Thermodynamics: An Engineering Approach, 6th Edition
Yunus A. Cengel, Michael A. Boles
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Chapter (6)

SECOND LAW OF THERMODYNAMICS

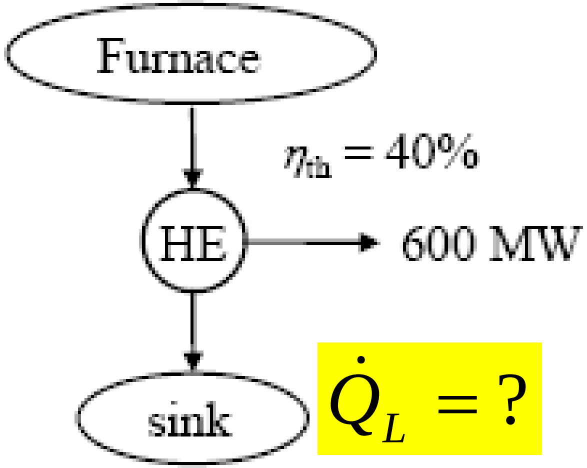
Heat Pumps

Example (6-17)

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.

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

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



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

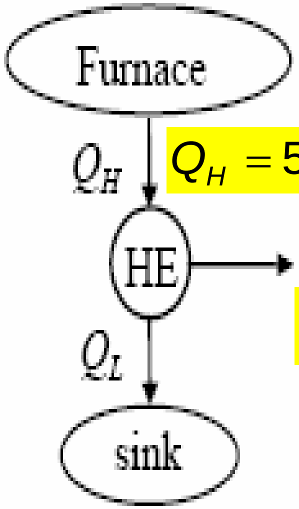
Example (6-19)

6-19 The work output and heat input of a heat engine are given. The heat rejection is to be determined.

Assumptions 1 The plant operates steadily. 2 Heat losses from the working fluid at the pipes and other components are negligible.

Analysis Applying the first law to the heat engine gives

$$Q_L = Q_H - W_{\text{net}} = 500\text{ kJ} - 200\text{ kJ} = \mathbf{300\text{ kJ}}$$



$Q_H = 500\, kJ$

$W_{net} = 200\, kJ$

$\dot{Q}_L = ?$

Example (6-21)- Homework

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

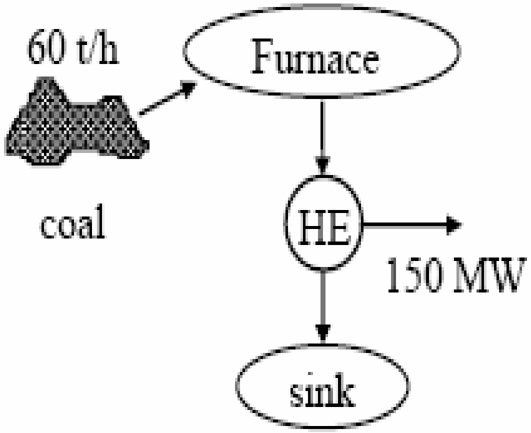
Assumptions The plant operates steadily.

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

$$\eta_{th} = ?$$

Analysis The rate of heat supply to this power plant is

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



Then the thermal efficiency of the plant becomes

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

Example (6-22)

6-22 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. $\rho_{Fuel} = 0.8\, g/cm^3$

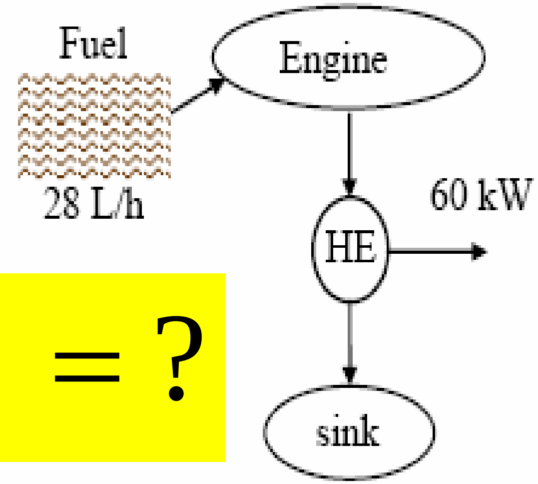
Analysis The mass consumption rate of the fuel is

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

The rate of heat supply to the car is

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

$$\eta_{th} = ?$$



Then the thermal efficiency of the car becomes

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

Example (6-28)

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.

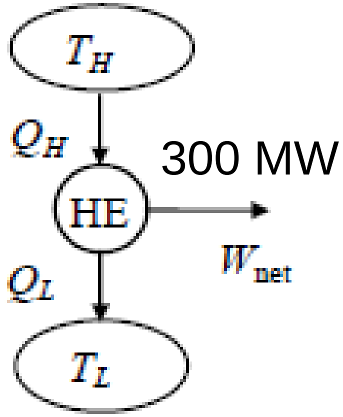
Assumptions **1** The power plant operates steadily. **2** The kinetic and potential energy changes are zero.

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

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

$$\eta = 32\%$$



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

The amount and rate of coal consumed during this period are

$$m_{\text{coal}} = \frac{Q_{\text{in}}}{q_{\text{HV}}} = \frac{8.1\times10^7\ \text{MW}}{28\ \text{MJ/kg}} = \mathbf{2.893\times10^6\ kg}$$

$$\dot{m}_{\text{coal}} = \frac{m_{\text{coal}}}{\Delta t} = \frac{2.893\times10^6\ \text{kg}}{24\times3600\ \text{s}} = 33.48\ \text{kg/s}$$

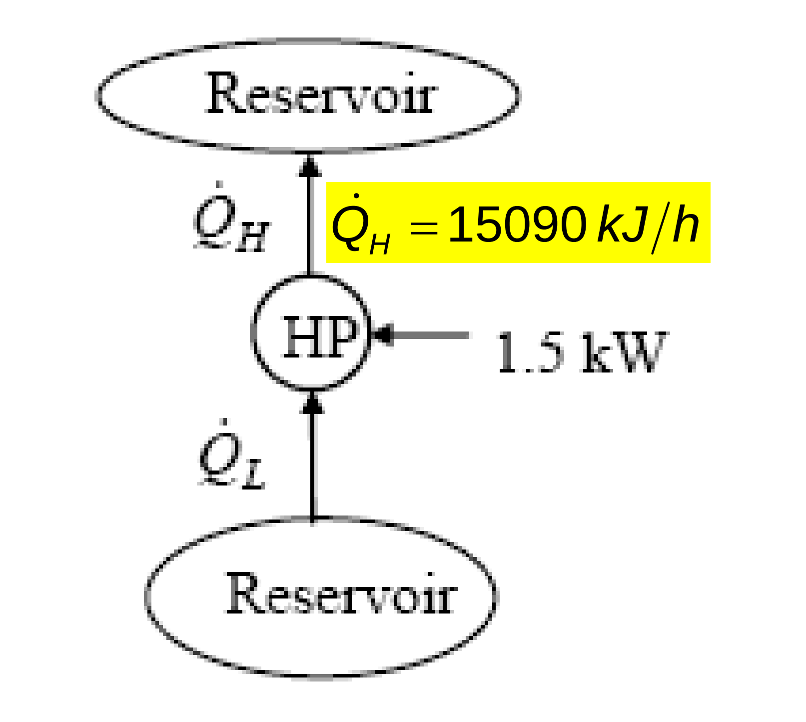
(*b*) Noting that the air-fuel ratio is 12, the rate of air flowing through the furnace is

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

Refrigerators and Heat Pumps

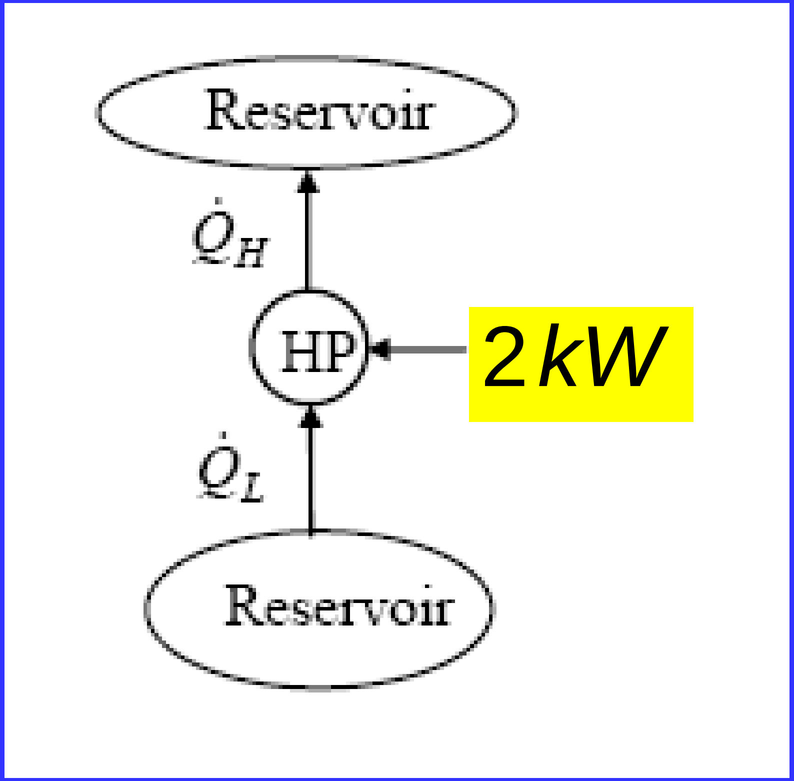
Example (6-40)

Find COP?



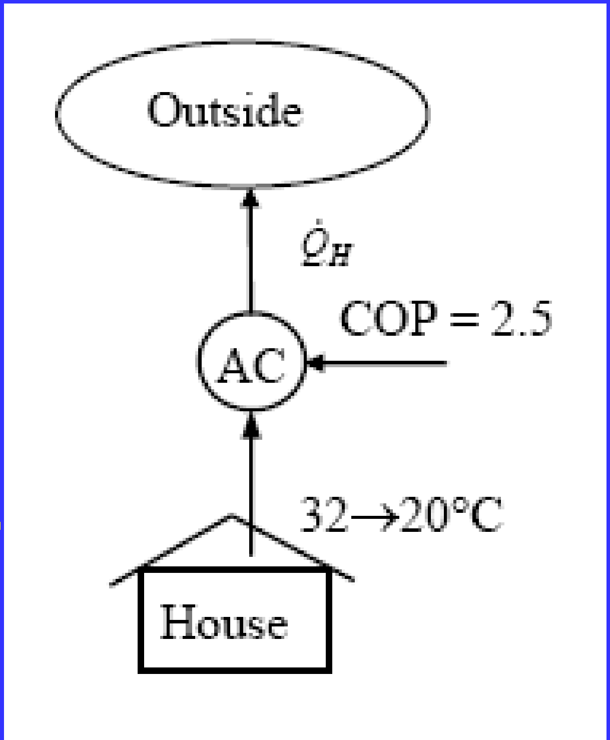
$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} = \frac{15{,}090\ \text{kJ/h}}{1.5\ \text{kW}}\left(\frac{1\ \text{kW}}{3600\ \text{kJ/h}}\right) = \mathbf{2.79}$$

Example (6-41)-Homework



$$\dot{Q}_H = \text{COP}_{\text{HP}} \dot{W}_{\text{net,in}} = (1.6)(2\text{ kW}) = 3.2\text{ kW} = \mathbf{3.2\ kJ/s}$$

Example (6-47)



Determine the power of Air-conditioner?

Given:

Time to cool the house from 32C to 20C is 15 min.

$$m_{air} = 800\,kg$$

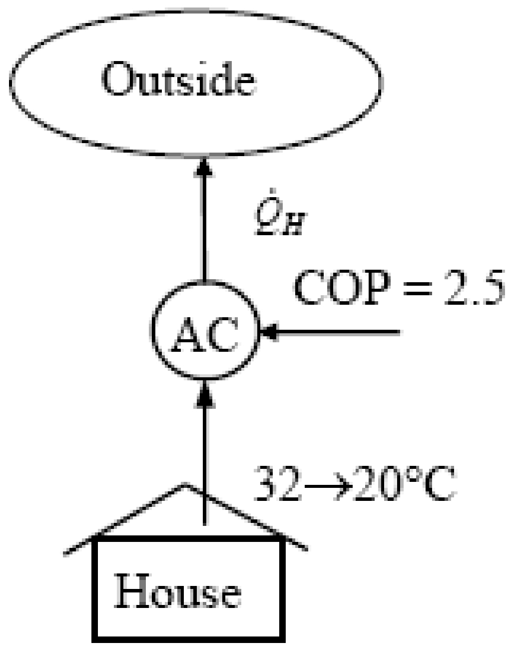
Assumptions 1 The air conditioner operates steadily. 2 The house is well-sealed so that no air leaks in or out during cooling. 3 Air is an ideal gas with constant specific heats at room temperature.

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

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

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

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



Example (6-50)

COP=?

6-50 The cooling effect and the rate of heat rejection of a refrigerator are given. The COP of the refrigerator is to be determined.

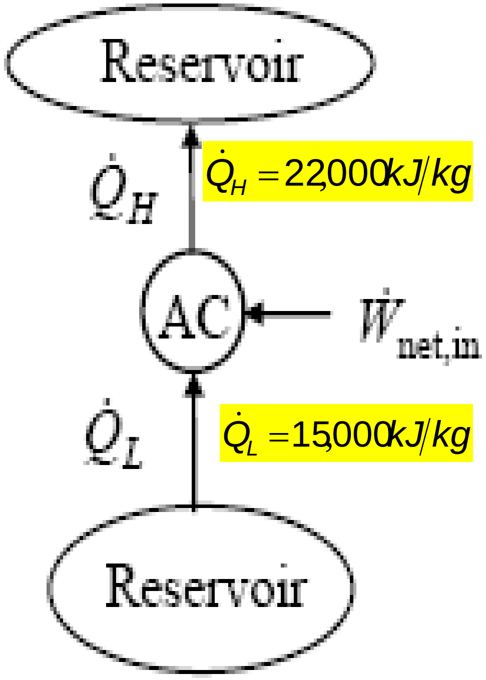
Assumptions The refrigerator operates steadily.

Analysis Applying the first law to the refrigerator gives

$$\dot{W}_{net,in} = \dot{Q}_H - \dot{Q}_L = 22{,}000 - 15{,}000 = 7000 \text{ kJ/h}$$

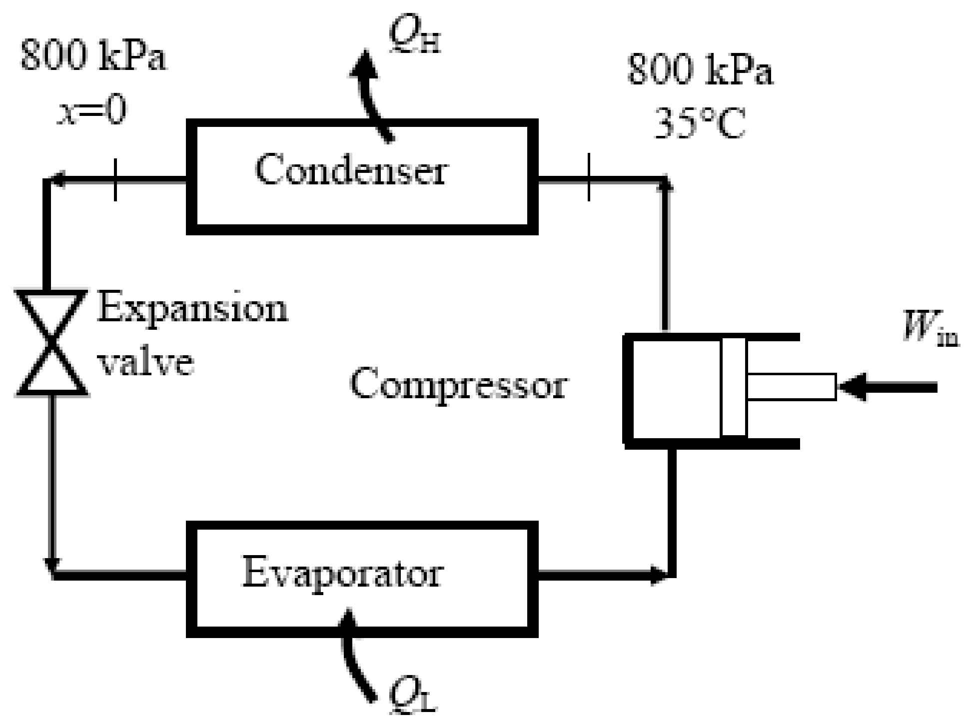
Applying the definition of the coefficient of performance,

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{15{,}000 \text{ kJ/h}}{7000} = \mathbf{2.14}$$



Example (6-55)

1. Find COP of the heat pump?
2. Heat of absorption from the outside air? $\dot{Q}_L$



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

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

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

$$\dot{m} = 0.018\, kg/s$$

$$\dot{W}_{Comp} = 1.2\, kW$$

$$\dot{m} = 0.018\, kg/s$$

$$\dot{W}_{Comp} = 1.2\, kW$$

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

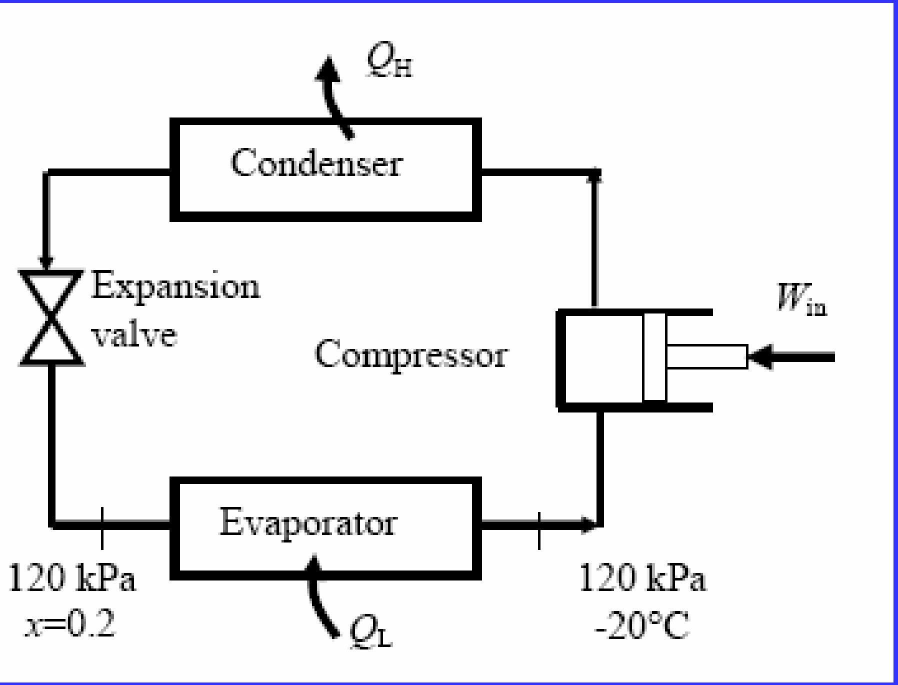
The COP of the heat pump is

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

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

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

Example (6-56)-Homework



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

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

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

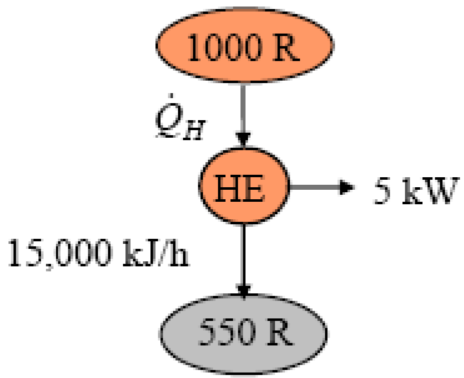
$$\dot{m}_R = \frac{\dot{Q}_L}{h_2 - h_1} = \frac{0.54\ \text{kW}}{(238.84 - 65.38)\ \text{kJ/kg}} = \mathbf{0.0031\ kg/s}$$

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

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

Carnot Heat Engines

Example (6-81)-Homework



$$\eta_{\text{th,max}} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\text{ K}}{550\text{ K}} = 0.455$$

When the first law is applied to the engine above,

$$\dot{Q}_H = \dot{W}_{\text{net}} + \dot{Q}_L = (5\text{ kW})\left(\frac{3600\text{ kJ/h}}{1\text{ kW}}\right) + 15{,}000\text{ kJ/h} = 33{,}000\text{ kJ/h}$$

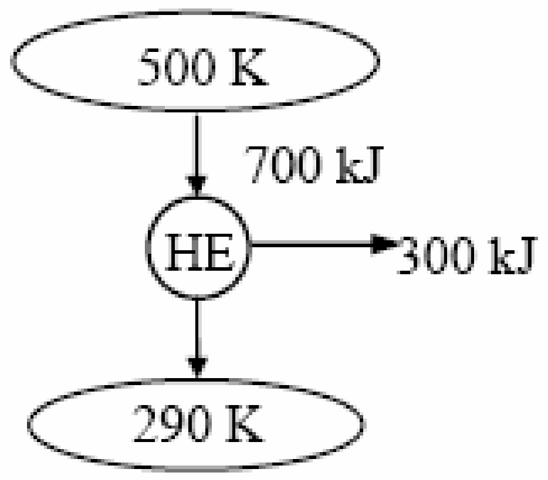
The actual thermal efficiency of the proposed heat engine is then

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net}}}{\dot{Q}_H} = \frac{5\text{ kW}}{33{,}000\text{ kJ/h}}\left(\frac{3600\text{ kJ/h}}{1\text{ kW}}\right) = 0.545$$

the inventor's claim is invalid.

Example (6-83)

Investigate this heat engine?



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

The actual thermal efficiency of the heat engine in question is

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

the claim is false.

Carnot Refrigerator and Heat Pumps

Example (6-94)

Determine the rate of cooling?

6-94 The rate of cooling provided by a reversible refrigerator with specified reservoir temperatures is to be determined.

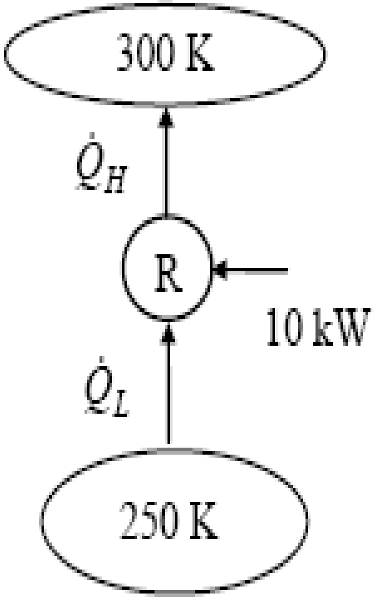
Assumptions The refrigerator operates steadily.

Analysis The COP of this reversible refrigerator is

$$COP_{R,max} = \frac{T_L}{T_H - T_L} = \frac{250\text{ K}}{300\text{ K} - 250\text{ K}} = 5$$

Rearranging the definition of the refrigerator coefficient of performance gives

$$\dot{Q}_L = COP_{R,max}\dot{W}_{net,in} = (5)(10\text{ kW}) = \mathbf{50\ kW}$$



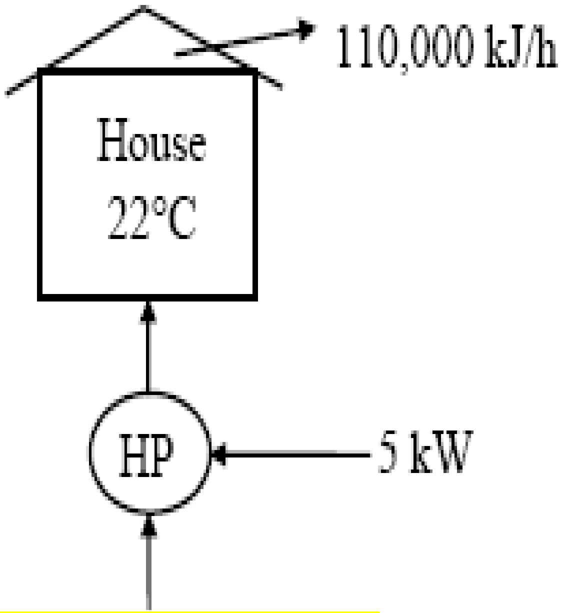
Example (6-99)-Homework

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

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

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

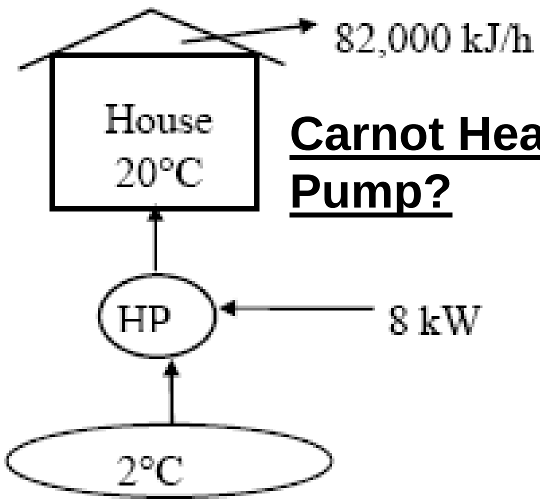
This heat pump is **powerful enough** since 5 kW > 2.07 kW.



Given $T_L = 2\ ^{\circ}C$

Example (6-105)

1. Determine the heat pump ran on that day?
2. Total heating cost?
3. Heating cost for the same day if resistance heating is used?



Carnot Heat Pump?

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

The amount of heat the house lost that day is

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

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

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

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

(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

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

<u>THE END</u>