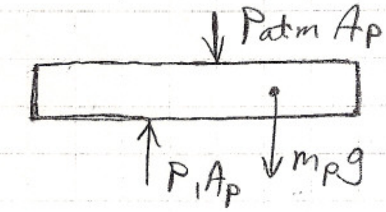
$\boxed{\#1.}$ Water, $x_1 = 0.25$, $m_p = 80.09$ kg, $D_p = 10$ cm

$P_{atm} = 100$ kPa



$\sum F_y = 0$: $P_{atm} A_p + m_p g = P_1 A_p$

(a) $A_p = \frac{\pi}{4}(0.1)^2 = 7.8539\times10^{-3}\ m^2$

$$P_1 = P_{atm} + \frac{m_p g}{A_p} = \underset{\uparrow\,[kPa]}{100} + \frac{80.09\times9.80665}{7.8539\times10^{-3}} \times \underbrace{\frac{1\,[kN]}{1000\,[N]}}_{\text{For weight of piston}}$$

$P_1 = 200.002$ kPa

$\simeq 200$ [kPa]

Table B.1.2 at $P = 200$ kPa, $T_{sat.} = 120.23\,°C$

$v_f = 0.001061\ m^3/kg$, $v_{fg} = 0.88467\ m^3/kg$

$\therefore v_1 = v_f + x_1 v_{fg} = 0.001061 + 0.25\times0.88467$

$v_1 = 0.2222285\ m^3/kg$

initial volume: $V_1 = A_p \times h_1 = 7.8539\times10^{-3}\times0.4 = 3.14159\times10^{-3}$ $[m^3]$

$$\therefore m = \frac{V_1}{v_1} = \frac{3.14159\times10^{-3}}{0.2222285} = 1.41367\times10^{-2}\ [kg]$$

(b) Pressure is constant while piston travels, $\therefore P = 200$ kPa

$P < 400$ kPa (Final pressure) $\therefore$ piston hits stops before the Final pressure is reached.

Let state 2 be when the piston just reaches the stops.

$\therefore P_2 = P_1 = 200$ kPa, new volume: $V_2 = A_p h_2 = 7.8539\times10^{-3}\times1.81$

$V_2 = 0.0142155\ m^3$

$$\therefore v_2 = \frac{V_2}{m} = \frac{0.0142155}{1.41367\times10^{-2}}$$

$v_2 = 1.005574\ m^3/kg$

At $P = 200$ kPa, $v_2 > v_g$ $\therefore$ state 2 is superheated vapor.

Table B.1.3

T	v
150	0.95964
T_2	1.005574
200	1.08034

$\therefore$ by interpolation,

$T_2 = 169.03\,°C$

#1 (c) Final state: $P_3 = 400$ kPa, $v_3 = v_2 = 1.005574\ m^3/kg$.

At 400 kPa, $v_3 > v_g$ ∴ state is superheated vapor.

Table B.1.3, $v_3 \simeq 1.00555\ m^3/kg$ which is a table entry corresponding to $T_3 = 600°C$

(d) Work done only during process 1-2

$${}_1W_2 = P(V_2 - V_1) = mP(v_2 - v_1)$$

$$= 1.41367 \times 10^{-2} \times 200 \times (1.005574 - 0.2222285)$$

$${}_1W_2 = 2.21478\ [kJ]$$

(e) First law: $Q_{c.m.} - W_{c.m.} = m(u_3 - u_1) + \Delta \cancel{KE} + \Delta \cancel{PE}$

$u_1 = u_f + x_1 u_{fg}$, Table B.1.2 at 200 kPa, $u_f = 504.47$ kJ/kg, $u_{fg} = 2025.02$ kJ/kg

$\therefore u_1 = 504.47 + 0.25 \times 2025.02$

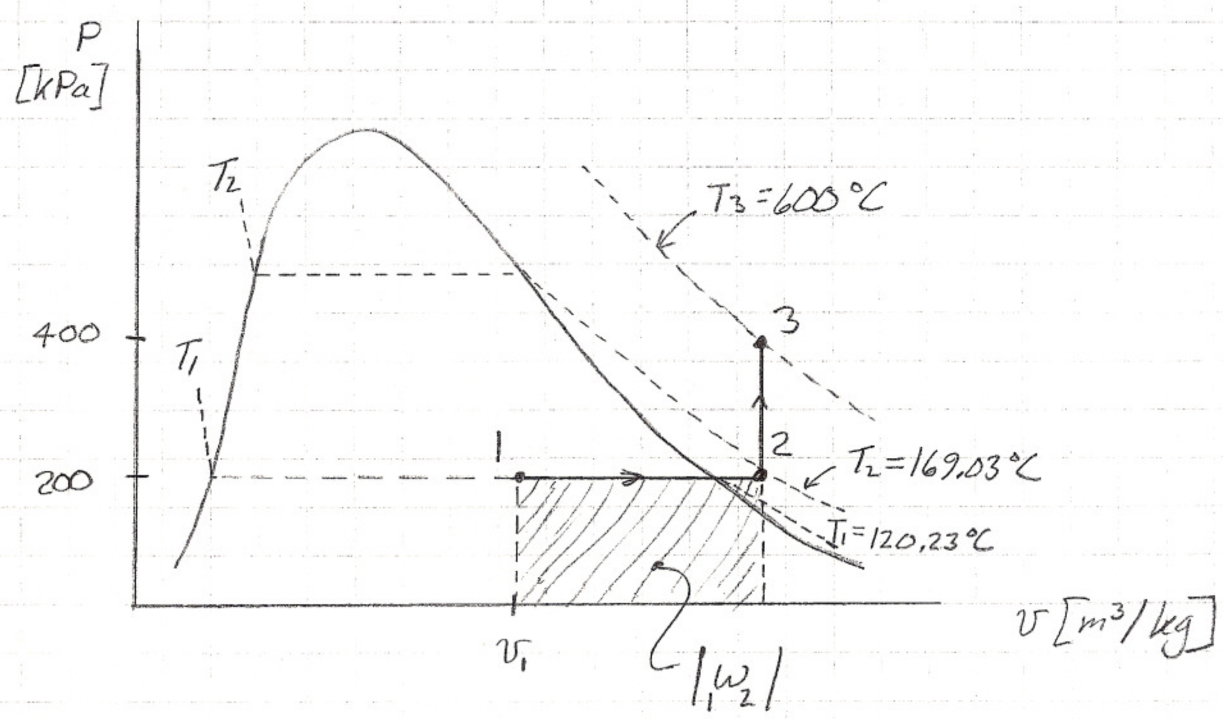
$u_1 = 1010.725$ kJ/kg

u_3: Table B.1.3, at 400 kPa, 600°C, $u_3 = 3300.22$ kJ/kg

$${}_1Q_3 = 2.21478 + 1.41367 \times 10^{-2} \times (3300.22 - 1010.725)$$

$${}_1Q_3 = 34.580\ [kJ]$$

(f)



2-1/4

#2. (a) First law for the condenser: ($\Delta pe = 0$, $\Delta ke = 0$)

$$\cancel{\dot{Q}_{cv}}^{0} - \cancel{\dot{W}_{cv}}^{0} = \Sigma(\dot{m}h)_{out} - \Sigma(\dot{m}h)_{in}$$

$$0 = \dot{m}_4 h_4 + \dot{m}_2 h_2 - \dot{m}_3 h_3 - \dot{m}_1 h_1$$

$$\dot{m}_4 = \dot{m}_3 = \dot{m}_W \qquad \dot{m}_1 = \dot{m}_2 = \dot{m}_{CW}$$

$$0 = \dot{m}_w (h_4 - h_3) + \dot{m}_{cw}(h_2 - h_1)$$

$$\dot{m}_w = \dot{m}_{cw} \frac{(h_2 - h_1)}{(h_3 - h_4)}$$

$$\dot{m}_w = 1750 \frac{(146.66 - 62.98)}{(2345.35 - 191.81)}$$

$$\dot{m}_w = 68.00 \; [kg/s] \leftarrow$$

$T_1 < T_{sat}(P_1) \Rightarrow$ compressed liquid

$h_1 = h_f|_{15°C} = 62.98 \left(\frac{kJ}{kg}\right)$

$T_2 < T_{sat}(P_2) \Rightarrow$ compressed liquid

$h_2 = h_f|_{35°C} = 146.66$

Table B.1.1

$h_3 = (1 - x_3) h_f + x_3 h_g$

$h_f|_{10kPa} = 191.81 \left(\frac{kJ}{kg}\right)$

$h_g|_{10kPa} = 2584.63 \left(\frac{kJ}{kg}\right)$

Table B.1.2

$h_3 = (1 - 0.9)\, 191.81 + (0.9)\, 2584.63$

$h_3 = 2345.35 \left(\frac{kJ}{kg}\right)$

$h_4 = h_f|_{P_4} = 191.81 \left(\frac{kJ}{kg}\right)$

(b) First law for the steam turbine ($\Delta pe = 0$, $\Delta ke = 0$)

$$\dot{Q}_{cv} - \dot{W}_{T1} = \dot{m}_w (h_3 - h_7)$$

$$h_7 = h|_{10MPa,\ 550°C} = 3500.92 \left(\frac{kJ}{kg}\right)$$

Table B.1.3

$$\dot{W}_{T1} = -\dot{m}_w (h_3 - h_7)$$

$$\dot{W}_{T1} = -68.00(2345.35 - 3500.92)$$

$$\dot{W}_{T1} = 78579 \; [kW] = 78.579 \; [MW]$$

2-2/4

2 (c) Must first compute $\dot{m}_H$ in order to be able to do the gas turbine analysis.
First law for the heat exchanger ($\Delta pe = 0$, $\Delta ke = 0$)

$$\cancel{\dot{Q}_{cv}}^{\,0} - \cancel{\dot{W}_{cv}}^{\,0} = \Sigma(\dot{m}h)_{out} - \Sigma(\dot{m}h)_{in}$$

$$0 = \dot{m}_9 h_9 + \dot{m}_6 h_6 - \dot{m}_8 h_8 - \dot{m}_5 h_5$$

$$\dot{m}_9 = \dot{m}_8 = \dot{m}_H \qquad \dot{m}_6 = \dot{m}_5 = \dot{m}_W$$

$$0 = \dot{m}_H (h_9 - h_8) + \dot{m}_W (h_6 - h_5)$$

$$\dot{m}_H = \frac{\dot{m}_W (h_6 - h_5)}{(h_8 - h_9)}$$

$$h_6 = h_g\big|_{10\,MPa} = 2724.67 \left[\frac{kJ}{kg}\right]$$

Table B.1.2

Helium is an ideal gas:

$$\Delta h = C_{po} \Delta T$$

$$(h_8 - h_9) = C_{po} (T_8 - T_9)$$

$$C_{po} = 5.193 \left(\frac{kJ}{kg\,K}\right) \text{ for Helium (Table A.5)}$$

$$\dot{m}_H = \frac{\dot{m}_W (h_6 - h_5)}{C_{po}(T_8 - T_9)}$$

$$= \frac{68.00(2724.67 - 207.53)}{5.193(395 - 80)}$$

$$\dot{m}_H = 104.64 \, [kg/s]$$

$T_5 < T_{sat}(P_5) \Rightarrow$ compressed liquid

$P_5 > 500\,(kPa) \rightarrow$ use Table B.1.4

P = 10 000 kPa

T [°C]	h [kJ/kg]
40	176.36
47.5	h_5
60	259.47

$$h_5 = 176.36 + \frac{(47.5 - 40)}{(60 - 40)}(259.47 - 176.36)$$

$$h_5 = 207.53 \left[\frac{kJ}{kg}\right]$$

To get the net work from the gas turbine, the work input to the compressor is needed.

First Law for the compressor ($\Delta pe = 0$, $\Delta ke = 0$, $\dot{W}_c$ in)

$$\cancel{\dot{Q}_{cv}}^{\,0} + \dot{W}_c = \dot{m}_H (h_{10} - h_9) = \dot{m}_H C_{po} (T_{10} - T_9)$$

$$\dot{W}_c = (104.64)\, 5.193\, (407 - 80) = 177690 \,[kW] = 177.69 \,(MW)$$

2 (c) continued 2-3/4

First law for the gas turbine ($\Delta pe = 0$, $\Delta ke = 0$)

$$\cancel{\dot{Q}_{cv}}^{\,0} - \dot{W}_{T2,total} = \dot{m}_H (h_8 - h_{11}) = \dot{m}_H C_{po} (T_8 - T_{11})$$

$$\dot{W}_{T2,total} = -\dot{m}_H C_{po} (T_8 - T_{11}) = -(104.64)\,5.193\,(395 - 760)$$

$$\dot{W}_{T2,total} = 198,339 \text{ (kW)} = 198.34 \text{ (MW)}$$

$$\dot{W}_{T2,net} = \dot{W}_{T2,total} - \dot{W}_c = 198.34 - 177.69 = 20.65 \text{ [MW]} \leftarrow$$

(d) Thermal efficiency $= \eta_{th} = \dfrac{\text{Net work output}}{\text{Heat input}} = \dfrac{\dot{W}_{T1} + \dot{W}_{T2,net} - \dot{W}_p}{\dot{Q}_S + \dot{Q}_R}$

First law for the pump ($\Delta ke = 0$, $\Delta pe = 0$, $\dot{W}_p$ in)

$$\cancel{\dot{Q}_{cv}}^{\,0} + \dot{W}_p = \dot{m}_W (h_5 - h_4) = 68.00\,(207.53 - 191.81)$$

$$\dot{W}_p = 1069 \text{ [kW]} = 1.069 \text{ (MW)}$$

First law for the superheater ($\Delta pe = 0$, $\Delta ke = 0$)

$$\dot{Q}_S - \cancel{\dot{W}_{cv}}^{\,0} = \dot{m}_W (h_7 - h_6) = 68.00\,(3500.92 - 2724.67)$$

$$\dot{Q}_S = 52785 \text{ (kW)} = 52.785 \text{ (MW)}$$

First Law for the heater ($\Delta pe = 0$, $\Delta ke = 0$)

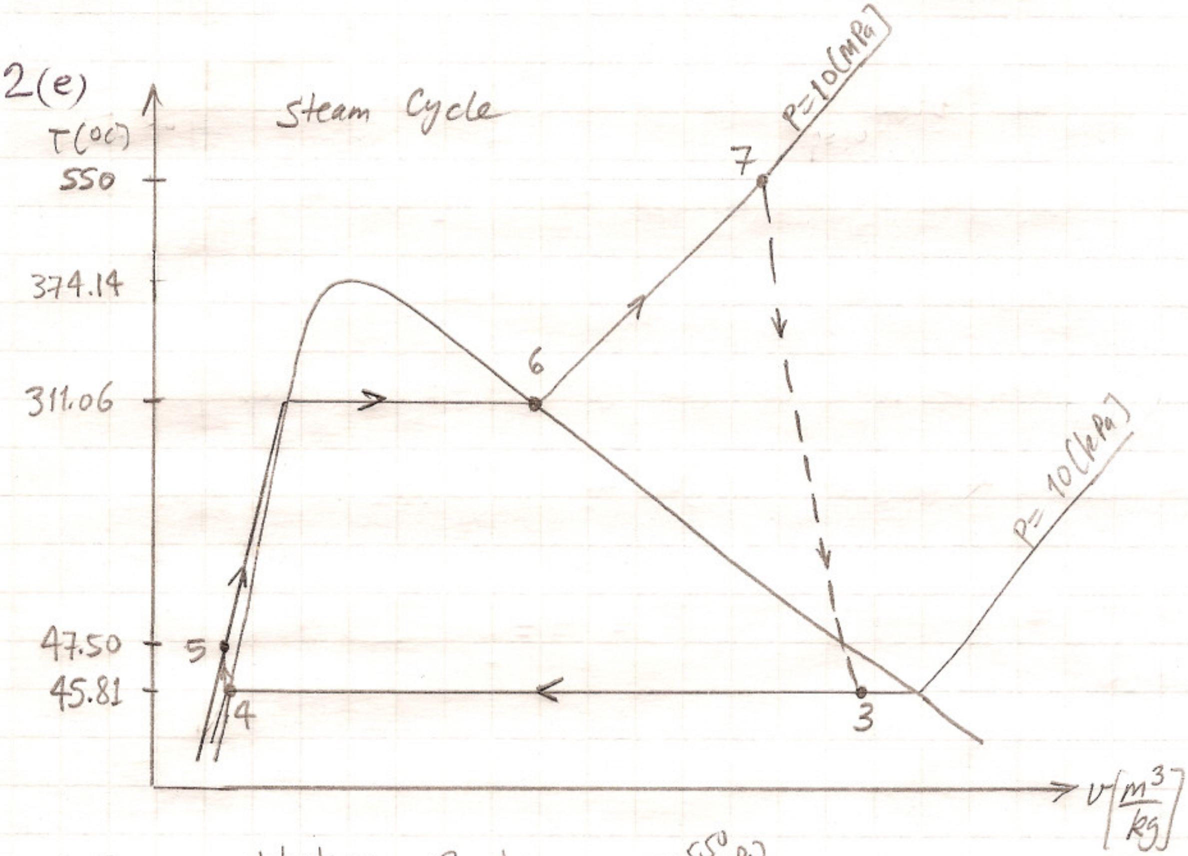
$$\dot{Q}_R - \cancel{\dot{W}_{cv}}^{\,0} = \dot{m}_H (h_{11} - h_{10}) = \dot{m}_H C_{po} (T_{11} - T_{10})$$

$$\dot{Q}_R = 104.64\,(5.193)\,(760 - 407) = 191819 \text{ (kW)} = 191.82 \text{ (MW)}$$

$$\eta_{th} = \frac{78.579 + 20.65 - 1.069}{52.785 + 191.82} = \frac{98.16}{244.61} = 0.401 = \underline{40.1\%}$$

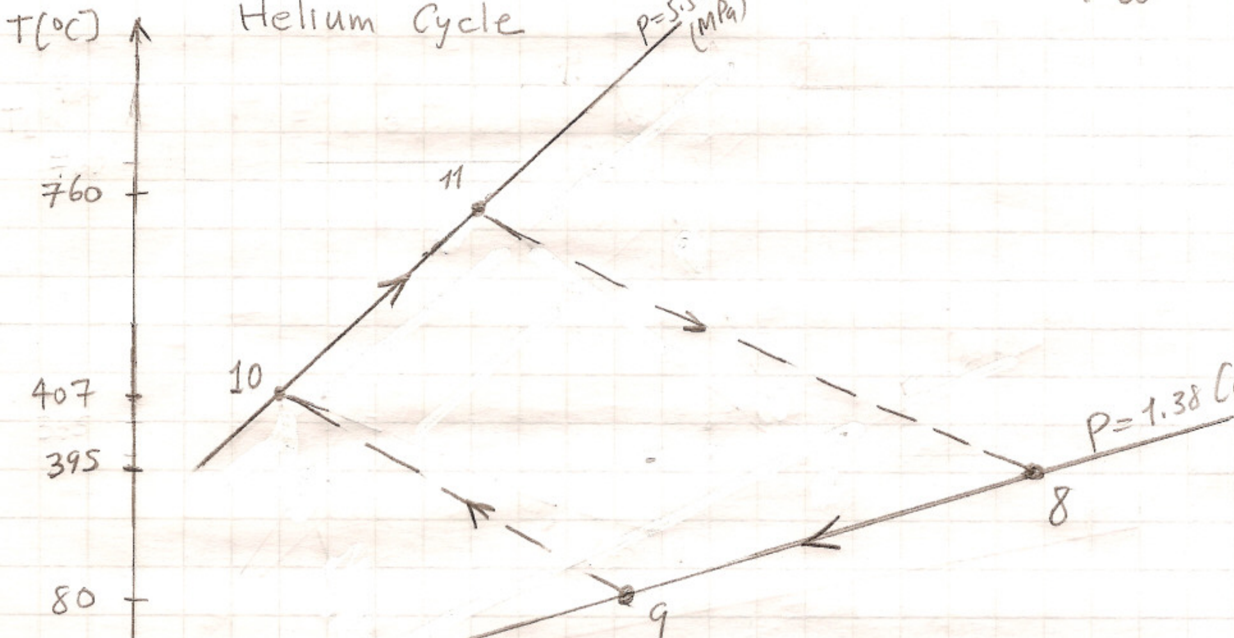
2-4/4

2(e)



Tsat (10[kPa]) = 45.81 (°C)

Tsat (10 [MPa]) = 311.06(°C)



$\boxed{\#3.}$ ideal gases, air & CO_2 Table A.5 $R_{air} = 0.287$ kJ/kg·K
$R_{CO_2} = 0.1889$ kJ/kg·K

Initial states:

air $m_{air} = 1.5$ kg $\quad PV = mRT$
$P_{air,1} = 500$ kPa $\quad \therefore V_{air,1} = \dfrac{1.5 \times 0.287 \times 350}{500} = 0.30135\ m^3$
$T_{air,1} = 350$ K

CO_2 $m_{CO_2} = 4$ kg
$P_{CO_2,1} = 200$ kPa $\quad \therefore V_{CO_2,1} = \dfrac{4 \times 0.1889 \times 478}{200} = 1.80588\ m^3$
$T_{CO_2,1} = 478$ K

Total volume in chamber $= V_{air,1} + V_{CO_2,1} = 0.30135 + 1.80588$
$$V_{tot} = 2.10723\ m^3$$

(a)

Final state corresponds to equilibrium, when $T_{air,2} = T_{CO_2,2}$
and $P_{air,2} = P_{CO_2,2}$

Apply First law to the whole chamber:

$$\cancel{{}_1Q_2} - \cancel{{}_1W_2} = U_2 - U_1 + \Delta \cancel{KE} + \Delta \cancel{PE}$$

insulated ↑ no boundary work: rigid container.

$$\therefore 0 = U_2 - U_1, \text{ i.e., } 0 = (m_{air} u_{air,2} + m_{CO_2} u_{CO_2,2}) - (m_{air} u_{air,1} + m_{CO_2} u_{CO_2,1})$$

$$\therefore 0 = m_{air}(u_{air,2} - u_{air,1}) + m_{CO_2}(u_{CO_2,2} - u_{CO_2,1})$$

(Total mass remains the same: $m_{air} + m_{CO_2} = m_{tot}$)

$$0 = m_{air} C_{v0,air}(T_2 - T_{air,1}) + m_{CO_2} C_{v0,CO_2}(T_2 - T_{CO_2,1})$$

Rearrange equation to isolate T_2:

Table A.5:
$C_{v0,air} = 0.717 \dfrac{kJ}{kg \cdot K}$
$C_{v0,CO_2} = 0.653 \dfrac{kJ}{kg \cdot K}$

$$T_2 = \frac{m_{air} C_{v0,air} T_{air,1} + m_{CO_2} C_{v0,CO_2} T_{CO_2,1}}{m_{air} C_{v0,air} + m_{CO_2} C_{v0,CO_2}}$$

$$T_2 = \frac{1.5 \times 0.717 \times 350 + 4 \times 0.653 \times 478}{1.5 \times 0.717 + 4 \times 0.653}$$

$$T_2 = 440.66\ [K]$$

#3 (b) Total volume, $V_{air} + V_{CO_2}$, remains conserved (constant) during process.

$$V_{air,2} = \frac{m_{air} R_{air} T_2}{P_{air,2}} \qquad V_{CO_2,2} = \frac{m_{CO_2} R_{CO_2} T_2}{P_{CO_2,2}}$$

Add equations:

$$V_{tot.} = \frac{m_{air} R_{air} T_2}{P_{air,2}} + \frac{m_{CO_2} R_{CO_2} T_2}{P_{CO_2,2}}$$

same

$$\therefore P_2 = \frac{(m_{air} R_{air} + m_{CO_2} R_{CO_2}) T_2}{V_{tot.}} = \frac{(1.5 \times 0.287 + 4 \times 0.1889) \times 440.66}{2.10723}$$

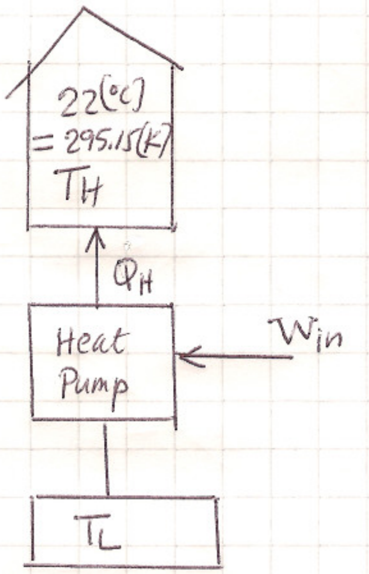
$P_2 = 248.03$ [kPa]

Not required:

$$V_{2,air} = \frac{1.5 \times 0.287 \times 440.66}{248.03} = 0.76483 \; [m^3] \qquad V_{2,CO_2} = \frac{4 \times 0.1889 \times 440.66}{248.03} = 1.3424 \; [m^3]$$

4-1/2

4. Heat Pump



Coefficient of performance for a heat pump

$$\beta' = \beta_{HP} = \frac{Q_H}{W_{in}} = \frac{Q_H}{Q_H - Q_L}$$

To find the maximum β_{HP} use a Carnot heat pump

$$\beta_{HP,rev} = \frac{T_H}{(T_H - T_L)}$$

$T_H = 295.15$ [K]

(a) $T_L = 0$ [°C] $= 273.15$ (K)

$$\beta_{HP,rev} = \frac{295.15}{295.15 - 273.15} = 13.42 \leftarrow$$

(b) $T_L = -20$ [°C] $= 253.15$ [K]

$$\beta_{HP,rev} = \frac{295.15}{295.15 - 253.15} = 7.03 \leftarrow$$

5-1/1

5. Cooling to room temperature first:

$$Q_{cool} = mc(T_{room} - T_{fridge})$$

Cooling directly from hot temperature:

$$Q_{hot} = mc(T_{hot} - T_{fridge})$$

Energy savings $\Delta Q = (Q_{hot} - Q_{cool})$

$$= mc(T_{hot} - T_{fridge}) - mc(T_{room} - T_{fridge})$$

$$\boxed{\Delta Q = mc(T_{hot} - T_{room})}$$

$$\Delta Q = 4.0\,(kg)\; 3.5\left[\frac{kJ}{kg\,K}\right](101 - 21) = 1120\,(kJ)$$ per time

ΔQ_{year} = ΔQ per time × Number of times per year

$$= 1120\,(156) = \underline{174\,720\,(kJ)}$$ per year

This is a savings in Q_L for the refrigerator.

Because $W_{in} = \frac{Q_L}{\beta}$ $\qquad \Delta W_{in} = \frac{\Delta Q_L}{\beta} = \frac{174720}{1.2}$

$\Delta W_{in} = 145\,600\,(kJ)$ per year saved in work input (ie, electrical power input to the refrigerator motor)

$$1\,(kWh) = 1\,\frac{kJ}{s} \cdot 3600\,s = 3600\,(kJ)$$

$$\frac{\text{Savings}}{\text{year}} = \frac{\Delta W_{in}}{\text{year}} \cdot \frac{\text{Cost}}{\text{unit energy}} = \frac{145\,600\,(kJ)}{\text{year}} \cdot \frac{0.10\,\$}{(kWh)} \cdot \frac{1\,(kWh)}{3600\,(kJ)}$$

$$\frac{\text{savings}}{\text{year}} = \underline{\underline{\$4.04}}$$