

Thermodynamic Dissection

MAE 2210 Final Project *Refrigeration Cycle for R-134a*

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December 2020

Question 1

State 1	State 2	State 3	State 4
$x = 1$ (sat. vapor) $P = 0.14$ MPa $T = -18.80$ C (table) $s = 0.9322$ kJ/kg.K $h = 236.04$ kJ/kg	$x =$ (superheated) $P = 1.2$ MPa <u>Calculated in Question 4:</u> $T = 57.657$ C $s = 0.9442$ kJ/kg.k $h = 284.647$ kJ/kg <u>Calculated in Question 4:</u> $T_{\text{ideal}} = 54.3526$ C $s_{\text{ideal}} = 0.9322$ kJ/kg.K $h_{\text{ideal}} = 280.758$ kJ/kg	$x = 0$ (sat. liquid) $P = 1.2$ MPa $T = 46.32$ C (table) $s = 0.4164$ kJ/kg.K $h = 115.76$ kJ/kg <u>Calculated in Question 5:</u> $T_R = 54.3526$ $s_{3,R} = 0.45437$ kJ/kg.K $h_{3,R} = 128.3148$ kJ/kg	$x =$ (2-phase) $P = 0.14$ MPa $T = -18.80$ C (table) <u>Calculated in Question 5:</u> $T_{\text{ideal}} = -18.80$ C $s_R = 0.45437$ kJ/kg.K $h_R = 114.5039$ kJ/kg

Calculated in Question 4:

$\dot{Q}_L = 12.028$ kJ	$\dot{Q}_H = -16.889$ kJ	$\dot{W}_{12} = 4.861$ kJ
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Energy Balance Equations (everything is in steady state, no KE or PE terms anywhere)

State 1 \rightarrow 2

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + KE_{terms} + PE_{terms}, \dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$$

Apply steady state and no KE/PE terms

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}, \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

Apply adiabatic

$$0 = \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

$$\dot{W}_{cv} = \dot{m}(h_{out} - h_{in})$$

$$\dot{W}_{12} = \dot{m}(h_2 - h_1)$$

State 2 → 3

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + KE_{terms} + PE_{terms}, \dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$$

Apply steady state and no KE/PE terms

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}, \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

Apply "no work"

$$0 = \dot{Q}_{cv} + \dot{m}(h_{in} - h_{out})$$

$$\dot{Q}_{cv} = \dot{m}(h_{out} - h_{in})$$

$$\dot{Q}_H = \dot{m}(h_3 - h_2)$$

State 3 → 4

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + KE_{terms} + PE_{terms}, \dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$$

Apply steady state and no KE/PE terms

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}, \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

Apply adiabatic

$$0 = \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

$$\dot{W}_{cv} = \dot{m}(h_{out} - h_{in})$$

Apply "no work"

$$0 = \dot{m}(h_{out} - h_{in})$$

$$h_3 = h_4$$

State 4 → 1

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + KE_{terms} + PE_{terms}, \dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$$

Apply steady state and no KE/PE terms

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}, \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

Apply "no work"

$$0 = \dot{Q}_{cv} + \dot{m}(h_{in} - h_{out})$$

$$\dot{Q}_{cv} = \dot{m}(h_{out} - h_{in})$$

$$\dot{Q}_L = \dot{m}(h_1 - h_4)$$

Description of Cycle:

The R-134a is in State 1. It is in the saturated vapor state at the minimum pressure of 0.14 MPa and is also therefore at -18.80°C , which is the corresponding saturated temperature at 0.14 MPa. This vapor travels towards the compressor where it gains energy from the in the form of electrical work which actuates the piston, making the temperature R-134a increase to a value that is hotter than the temperature of the warm outside environment.

The R-134a is in State 2 now. The only known properties of the R-134a is that it is at the maximum possible pressure (1.2 MPa) and in a superheated vapor state. This vapor travels to the condenser where the R-134a is at a higher temperature than the warm outside environment and therefore loses energy in the form of heat to the outside environment, removing it from the system. This happens as empirically observed by the Clausius Statement because heat only travels naturally from the hotter reservoir to the colder reservoir. This process also happens at constant pressure and is therefore modelled as isobaric.

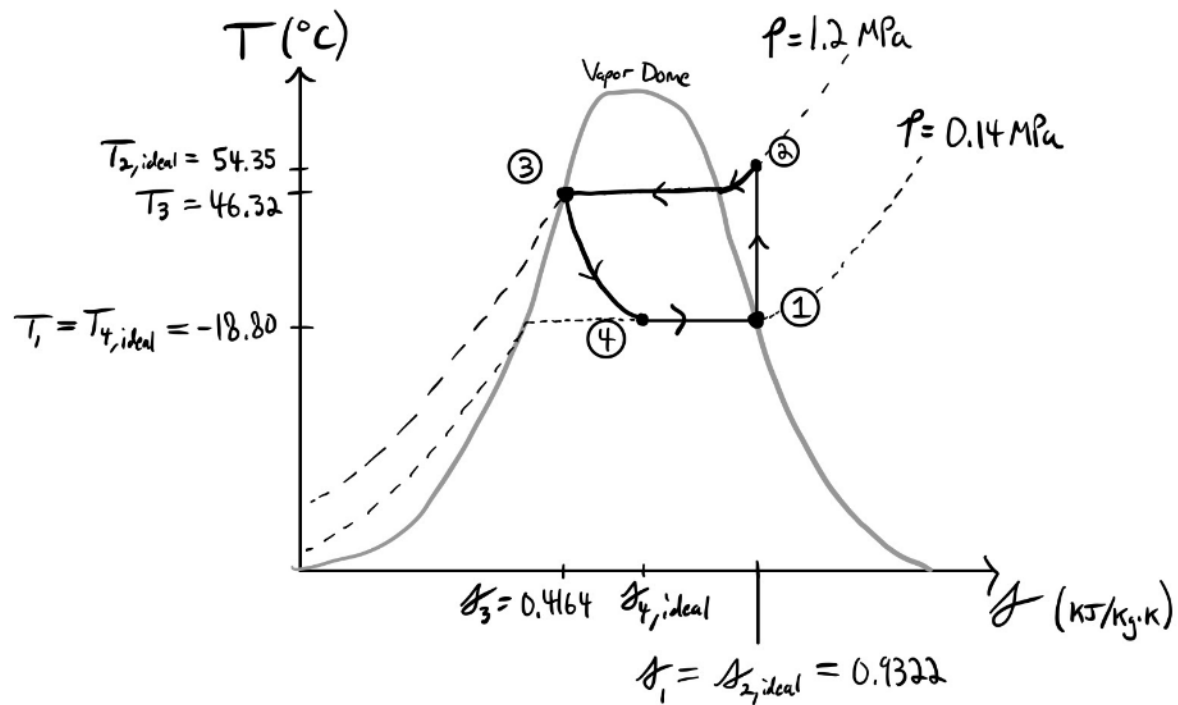
The R-134a is in State 3 now. It is in the saturated liquid state at the maximum pressure of 1.2 MPa and is also therefore at 46.32°C , which is the corresponding saturated temperature at 1.2 MPa, just slightly cooler than the temperature of State 2. This liquid travels towards the expansion valve where the R-134a is able to expand without heat or work transfers. Therefore, there is no change in specific enthalpy. This expansion of the R-134a—corresponding to a drop in pressure as well—allows it to cool down to a temperature that is lower than the temperature inside the cold refrigerated space (inside the fridge).

The R-134a is in State 4 now. The only known property of the R-134a is that it is in the two-phase mixture state. The R-134a enters into the evaporator and comes out at a temperature of -18.80°C corresponding to property tables for the minimum possible pressure (0.14 MPa). The temperature that the R-134a entered the evaporator with is much lower than that of the fridge's contents, therefore heat is transferred from the inside of the fridge and into the evaporator in accordance with the Clausius statement. This causes the R-134a to isothermally change phase from two-phase to saturated vapor.

The R-134a is at State 1 now and the cycle repeats.

Question 2

The expansion valve CANNOT be ideal (free expansion of gas)



State 1 \rightarrow State 2

No heat exchanges, work is being added to working fluid from surroundings

State 2 \rightarrow State 3

Heat is being added to the surroundings from the working fluid, no work exchanges

State 3 \rightarrow State 4

No heat exchanges, no work exchanges

State 4 \rightarrow State 1

Heat is being added to the working fluid from the surroundings, no work exchanges

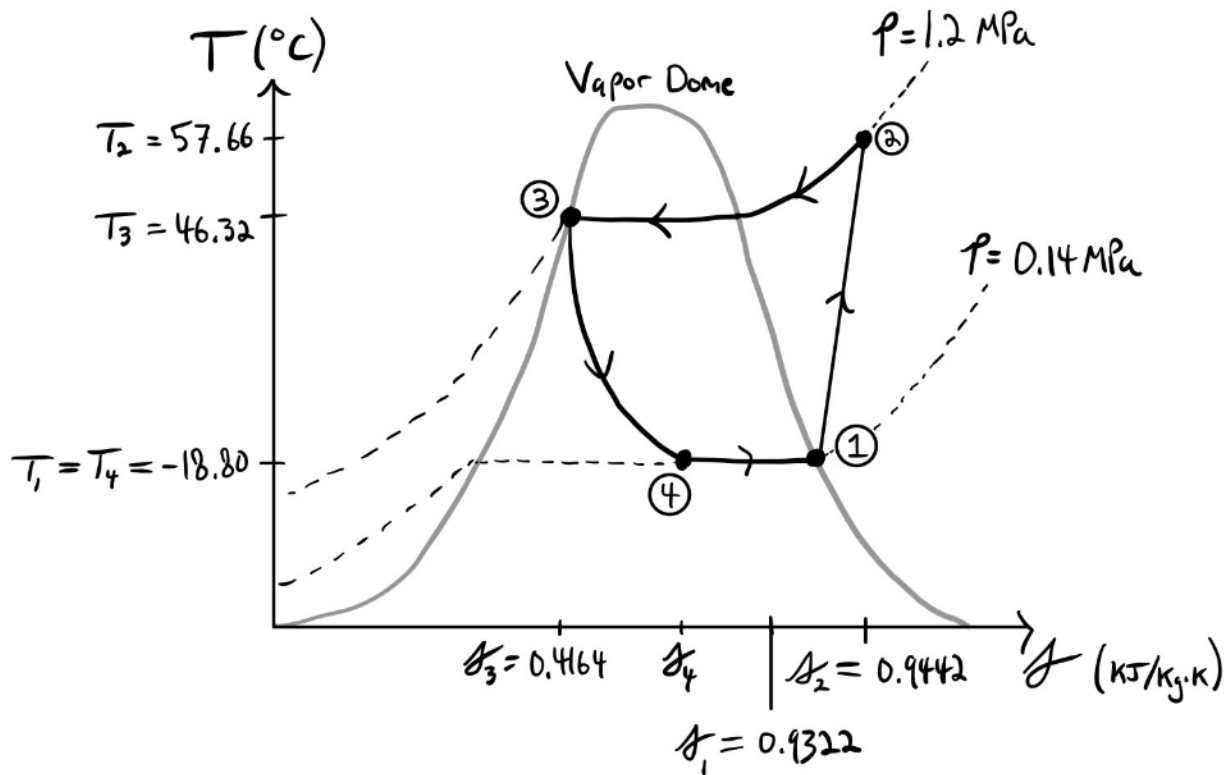
Question 3

Entropy Balance Equations (everything is in steady state, now it is non-ideal)

State 1 → 2

$$\frac{dS}{dt} = \dot{Q} + \dot{\sigma} + \dot{m}(s_{in} - s_{out})$$

$$\dot{\sigma} = \dot{m}(s_{out} - s_{in}) \quad \dot{\sigma} > 0 \text{ for non-ideal devices, so } s_{out} > s_{in} \text{ and so entropy goes up}$$



The compressor would no longer be isentropic, therefore entropy would increase and the T-s diagram from 1→2 is no longer vertical.

Question 4

Assume that the valve is still ideal, but the compressor has an isentropic efficiency of 92%.
What is the power required to run this cycle? How much heat is extracted from the cold space?

$$\begin{aligned}\Delta U &= \dot{Q}_{12} + \dot{Q}_H + \dot{Q}_L + \dot{Q}_{41} + \dot{W}_{12} + \dot{W}_{23} + \dot{W}_{34} + \dot{W}_{41} \\ 0 &= \dot{Q}_H + \dot{Q}_L + \dot{W}_{12} \\ \dot{W}_{12} &= -\dot{Q}_H - \dot{Q}_{L_i}\end{aligned}$$

$$s_1 = s_{2, ideal} \rightarrow s_g |_{P=1.2 \text{ MPa}} < s_{2, ideal} \rightarrow \text{state 2 is superheated vapor}$$

Interpolate between $T = 50 \text{ C}$ & $T = 60 \text{ C}$ to find T where $s_1 = s_{2, ideal}$ in superheated vapor table:

$s \text{ (kJ/kg.K)}$	$T \text{ (}^\circ\text{C)}$
$s_1 = 0.9164$	$T_1 = 50$
$s_{2, ideal} = 0.9322$	$T_{2, ideal}$
$s_{11} = 0.9527$	$T_{11} = 60$

$$\begin{aligned}T_{2, ideal} &= T_1 + (s_{2, ideal} - s_1)(T_{11} - T_1) / (s_{11} - s_1) \\ &= 50 + (0.9322 - 0.9164)(60 - 50) / (0.9527 - 0.9164)\end{aligned}$$

$$T_{2, ideal} = 54.3526 \text{ C}$$

Interpolation to find h_2 (ideal):

$s \text{ (kJ/kg.K)}$	$h \text{ (kJ/kg)}$
$s_1 = 0.9164$	$h_1 = 275.52$
$s_{2, ideal} = 0.9322$	$h_{2, ideal}$
$s_{11} = 0.9527$	$h_{11} = 287.44$

$$\begin{aligned}h_2(ideal) &= h_1 + (h_{11} - h_1 / s_{11} - s_1)(s_{2, ideal} - s_1) \\ &= 275.52 + (287.44 - 275.52 / 0.9527 - 0.9164) * (0.9322 - 0.9164) \\ h_2(ideal) &= 280.758 \text{ kJ/kg}\end{aligned}$$

Using the isentropic efficiency we can now solve for the real h_2 value:

$$\begin{aligned}0.92 &= \frac{W/m(ideal)}{W/m(real)} = \frac{h_2 - h_1(ideal)}{h_2 - h_1(real)} = \frac{280.758 - 236.04}{h_2 - 236.04} \\ h_{2(real)} &= 284.647 \text{ kJ/kg}\end{aligned}$$

Interpolate using h_2 to find T_2

h (kJ/kg)	T (°C)
$h_1 = 275.52$	$T_1 = 50$
$h_2 = 284.647$	T_2
$h_{11} = 287.44$	$T_{11} = 60$

$$T_2 = T_1 + (h_2 - h_1)(T_{11} - T_1) / (h_{11} - h_1)$$

$$= 50 + (284.647 - 275.52)(60 - 50) / (287.44 - 275.52)$$

$$T_2 = 57.65687 \text{ } ^\circ\text{C}$$

Interpolate again to find s_2

h (kJ/kg)	s (kJ/kg.K)
$h_1 = 275.52$	$s_1 = 0.9164$
$h_2 = 284.647$	s_2
$h_{11} = 287.44$	$s_{11} = 0.9527$

$$s_2 = s_1 + (h_2 - h_1)(s_{11} - s_1) / (h_{11} - h_1)$$

$$= 0.9164 + (284.647 - 275.52)(0.9527 - 0.9164) / (287.44 - 275.52)$$

$$s_2 = 0.94419 \text{ kJ/kg.k}$$

State 1 \rightarrow 2

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + KE_{terms} + PE_{terms}, \quad \dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$$

Apply steady state and no KE/PE terms

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}, \quad \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

Apply adiabatic

$$0 = \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

$$\dot{W}_{cv} = \dot{m}(h_{out} - h_{in})$$

$$\dot{W}_{12} = \dot{m}(h_2 - h_1)$$

$$\dot{W}_{12} = 0.1 \text{ kg/s} (284.647 \text{ kJ/kg} - 236.04 \text{ kJ/kg})$$

$$\dot{W}_{12} = 4.861 \text{ kJ/s} \quad (\text{Power Required to run cycle})$$

State 2 → 3

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + KE_{terms} + PE_{terms}, \dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$$

Apply steady state and no KE/PE terms

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}, \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

Apply "no work"

$$0 = \dot{Q}_{cv} + \dot{m}(h_{in} - h_{out})$$

$$\dot{Q}_{cv} = \dot{m}(h_{out} - h_{in})$$

$$\dot{Q}_H = \dot{m}(h_3 - h_2) \quad \dot{m} = 0.1 \text{ kg/s}$$

$$\dot{Q}_H = 0.1 \text{ kg/s}(115.76 \text{ kJ/kg} - 284.64 \text{ kJ/kg})$$

$$\dot{Q}_H = -16.889 \text{ kJ/s (Heat extracted from refrigerant)}$$

State 4 → 1

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + KE_{terms} + PE_{terms}, \dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$$

Apply steady state and no KE/PE terms

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}, \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

Apply "no work"

$$0 = \dot{Q}_{cv} + \dot{m}(h_{in} - h_{out})$$

$$\dot{Q}_{cv} = \dot{m}(h_{out} - h_{in})$$

$$\dot{Q}_L = \dot{m}(h_1 - h_{4, ideal})$$

$$\dot{Q}_L = 0.1 \text{ kg/s}(236.04 \text{ kJ/kg} - 115.76 \text{ kJ/kg})$$

$$\dot{Q}_L = 12.028 \text{ kJ/s (Heat extracted from cold space)}$$

To check our answers using the First Law:

$$\Delta U = Q_{12} + Q_H + Q_L + Q_{41} + W_{23} + W_{34} + W_{41}$$

$$0 = Q_H + Q_L + W_{12}$$

$$0 = -16.889 \text{ kJ} + 12.028 \text{ kJ} + 4.861 \text{ kJ}$$

$$0 \simeq 0$$

Question 5

$$\beta = \frac{\dot{Q}_L}{|\dot{Q}_H| - |\dot{Q}_L|} = \frac{12.028 \text{ kJ/s}}{16.889 \text{ kJ/s} - 12.028 \text{ kJ/s}} \quad \beta = 2.4744$$

For a fully reversible cycle, all values are the same as the ideal case in (2) except the valve is now isentropic and the condenser is isothermal. This is because in (2) we already assumed all devices were internally reversible except for the expansion valve, therefore the carnot cycle will be mostly the same values except we must now calculate state 4 using the internally reversible case and state 3 using the isothermal case:

Entropy Balance

$$\frac{dS}{dt} = \frac{\dot{Q}}{T} + \dot{\sigma} + \dot{m}(s_{in} - s_{out})$$

Apply adiabatic & steady state

$$0 = \dot{\sigma} + \dot{m}(s_{in} - s_{out})$$

Apply fully reversible

$$0 = \dot{m}(s_{in} - s_{out})$$

$$s_{in} = s_{out}$$

$$s_{3,R} = s_{4,R}$$

Process 2 → 3 is now isothermal therefore $T_{3,R} = T_{2,ideal}$ using the state 2 temperature from Question (4)

$$s_{3,R} = s_f |_{T=54.3526 \text{ C}}$$

Now we interpolate in order to find the value of s_f for this temperature:

T (°C)	s (kJ/kg.K)
$T_l = 52$	$s_l = 0.4432$
$T_{2,ideal} = 54.3526$	s_f
$T_{ll} = 56$	$s_{ll} = 0.4622$

$$s_f = s_l + (T_{2,ideal} - T_l)(s_{ll} - s_l) / (T_{ll} - T_l)$$

$$s_f = 0.4432 + (54.3526 - 52)(0.4622 - 0.4432) / (56 - 52)$$

$$s_{3,R} = 0.45437 \text{ kJ/kg.K}$$

We interpolate once more to find $h_{3,R}$ for this temperature:

T ($^{\circ}\text{C}$)	s (kJ/kg.K)
$T_1 = 52$	$h_1 = 124.58$
$T_{2, ideal} = 54.3526$	h_f
$T_{11} = 56$	$h_{11} = 130.93$

$$h_f = h_1 + (T_{2, ideal} - T_1)(h_{11} - h_1) / (T_{11} - T_1)$$

$$h_f = 124.58 + (54.3526 - 52)(130.93 - 124.58) / (56 - 52)$$

$$h_{3,R} = 128.3148 \text{ kJ/kg}$$

We can now find the quality of state 4 using $s_{4,R}$ since it must be at the same pressure as state 1, which is unchanged:

$$x = \frac{s_{4,R} - s_f}{s_g - s_f} = \frac{0.45437 \text{ kJ/kg}\cdot\text{K} - 0.1055 \text{ kJ/kg}\cdot\text{K}}{0.9322 \text{ kJ/kg}\cdot\text{K} - 0.1055 \text{ kJ/kg}\cdot\text{K}}$$

$$x = 0.4220$$

$$h_{4,R} = (1 - x)h_f + xh_g = (1 - 0.4220)(25.77 \text{ kJ/kg}) + (0.4220)(236.04 \text{ kJ/kg})$$

$$h_{4,R} = 114.50394 \text{ kJ/kg}$$

$$\dot{Q}_{L,R} = \dot{m}(h_1 - h_{4,R})$$

$$\dot{Q}_{L,R} = 0.1 \text{ kg/s} (236.04 \text{ kJ/kg} - 114.50394 \text{ kJ/kg})$$

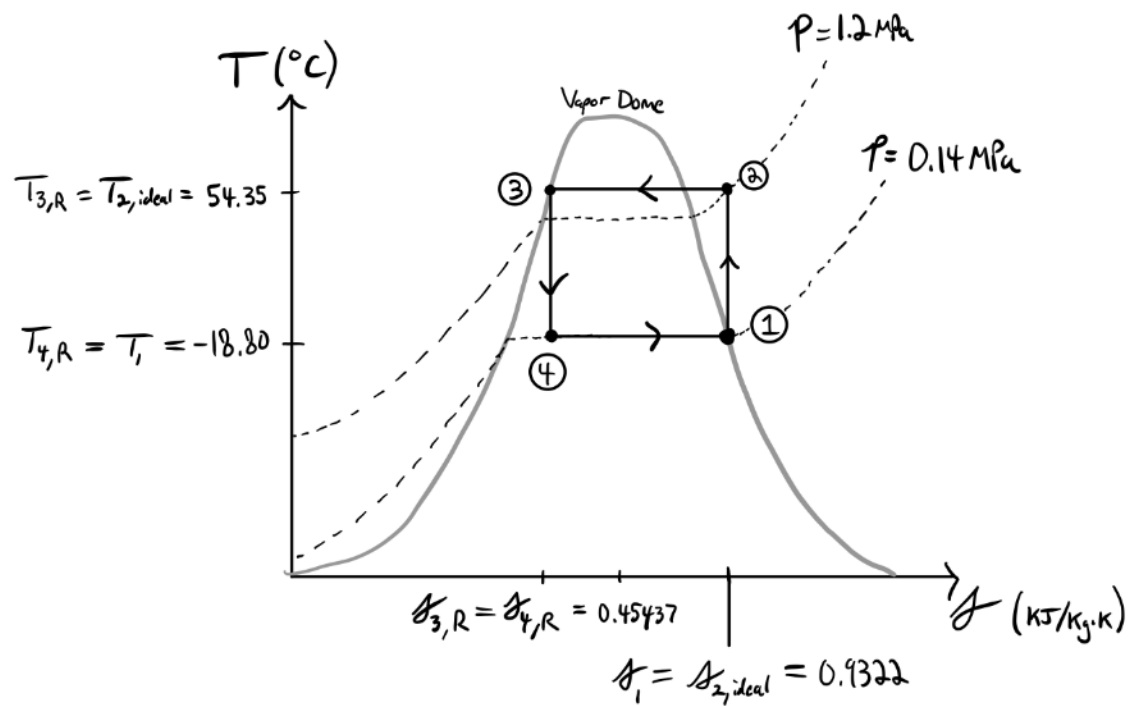
$$\dot{Q}_{L,R} = 12.1536 \text{ kJ/s}$$

$$\dot{Q}_{H,R} = \dot{m}(h_{3,R} - h_{2, ideal})$$

$$\dot{Q}_{H,R} = 0.1 \text{ kg/s} (128.3148 \text{ kJ/kg} - 280.758 \text{ kJ/kg})$$

$$\dot{Q}_{H,R} = -15.24432 \text{ kJ/s}$$

$$\beta_R = \frac{\dot{Q}_{L,R}}{|\dot{Q}_{H,R}| - |\dot{Q}_{L,R}|} = \frac{12.1536 \text{ kJ/s}}{15.24432 \text{ kJ/s} - 12.1536 \text{ kJ/s}} \quad \beta_R = 3.93229$$



The difficulty of reproducing the Carnot cycle is that the expansion valve allows for free expansion of gas, which necessitates internal irreversibilities to occur spontaneously. While the process can be compressed via work to bring the system back to its initial state, the surroundings would have to be permanently altered via the gas expelling heat energy (and therefore entropy) into the surroundings by the 1st law; therefore it is fundamentally an irreversible process. In reality, the Carnot cycle for this expansion valve has a zero probability of occurring in nature because of this requirement, which is a pretty tough practical difficulty to get around.

Question 6

All state properties for States 1, 2, and 3 stay the same since their derivations do not involve the device properties in between States 3 and 4 and the pressure ratio across the device is the same, thus our known pressures are also the same. Additionally, \dot{W}_{12} and \dot{Q}_H remain unchanged for the same reasons.

Entropy Balance

$$\frac{dS}{dt} = \frac{\dot{Q}}{T} + \dot{\sigma} + \dot{m}(s_{in} - s_{out})$$

Apply Steady State and adiabatic:

$$0 = 0 + \dot{\sigma} + \dot{m}(s_{in} - s_{out})$$

Because an ideal turbine will have zero irreversibilities:

$$0 = \dot{m}(s_{in} - s_{out})$$

$$s_{in} = s_{out}$$

$$s_{4, ideal} = s_3 = 0.4164 \text{ kJ/kg}\cdot\text{K}$$

We can now solve for the quality of the ideal state 4 using the pressure of $P = 0.14 \text{ MPa}$:

$$x = \frac{s_{4, ideal} - s_f}{s_g - s_f} = \frac{0.4164 \text{ kJ/kg}\cdot\text{K} - 0.1055 \text{ kJ/kg}\cdot\text{K}}{0.9322 \text{ kJ/kg}\cdot\text{K} - 0.1055 \text{ kJ/kg}\cdot\text{K}}$$

$$x = 0.3761$$

$$h_{4, ideal} = (1 - x)h_f + xh_g = (1 - 0.3761)(25.77 \text{ kJ/kg}) + (0.3761)(236.04 \text{ kJ/kg})$$

$$h_{4, ideal} = 104.85 \text{ kJ/kg}$$

State 3 → 4

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + KE_{terms} + PE_{terms}, \dot{m}_{net} = \dot{m}_{in} - \dot{m}_{out}$$

Apply steady state and no KE/PE terms

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out}, \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

$$0 = \dot{Q}_{cv} + \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

Apply adiabatic

$$0 = \dot{W}_{cv} + \dot{m}(h_{in} - h_{out})$$

$$\dot{W}_{cv} = \dot{m}(h_{out} - h_{in})$$

$$\dot{W}_{34} = \dot{m}(h_{4, ideal} - h_3)$$

$$\dot{W}_{34} = 0.1 \text{ kg/s} (104.85 \text{ kJ/kg} - 115.76 \text{ kJ/kg})$$

$$\dot{W}_{34} = -1.091 \text{ kJ/s} \text{ (Work extracted from refrigerant fluid by the turbine)}$$

Using the same equation derived in (4), and plugging in our new value for $h_{4, \text{ideal}}$ we get a new value for the heat extracted from the cold space:

$$\dot{Q}_L = \dot{m} (h_1 - h_{4, \text{ideal}})$$

$$\dot{Q}_L = 0.1 \text{ kg/s} (236.04 \text{ kJ/kg} - 104.85 \text{ kJ/kg})$$

$$\dot{Q}_L = 13.12 \text{ kJ/s}$$

Originally without the turbine $\dot{Q}_L = 12.028 \text{ kJ/s}$ therefore more heat is now being extracted from the cold space, by approximately the same amount of energy that is extracted as work by the turbine such that the 1st law for the entire cycle is still obeyed.