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.

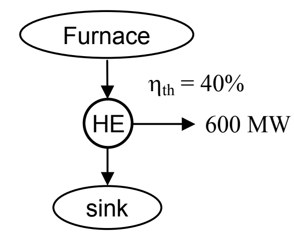
6-16C No. The Kelvin-Plank limitation applies only to heat engines; engines that receive heat and convert some of it to work.

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,

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



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

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

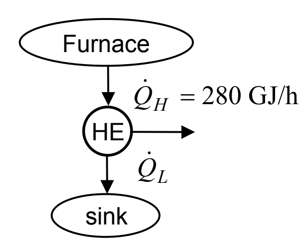
In reality the amount of heat rejected to the river will be **lower** since part of the heat will be lost to the surrounding air from the working fluid as it passes through the pipes and other components.

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

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

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

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

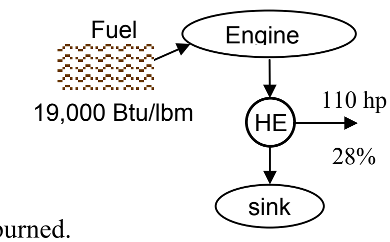
6-19E The power output and thermal efficiency of a car engine are given. The rate of fuel consumption is to be determined.

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 110 hp is determined from the definition of thermal efficiency to be

$$\dot{Q}_H = \frac{\dot{W}_{\text{net,out}}}{\eta_{th}} = \frac{110 \text{ hp}}{0.28}\left(\frac{2545 \text{ Btu/h}}{1 \text{ hp}}\right) = 999{,}598 \text{ Btu/h}$$



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

$$\dot{m} = \frac{999{,}598 \text{ Btu/h}}{19{,}000 \text{ Btu/lbm}} = \mathbf{52.6\ lbm/h}$$

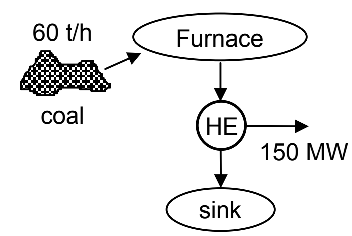
since 19,000 Btu of thermal energy is released for each lbm of fuel burned.

6-20 The power output and fuel consumption rate of a power plant are given. The thermal 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 heat supply to this power plant is



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

Then the thermal efficiency of the plant becomes

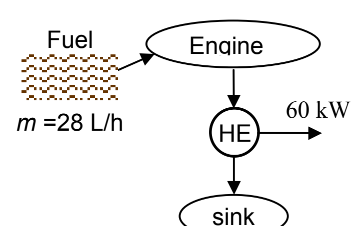
$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_H} = \frac{150 \text{ MW}}{500 \text{ MW}} = 0.300 = \mathbf{30.0\%}$$

6-21 The power output and fuel consumption rate of a car engine are given. The thermal 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



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

The rate of heat supply to the car is

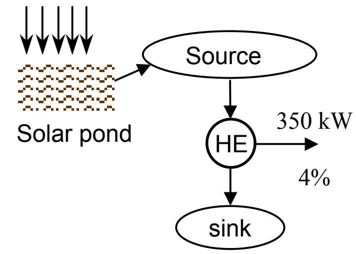
$$\dot{Q}_H = \dot{m}_{\text{coal}} u_{\text{coal}} = (22.4 \text{ kg/h})(44{,}000 \text{ kJ/kg}) = 985{,}600 \text{ kJ/h} = 273.78 \text{ kW}$$

Then the thermal efficiency of the car becomes

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

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

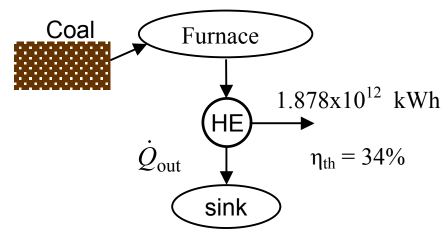
Assumptions The plant operates steadily.



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

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

6-23 The United States produces about 51 percent of its electricity from coal at a conversion efficiency of about 34 percent. The amount of heat rejected by the coal-fired power plants per year is to be determined.

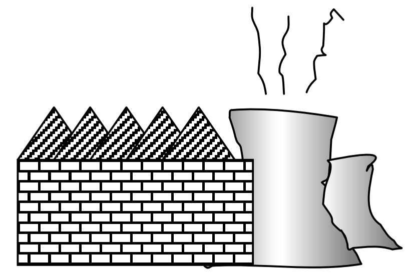


Analysis Noting that the conversion efficiency is 34%, the amount of heat rejected by the coal plants per year is

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

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

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

Analysis The problem is solved using EES, and the solution is given below.

```
"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 [$/kW]
CostPerkW_IGCC=1500 [$/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
ConstructionCost_IGCC= W_dot *CostPerkW_IGCC
ConstructionCost_diff = ConstructionCost_IGCC - ConstructionCost_coal

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

"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

"For  to pay for the construction cost difference of $30 billion, the price of coal should be"
UnitCost_coal = ConstructionCost_diff /DELTAm_coal

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

SOLUTION
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]
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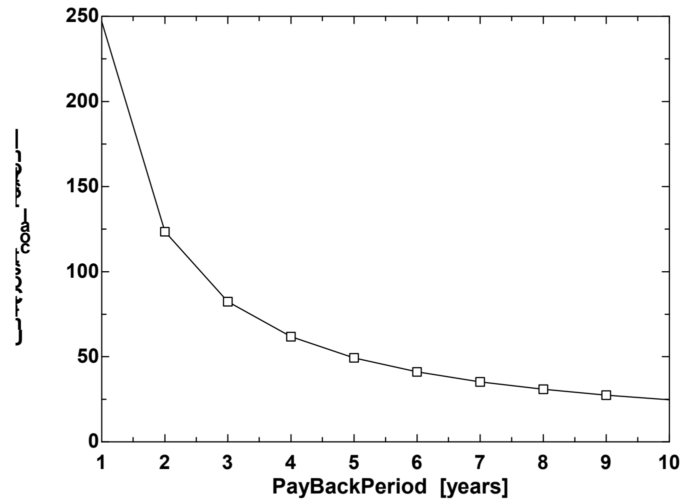
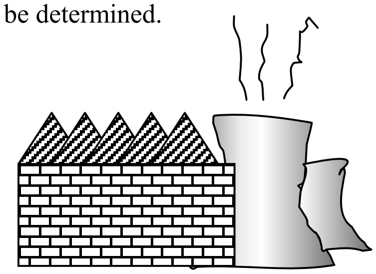
Following is a study on how unit cost of fuel changes with payback period:

PaybackPeriod [years]	$\text{UnitCost}_{\text{coal}}$ [\$/ton]
1	247
2	123.5
3	82.33
4	61.75
5	49.4
6	41.17
7	35.28
8	30.87
9	27.44
10	24.7



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

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

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

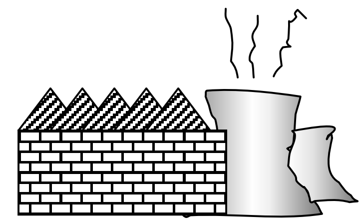
$$\Delta m_{\text{coal}} = m_{\text{coal, coal plant}} - m_{\text{coal, IGCC plant}} = 1.491\times10^9 - 1.126\times10^9 = 0.365\times10^9\ \text{tons}$$

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.

6-27E 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 taken 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.

6-28 A coal-burning power plant produces 300 MW of power. The amount of coal consumed during a one-day period and the rate of air flowing through the furnace are to be determined.

Assumptions **1** The power plant operates steadily. **2** The kinetic and potential energy changes are zero.

Properties The heating value of the coal is given to be 28,000 kJ/kg.

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

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

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

The amount and rate of coal consumed during this period are

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

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

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

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

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.

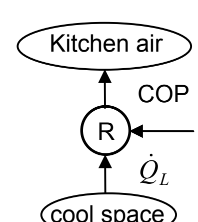
6-38C The violation of one statement leads to the violation of the other one, as shown in Sec. 6-4, and thus we conclude that the two statements are equivalent.

6-39 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

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



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

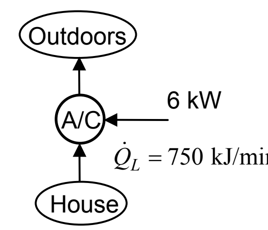
$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{net,in}} = 60 + 50 = \mathbf{110\ kJ/min}$$

6-40 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,

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



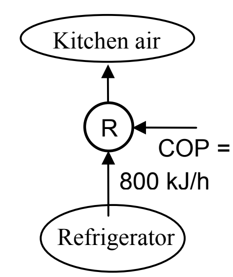
(*b*) The rate of heat discharge to the outside air is determined from the energy balance,

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

6-41 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



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

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

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

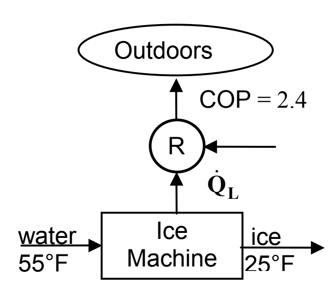
6-42E The COP and the refrigeration rate of an ice machine are given. The power consumption is to be determined.

Assumptions The ice machine operates steadily.

Analysis The cooling load of this ice machine is

$$\dot{Q}_L = \dot{m}q_L = (28\text{ lbm/h})(169\text{ Btu/lbm}) = 4732\text{ Btu/h}$$

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



$$\dot{W}_\text{net,in} = \frac{\dot{Q}_L}{\text{COP}_\text{R}} = \frac{4732\text{ Btu/h}}{2.4}\left(\frac{1\text{ hp}}{2545\text{ Btu/h}}\right) = \mathbf{0.775\ hp}$$

6-43 The COP and the power consumption of a refrigerator are given. The time it will take to cool 5 watermelons is to be determined.

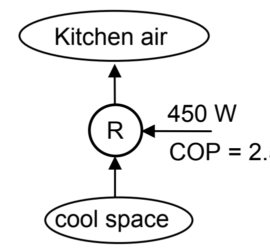
Assumptions **1** The refrigerator operates steadily. **2** The heat gain of the refrigerator through its walls, door, etc. is negligible. **3** The watermelons are the only items in the refrigerator to be cooled.

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

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

The rate at which this refrigerator removes heat is



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

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

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

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.

6-44 **[***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.

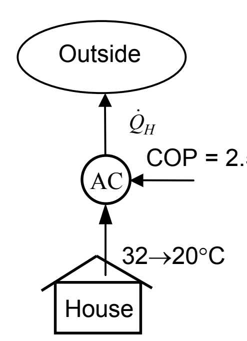
Assumptions **1** The air conditioner operates steadily. **2** The house is well-sealed so that no air leaks in or out during cooling. **3** Air is an ideal gas with constant specific heats at room temperature.

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

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

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

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

6-45 EES Problem 6-44 is reconsidered. The rate of power drawn by the air conditioner required to cool the house as a function for air conditioner EER ratings in the range 9 to 16 is to be investigated. Representative costs of air conditioning units in the EER rating range are to be included.

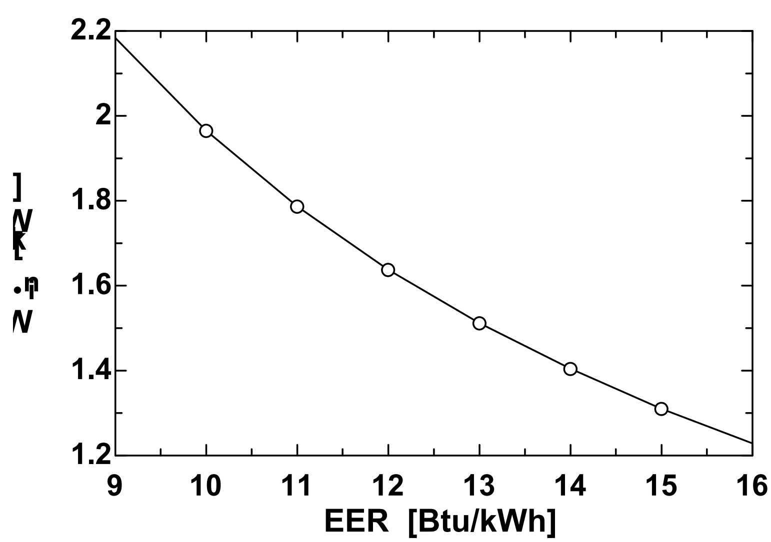
Analysis The problem is solved using EES, and the results are tabulated and plotted below.

```
"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}
COP=EER/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
E_dot_in = 0
E_dot_out = Q_dot_L
DELTAE_dot = m_house*DELTAu_house/DELTAtime
DELTAu_house = C_v*(T_2-T_1)

"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"
```

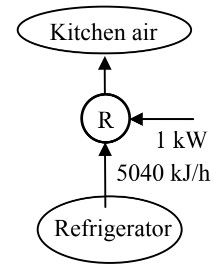
EER [Btu/kWh]	W_{in} [kW]
9	2.184
10	1.965
11	1.787
12	1.638
13	1.512
14	1.404
15	1.31
16	1.228



6-46 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,



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

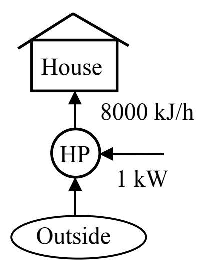
The rate of heat rejection to the surrounding air, per kW of power consumed, is determined from the energy balance,

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

6-47 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,



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

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

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

6-48 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

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

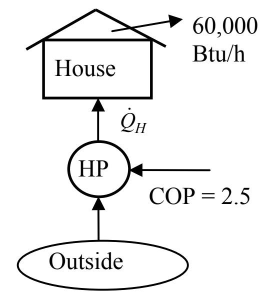
which represent a savings of 1200 – 500 = 700 kWh. Thus the homeowner would have saved

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

6-49E 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



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

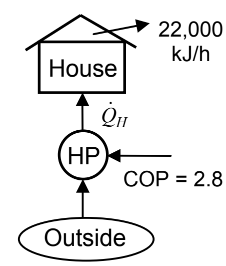
(*b*) The rate of heat transfer from the outdoor air is determined from the conservation of energy principle,

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

6-50 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 22,000 kJ/h, the heat pump supplies heat at a rate of



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

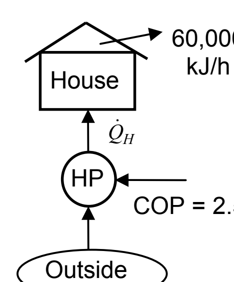
when running. Thus the power the heat pump draws when it is running is

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

6-51 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

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

6-52E 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 computers are operated by 4 adult men. **2** The computers consume 40 percent of their rated power at any given time.

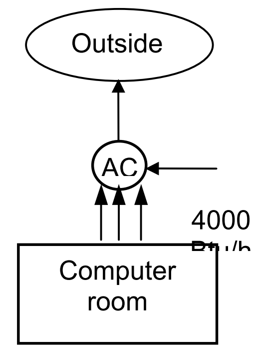
Properties The average rate of heat generation from a person seated in a room/office is 100 W (given).

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

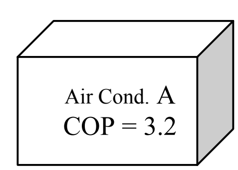
$$\text{No. of air conditioners} = \frac{\text{Cooling load}}{\text{Cooling capacity of A/C}} = \frac{6142 \text{ Btu/h}}{4000 \text{ Btu/h}}$$
$$= 1.5 \approx \mathbf{2\ Air\ conditioners}$$

6-53 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

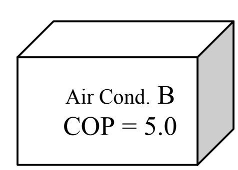
$$\begin{aligned}
\text{Energy savings} &= (\text{Annual energy usage of A}) - (\text{Annual energy usage of B}) \\
&= (\text{Annual cooling load})(1/\text{COP}_A - 1/\text{COP}_B) \\
&= (120{,}000 \text{ kWh/year})(1/3.2 - 1/5.0) \\
&= 13{,}500 \text{ kWh/year}
\end{aligned}$$



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

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.

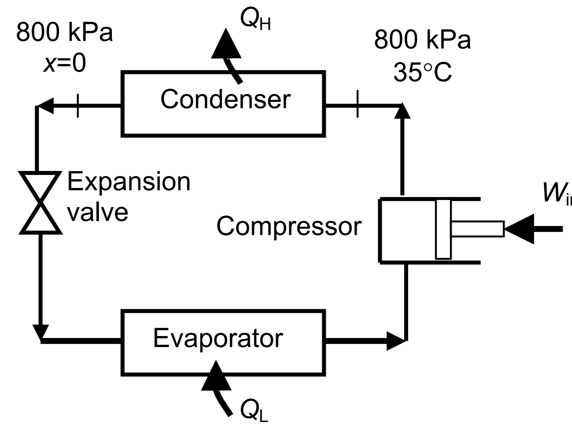
6-54 Refrigerant-134a flows through the condenser of a residential heat pump unit. For a given compressor power consumption the COP of the heat pump and the rate of heat absorbed from the outside air are to be determined.

Assumptions **1** The heat pump operates steadily. **2** The kinetic and potential energy changes are zero.

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

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

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



Analysis (*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

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

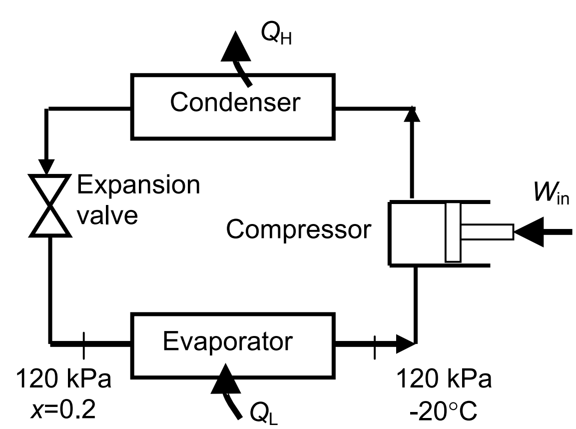
6-55 A commercial refrigerator with R-134a as the working fluid is considered. The evaporator inlet and exit states are specified. The mass flow rate of the refrigerant and the rate of heat rejected are to be determined.

Assumptions **1** The refrigerator operates steadily. **2** The kinetic and potential energy changes are zero.

Properties The properties of R-134a at the evaporator inlet and exit states are (Tables A-11 through A-13)

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

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



Analysis (*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

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

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

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

Perpetual-Motion Machines

6-56C This device creates energy, and thus it is a PMM1.

6-57C This device creates energy, and thus it is a PMM1.

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.