine operates steadily.

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

Thus the temperature of the source T_H must be



$$T_H = \left(\frac{Q_H}{Q_L}\right)_{rev} T_L = \left(\frac{650\text{ kJ}}{200\text{ kJ}}\right)(290\text{ K}) = \mathbf{942.5\ K}$$

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

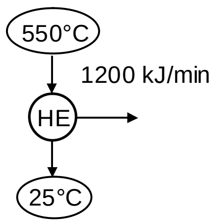
$$\eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{290\text{ K}}{942.5\text{ K}} = 0.69 \text{ or } \mathbf{69\%}$$

6-82 [*Also solved by EES on enclosed CD***]** The source and sink temperatures of a heat engine and the rate of heat supply are given. The maximum possible power output of this engine is to be determined.

Assumptions The heat engine operates steadily.

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

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



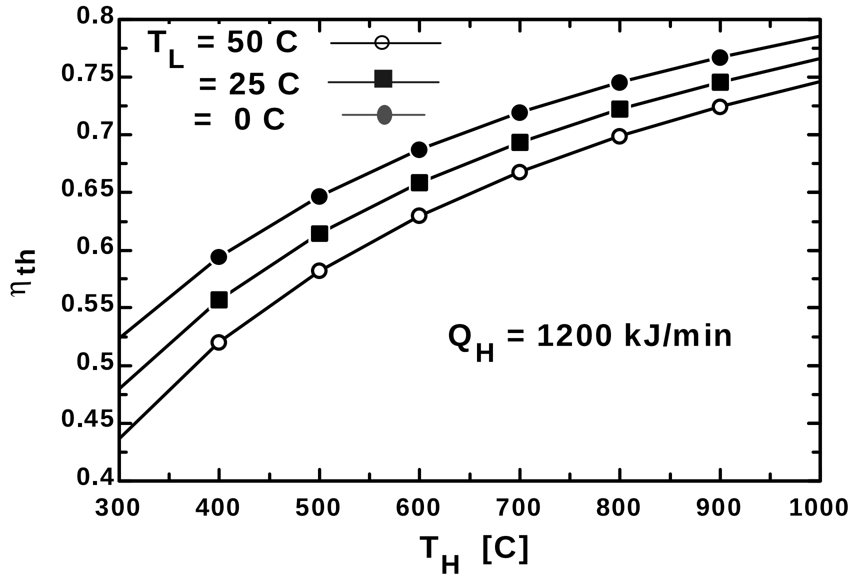
Then the maximum power output of this heat engine is determined from the definition of thermal efficiency to be

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

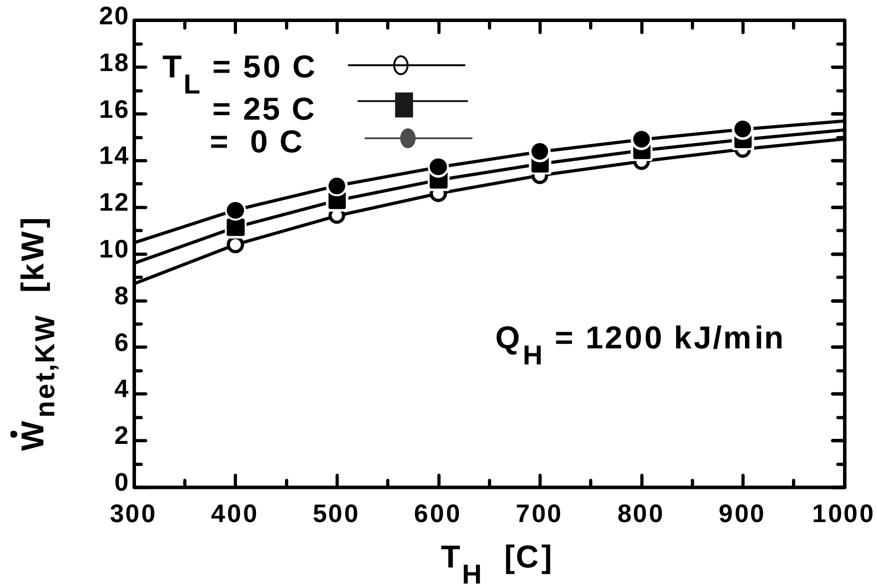
6-83 Problem 6-82 is reconsidered. The effects of the temperatures of the heat source and the heat sink on the power produced and the cycle thermal efficiency as the source temperature varies from 300°C to 1000°C and the sink temperature varies from 0°C to 50°C is to be studied. The power produced and the cycle efficiency against the source temperature for sink temperatures of 0°C, 25°C, and 59°C are to be plotted.

```
"Input Data from the Diagram Window"
{T_H = 550"C"
T_L = 25"C"}
{Q_dot_H = 1200"kJ/min"}

"First Law applied to the heat engine"
Q_dot_H - Q_dot_L- W_dot_net = 0
W_dot_net_KW=W_dot_net*convert(kJ/min,kW)

"Cycle Thermal Efficiency - Temperatures must be absolute"
eta_th = 1 - (T_L + 273)/(T_H + 273)

"Definition of cycle efficiency"
eta_th=W_dot_net / Q_dot_H
```

η_{th}	T_H [C]	W_{netkW} [kW]
0.52	300	10.47
0.59	400	11.89
0.65	500	12.94
0.69	600	13.75
0.72	700	14.39
0.75	800	14.91
0.77	900	15.35
0.79	1000	15.71



T_L = 50 C
= 25 C
= 0 C
Q_H = 1200 kJ/min
η_{th}
T_H [C]
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
300
400
500
600
700
800
900
1000



T_L = 50 C
= 25 C
= 0 C
Q_H = 1200 kJ/min
$\dot{W}_{net,KW}$ [kW]
T_H [C]
20
18
16
14
12
10
8
6
4
2
0
300
400
500
600
700
800
900
1000

6-84E The sink temperature of a Carnot heat engine, the rate of heat rejection, and the thermal efficiency are given. The power output of the engine and the source temperature are to be determined.

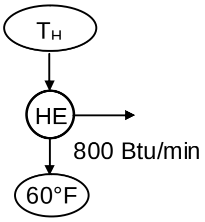
Assumptions The Carnot heat engine operates steadily.

Analysis (a) The rate of heat input to this heat engine is determined from the definition of thermal efficiency,

$$\eta_{th} = 1 - \frac{\dot{Q}_L}{\dot{Q}_H} \longrightarrow 0.55 = 1 - \frac{800 \text{Btu/min}}{\dot{Q}_H} \longrightarrow \dot{Q}_H = 1777.8 \text{Btu/min}$$

Then the power output of this heat engine can be determined from

$$\dot{W}_{net,out} = \eta_{th} \dot{Q}_H = (0.55)(1777.8 \text{Btu/min}) = 977.8 \text{Btu/min} = \mathbf{23.1 hp}$$

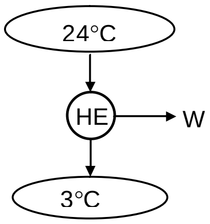


(*b*) For reversible cyclic devices we have $\left(\frac{\dot{Q}_H}{\dot{Q}_L}\right)_{rev} = \left(\frac{T_H}{T_L}\right)$

Thus the temperature of the source T_H must be

$$T_H = \left(\frac{\dot{Q}_H}{\dot{Q}_L}\right)_{rev} T_L = \left(\frac{1777.8 \text{Btu/min}}{800 \text{Btu/min}}\right)(520 \text{R}) = \mathbf{1155.6R}$$

6-85 The source and sink temperatures of a OTEC (Ocean Thermal Energy Conversion) power plant are given. The maximum thermal efficiency is to be determined.

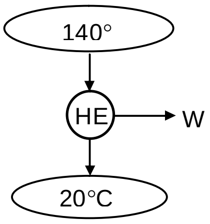


Assumptions The power plant operates steadily.

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

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

6-86 The source and sink temperatures of a geothermal power plant are given. The maximum thermal efficiency is to be determined.



Assumptions The power plant operates steadily.

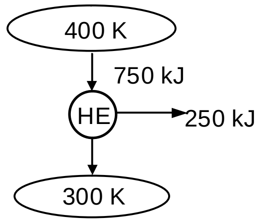
Analysis The highest thermal efficiency a heat engine operating between two specified temperature limits can have is the Carnot efficiency, which is determined from

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

6-87 An inventor claims to have developed a heat engine. The inventor reports temperature, heat transfer, and work output measurements. The claim is to be evaluated.

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

$$\eta_{th,\max} = \eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\text{ K}}{400\text{ K}} = 0.25 \quad \textit{or} \quad \mathbf{25\%}$$



The actual thermal efficiency of the heat engine in question is

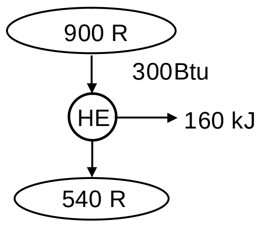
$$\eta_{th} = \frac{W_{net}}{Q_H} = \frac{250\text{ kJ}}{750\text{ kJ}} = 0.333 \text{ or } \mathbf{33.3\%}$$

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

6-88E An inventor claims to have developed a heat engine. The inventor reports temperature, heat transfer, and work output measurements. The claim is to be evaluated.

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

$$\eta_{th,\max} = \eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{540\text{ R}}{900\text{ R}} = 0.40 \quad \textit{or} \quad \mathbf{40\%}$$



The actual thermal efficiency of the heat engine in question is

$$\eta_{th} = \frac{W_{net}}{Q_H} = \frac{160\text{ Btu}}{300\text{ Btu}} = 0.533 \quad \text{or} \quad \mathbf{53.3\%}$$

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

6-89C By increasing T_L or by decreasing T_H.

6-90C It is the COP that a Carnot refrigerator would have, $COP_R = \dfrac{1}{T_H / T_L - 1}$.

6-91C 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.

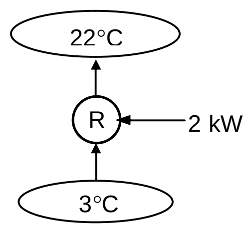
6-92C No. At best (when everything is reversible), the increase in the work produced will be equal to the work consumed by the refrigerator. In reality, the work consumed by the refrigerator will always be greater than the additional work produced, resulting in a decrease in the thermal efficiency of the power plant.

6-93C 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.

6-94 The refrigerated space and the environment temperatures of a Carnot refrigerator and the power consumption are given. The rate of heat removal from the refrigerated space is to be determined.

Assumptions The Carnot refrigerator operates steadily.

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



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

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

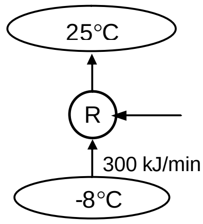
$$\dot{Q}_L = COP_R \times \dot{W}_{net,in} = (14.5)(2\text{ kW}) = 29.0\text{ kW} = \mathbf{1740\ \ kJ/min}$$

6-95 The refrigerated space and the environment temperatures for a refrigerator and the rate of heat removal from the refrigerated space are given. The minimum power input required is to be determined.

Assumptions The refrigerator operates steadily.

Analysis 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

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



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

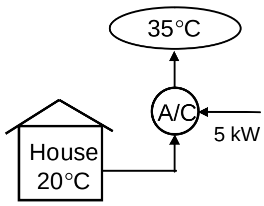
$$\dot{W}_{net,in,\min} = \frac{\dot{Q}_L}{COP_{R,\max}} = \frac{300 \text{ kJ/min}}{8.03} = 37.36 \text{ kJ/min} = \mathbf{0.623\ kW}$$

6-96 The cooled space and the outdoors temperatures for a Carnot air-conditioner and the rate of heat removal from the air-conditioned room are given. The power input required is to be determined.

Assumptions The air-conditioner operates steadily.

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

$$COP_{R,C} = \frac{1}{(T_H / T_L) - 1} = \frac{1}{(35 + 273\text{K})/(20 + 273\text{K}) - 1} = 19.5$$



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

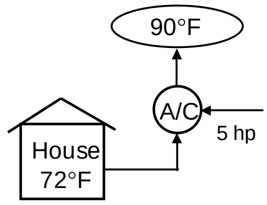
$$\dot{W}_{net,in} = \frac{\dot{Q}_L}{COP_{R,\max}} = \frac{750 \text{ kJ/min}}{19.5} = 38.5 \text{ kJ/min} = \mathbf{0.64\ kW}$$

6-97E The cooled space and the outdoors temperatures for an air-conditioner and the power consumption are given. The maximum rate of heat removal from the air-conditioned space is to be determined.

Assumptions The air-conditioner operates steadily.

Analysis The rate of heat removal from a house will be a maximum when the air-conditioning system operates in a reversible manner. The coefficient of performance of a reversible air-conditioner (or refrigerator) depends on the temperature limits in the cycle only, and is determined from

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



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

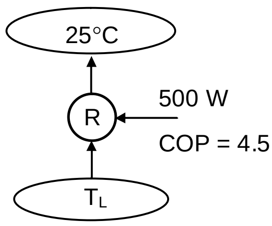
$$\dot{Q}_L = COP_R \times \dot{W}_{net,in} = (29.6)(5\text{ hp})\left(\frac{42.41\text{ Btu/min}}{1\text{ hp}}\right) = \mathbf{6277\ \ Btu/min}$$

6-98 The refrigerated space temperature, the COP, and the power input of a Carnot refrigerator are given. The rate of heat removal from the refrigerated space and its temperature are to be determined.

Assumptions The refrigerator operates steadily.

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

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



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

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

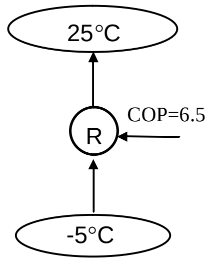
It yields

T_L = 243.8 K = **-29.2°C**

6-99 An inventor claims to have developed a refrigerator. The inventor reports temperature and COP measurements. The claim is to be evaluated.

Analysis The highest coefficient of performance a refrigerator can have when removing heat from a cool medium at -5°C to a warmer medium at 25°C is

$$COP_{R,\max} = COP_{R,rev} = \frac{1}{(T_H / T_L) - 1} = \frac{1}{(25 + 273\text{K})/(-5 + 273\text{K}) - 1} = 8.9$$

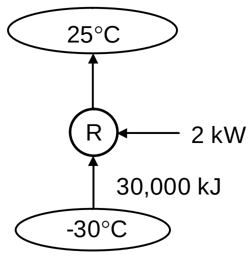


The COP claimed by the inventor is below this maximum value, thus the claim is **reasonable**.

6-100 An experimentalist claims to have developed a refrigerator. The experimentalist reports temperature, heat transfer, and work input measurements. The claim is to be evaluated.

Analysis 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

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



The work consumed by the actual refrigerator during this experiment is

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

Then the coefficient of performance of this refrigerator becomes

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

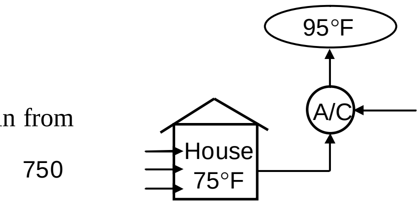
which is above the maximum value. Therefore, these measurements are **not reasonable**.

6-101E An air-conditioning system maintains a house at a specified temperature. The rate of heat gain of the house and the rate of internal heat generation are given. The maximum power input required is to be determined.

Assumptions The air-conditioner operates steadily.

Analysis The power input to an air-conditioning system will be a minimum when the air-conditioner operates in a reversible manner. The coefficient of performance of a reversible air-conditioner (or refrigerator) depends on the temperature limits in the cycle only, and is determined from

$$COP_{R,rev} = \frac{1}{(T_H / T_L) - 1} = \frac{1}{(95 + 460\text{R})/(75 + 460\text{R}) - 1} = 26.75$$



The cooling load of this air-conditioning system is the sum of the heat gain from the outside and the heat generated within the house,

$$\dot{Q}_L = 750 + 150 = 900\ \text{Btu/min}$$

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

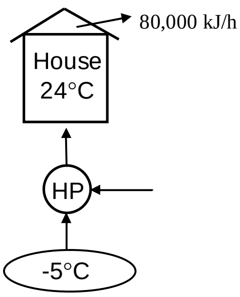
$$\dot{W}_{net,in,\min} = \frac{\dot{Q}_L}{COP_{R,\max}} = \frac{900\ \text{Btu/min}}{26.75} = 33.6\ \text{Btu/min} = \mathbf{0.79\ hp}$$

6-102 A heat pump maintains a house at a specified temperature. The rate of heat loss of the house is given. The minimum power input required is to be determined.

Assumptions The heat pump operates steadily.

Analysis 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

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



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

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

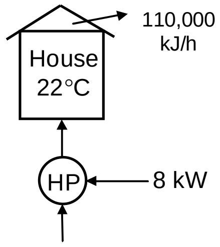
which is the *minimum* power input required.

6-103 A heat pump maintains a house at a specified temperature. The rate of heat loss of the house and the power consumption of the heat pump are given. It is to be determined if this heat pump can do the job.

Assumptions The heat pump operates steadily.

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

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



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

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

This heat pump is **powerful enough** since 8 kW > 2.07 kW.

6-104 A heat pump that consumes 6-kW of power when operating maintains a house at a specified temperature. The house is losing heat in proportion to the temperature difference between the indoors and the outdoors. The lowest outdoor temperature for which this heat pump can do the job is to be determined.

Assumptions The heat pump operates steadily.

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

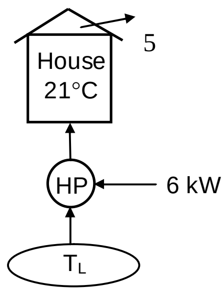
$$\dot{Q}_H = (5400\text{kJ/h}\cdot\text{K})(294-T_L) = (1.5\text{kW/K})(294-T_L)$$

The coefficient of performance of a Carnot heat pump depends on the temperature limits in the cycle only, and can be expressed as

$$COP_{HP} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-\text{T}_L/294\text{K}}$$

or, as

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



Equating the two relations above and solving for T_L, we obtain

T_L = 259.7 K = **-13.3°C**

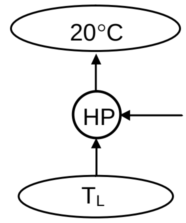
6-105 A heat pump maintains a house at a specified temperature in winter. The maximum COPs of the heat pump for different outdoor temperatures are to be determined.

Analysis The coefficient of performance of a heat pump will be a maximum when the heat pump operates in a reversible manner. The coefficient of performance of a reversible heat pump depends on the temperature limits in the cycle only, and is determined for all three cases above to be

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

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

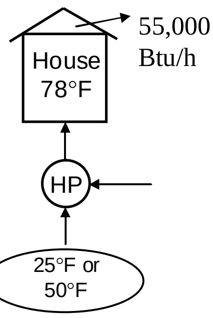
$$COP_{HP,rev} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(-30+273\text{K})/(20+273\text{K})} = \mathbf{5.86}$$



6-106E A heat pump maintains a house at a specified temperature. The rate of heat loss of the house is given. The minimum power inputs required for different source temperatures are to be determined.

Assumptions The heat pump operates steadily.

Analysis (*a*) The power input to a heat pump will be a minimum when the heat pump operates in a reversible manner. If the outdoor air at 25°F is used as the heat source, the COP of the heat pump and the required power input are determined to be



$$COP_{HP,\max} = COP_{HP,rev} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(25+460\text{R})/(78+460\text{R})} = 10.15$$

and

$$\dot{W}_{net,in,\min} = \frac{\dot{Q}_H}{COP_{HP,\max}} = \frac{55{,}000\text{ Btu/h}}{10.15}\left(\frac{1\text{ hp}}{2545\text{ Btu/h}}\right) = \mathbf{2.13\ hp}$$

(*b*) If the well-water at 50°F is used as the heat source, the COP of the heat pump and the required power input are determined to be

$$COP_{HP,\max} = COP_{HP,rev} = \frac{1}{1-(T_L/T_H)} = \frac{1}{1-(50+460\text{R})/(78+460\text{R})} = 19.2$$

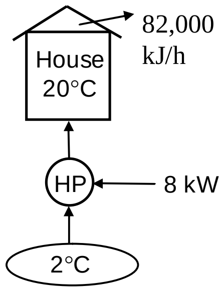
and

$$\dot{W}_{net,in,\min} = \frac{\dot{Q}_H}{COP_{HP,\max}} = \frac{55{,}000\text{ Btu/h}}{19.2}\left(\frac{1\text{ hp}}{2545\text{ Btu/h}}\right) = \mathbf{1.13\ hp}$$

6-107 A Carnot heat pump consumes 8-kW of power when operating, and maintains a house at a specified temperature. The average rate of heat loss of the house in a particular day is given. The actual running time of the heat pump that day, the heating cost, and the cost if resistance heating is used instead are to be determined.

Analysis (*a*) The coefficient of performance of this Carnot heat pump depends on the temperature limits in the cycle only, and is determined from

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



The amount of heat the house lost that day is

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

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

$$W_{net,in} = \frac{Q_H}{COP_{HP}} = \frac{1{,}968{,}000\text{ kJ}}{16.3} = 120{,}736\text{ kJ}$$

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

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

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

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

(*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

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

6-108 A Carnot heat engine is used to drive a Carnot refrigerator. The maximum rate of heat removal from the refrigerated space and the total rate of heat rejection to the ambient air are to be determined.

Assumptions The heat engine and the refrigerator operate steadily.

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

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

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

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

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

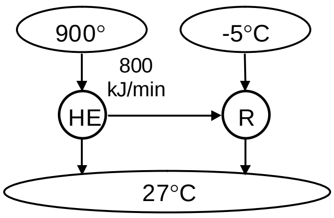
The rate of heat removal from the refrigerated space will be a maximum if a Carnot refrigerator is used. The COP of the Carnot refrigerator is

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

Then the rate of heat removal from the refrigerated space becomes

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

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



$$\dot{Q}_{L,HE} = \dot{Q}_{H,R} - \dot{W}_{net,out} = 800 - 595.2 = 204.8\text{ kJ/min}$$
$$\dot{Q}_{H,R} = \dot{Q}_{L,R} - \dot{W}_{net,in} = 4982 - 595.2 = 5577.2\text{ kJ/min}$$

and

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

6-109E A Carnot heat engine is used to drive a Carnot refrigerator. The maximum rate of heat removal from the refrigerated space and the total rate of heat rejection to the ambient air are to be determined.

Assumptions The heat engine and the refrigerator operate steadily.

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

$$\eta_{th,\max} = \eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{540\text{R}}{2160\text{R}} = 0.75$$

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

$$\dot{W}_{net,out} = \eta_{th}\dot{Q}_H = (0.75)(700\text{ Btu/min}) = 525\text{ Btu/min}$$

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

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

$$COP_{R,rev} = \frac{1}{(T_H\ /T_L) - 1} = \frac{1}{(80 + 460\text{R})/(20 + 460\text{R}) - 1} = 8.0$$

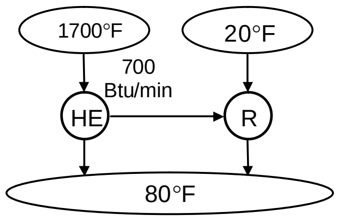
Then the rate of heat removal from the refrigerated space becomes

$$\dot{Q}_{L,R} = (COP_{R,rev})(\dot{W}_{net,in}) = (8.0)(525\text{ Btu/min}) = \mathbf{4200\ Btu/min}$$

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

$$\dot{Q}_{L,HE} = \dot{Q}_{H,R} - \dot{W}_{net,out} = 700 - 525 = 175\text{ Btu/min}$$

$$\dot{Q}_{H,R} = \dot{Q}_{L,R} + \dot{W}_{net,in} = 4200 + 525 = 4725\text{ Btu/min}$$



and

$$\dot{Q}_{Ambient} = \dot{Q}_{L,HE} + \dot{Q}_{H,R} = 175 + 4725 = \mathbf{4900\ \ Btu/min}$$