CAE 208 Thermal-Fluids Engineering I
MMAE 320: Thermodynamics

Fall 2022

December 1, 2022

Power and refrigeration cycles (II)

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ANNOUNCEMENTS

Announcements

- Assignment 9 (the extra assignment) is due tonight

- The final exam is
  - December 6, 10:30– 12:30, PS 152
  - Follow the instructions about the exam
  - https://www.iit.edu/sites/default/files/2022-11/final_exam_schedule_2.pdf

Announcements

- The final exam:
  - ❑ Open book and open notes. You can use your notes (hard copy or electronic), class lecture notes (hard copy or electronic), and only the course book (hard copy or electronic). No additional items are allowed
  - ❑ I will not provide any handouts for equations or tables, and it is your responsibility to have them for the final exam
  - ❑ You can use your electronic device (e.g., your iPad or laptop). If you plan to use any electronic device, the internet access should be disabled. Violation of these policies will lead to the violation of the exam instructions and the violation of the IIT Academic Honesty Guideline

Announcements

- The final exam structure
  - ❑ It is similar to the two midterms
  - ❑ 65% short questions (22 to 28 short questions and will cover all the materials)
  - ❑ 35% problems (3 problems with 1 problem from Chapter 9, 1 problem from Chapter 6, and one problem from the earlier topics)
  - ❑ Make sure to be concise and precise

Announcements

- If you are interested

ILLINOIS TECH | Armour College of Engineering

Request for Proposals

Armour R&D

Armour College of Engineering is pleased to announce the Spring 2023 request for Armour R&D project proposals. The Spring 2023 Armour R&D program will run from February 6, 2023 through April 28, 2023.

Armour R&D provides opportunities for engineering students to perform hands-on, mentored research and development in faculty laboratories. Students selected for the program receive a stipend during the semester.

How the program works

In order to participate in Armour R&D, students must complete an application, which includes details on the proposed research or development projectin coordination with a faculty mentor. Students are selected for the program based on the quality of their submitted proposal. Under the guidance of their faculty mentor, students work on their semester project for ten weeks while receiving a stipend. Upon completing their semester-long project, students will be required to submit a report by the end of the semester and showcase their research through a poster presentation by participating in the Annual Armour R&D Expo in the fall of 2023.

Applications are due December 22, 2023 at 5 PM

Application Process

1. Please review specific application requirements prior to starting your application.
2. Complete your application in coordination with your faculty mentor.
3. Submit your application no later than **December 22, 2022 at 5 PM CDT**. Late applications are not accepted.

RECAP

Recap

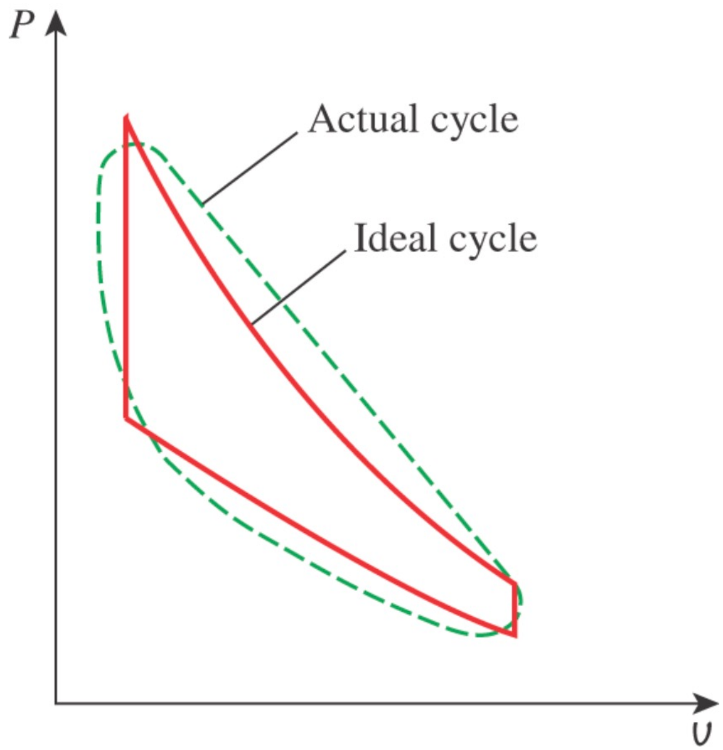
- Two important applications for thermodynamics are:
  - ❑ Power generation
  - ❑ Refrigeration

- Remember to produce work we need a cycle:
  - ❑ Power cycles for heat engines
  - ❑ Refrigeration cycles for refrigerators, heat pumps, air conditioners

- Depending on the working fluid and its phases we can call them:
  - ❑ Gas cycles
  - ❑ Vapor cycles

Recap

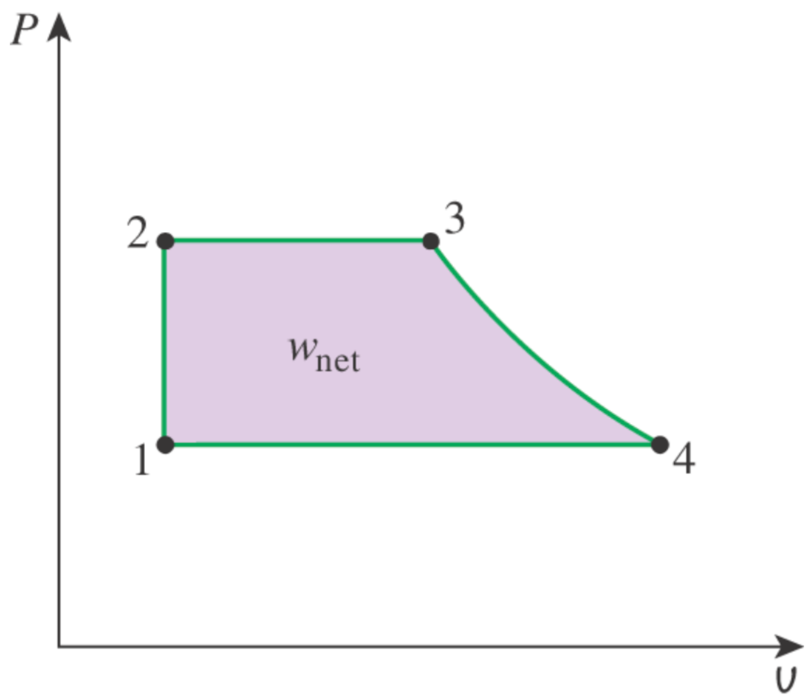
- We resemble most of actual cycles with internal irreversibilities and complexities with internal reversible cycles known as ideal cycles

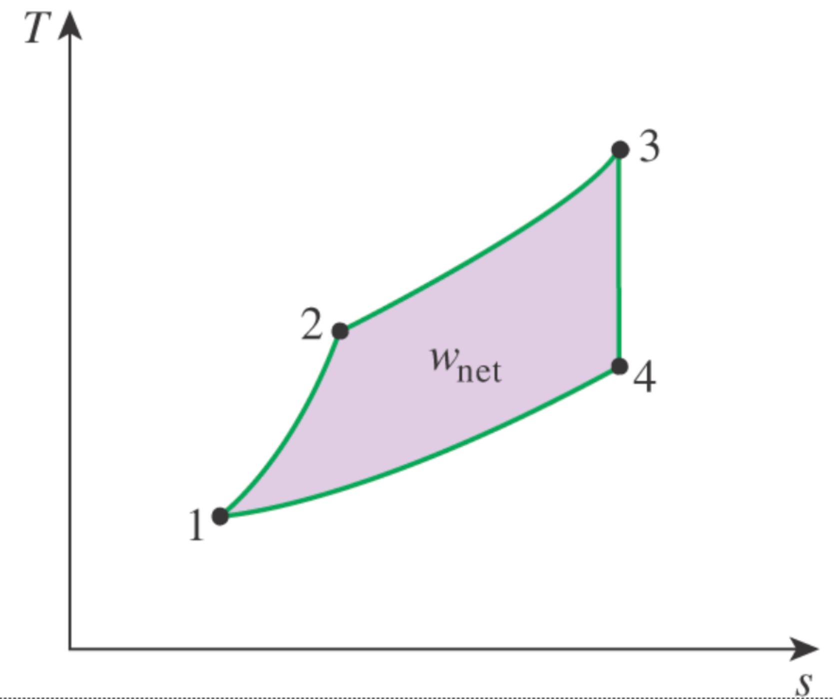


$$\eta_{thermal} = \frac{desired\ output}{Input}$$

Recap

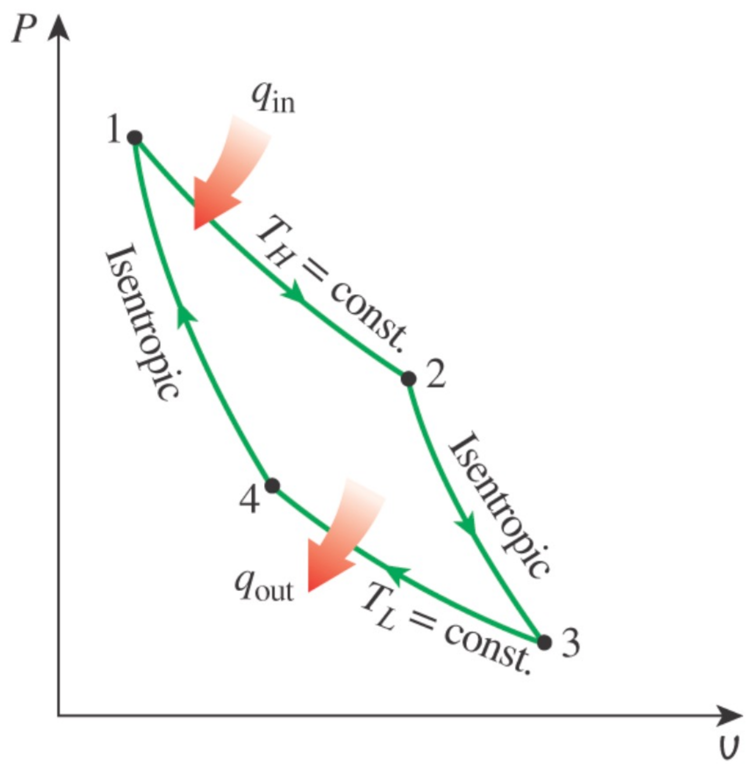
- Property diagrams such as T-s and P-V diagrams can serve as valuable aids in understanding and analysis of thermodynamics process:

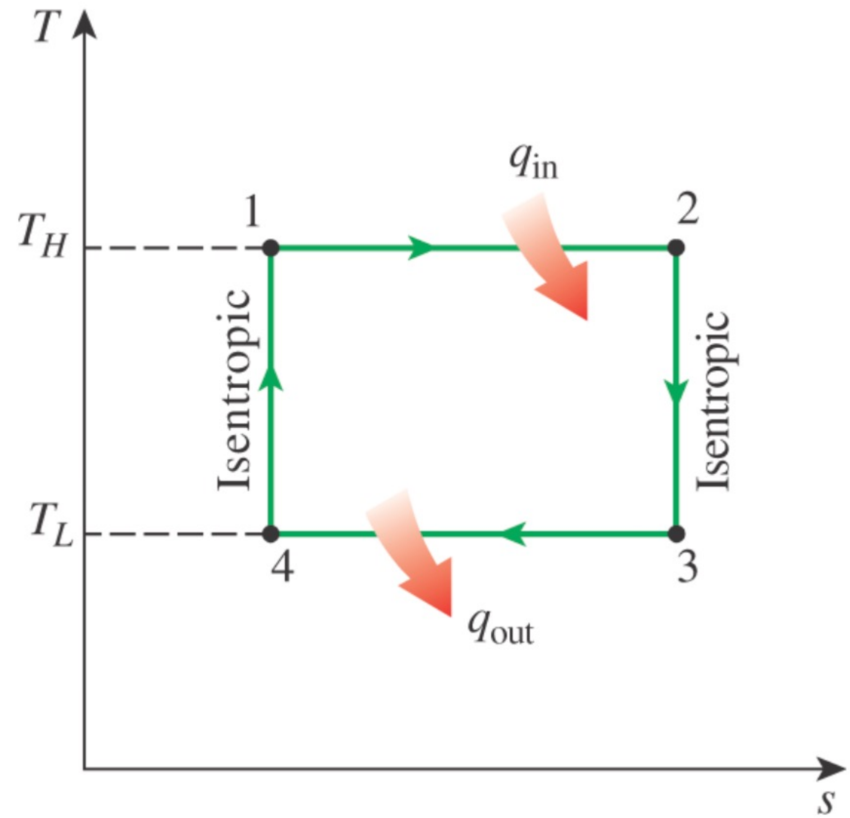




Recap

- Property diagrams such as T-s and P-V diagrams can serve as valuable aids in understanding and analysis of thermodynamics process:

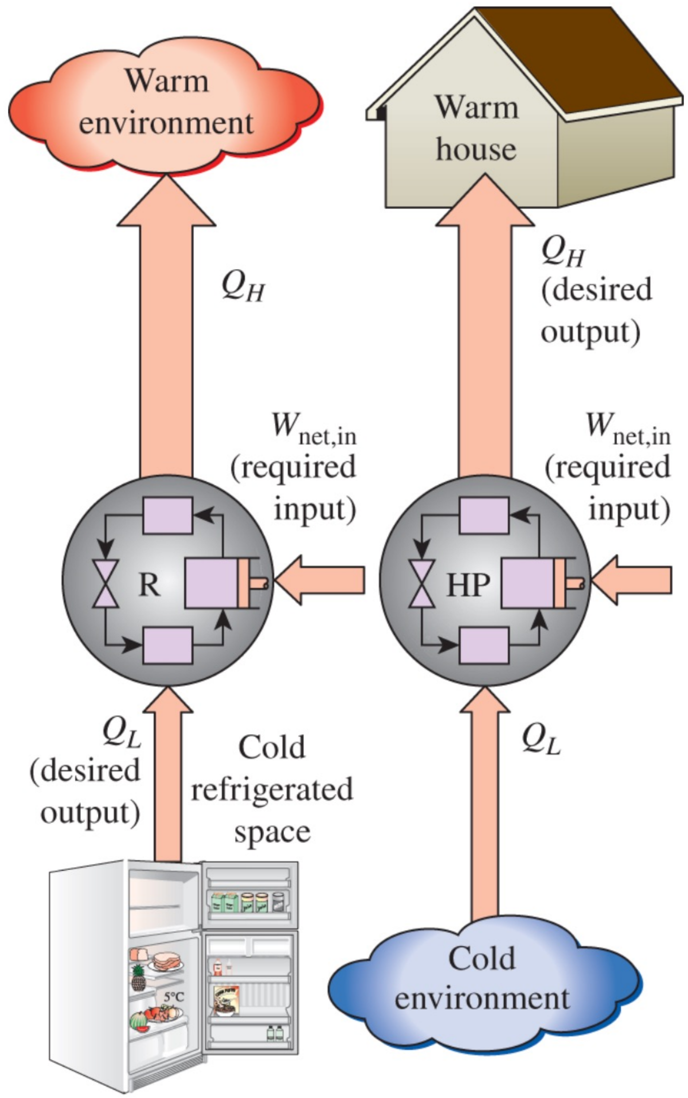




REFRIGERATORS AND HEAT PUMPS (SECTION 9-14 AND 9-15)

Refrigerators and Heat Pumps

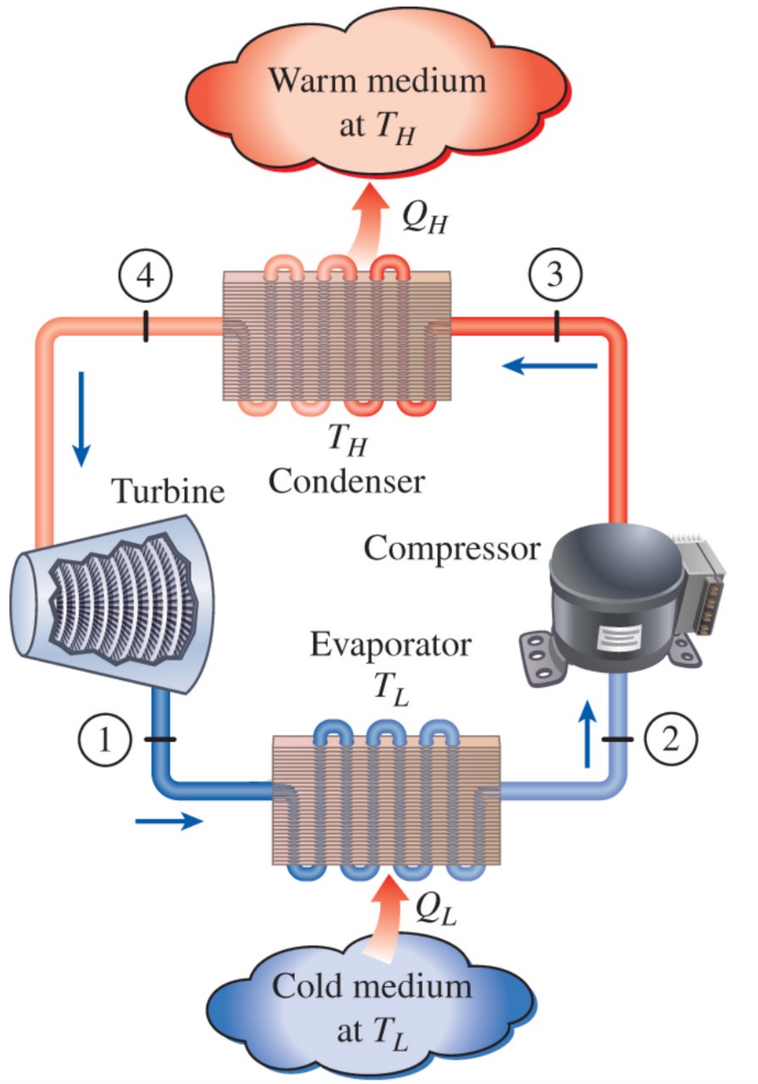
- We looked at this in Chapter 7



(*a*) Refrigerator (*b*) Heat pump

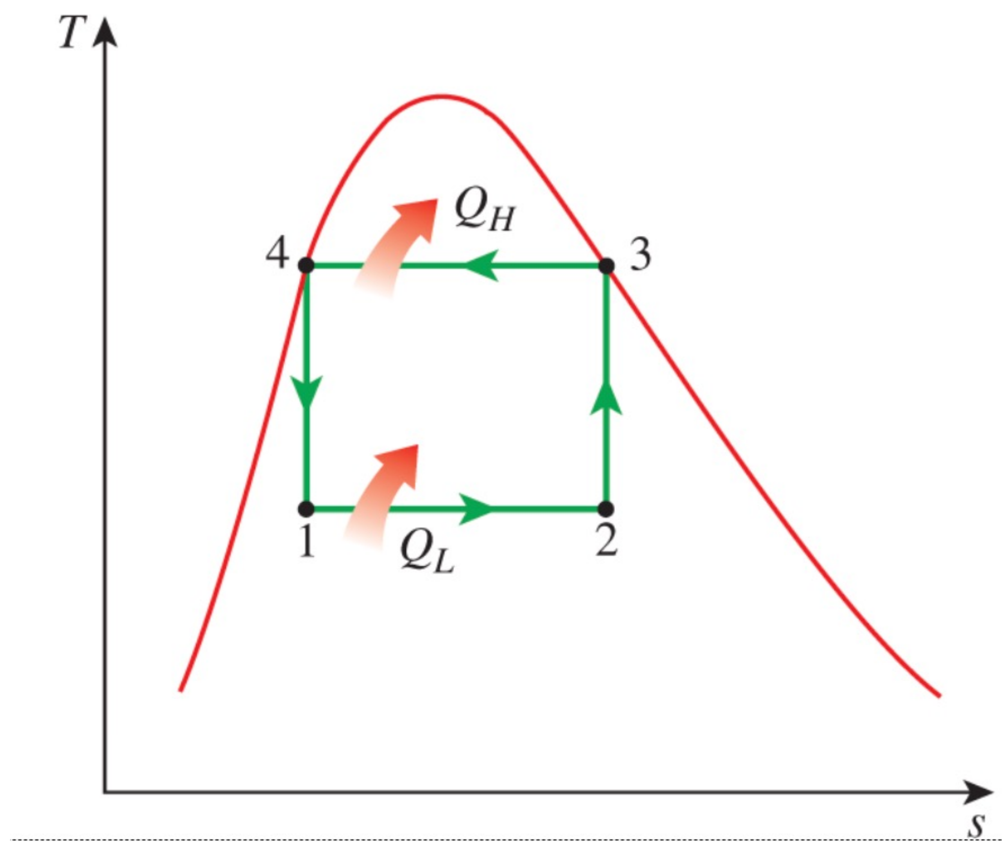
Refrigerators and Heat Pumps

- The Carnot cycle includes:



Refrigerators and Heat Pumps

- The T-s diagram for the Carnot cycle is:



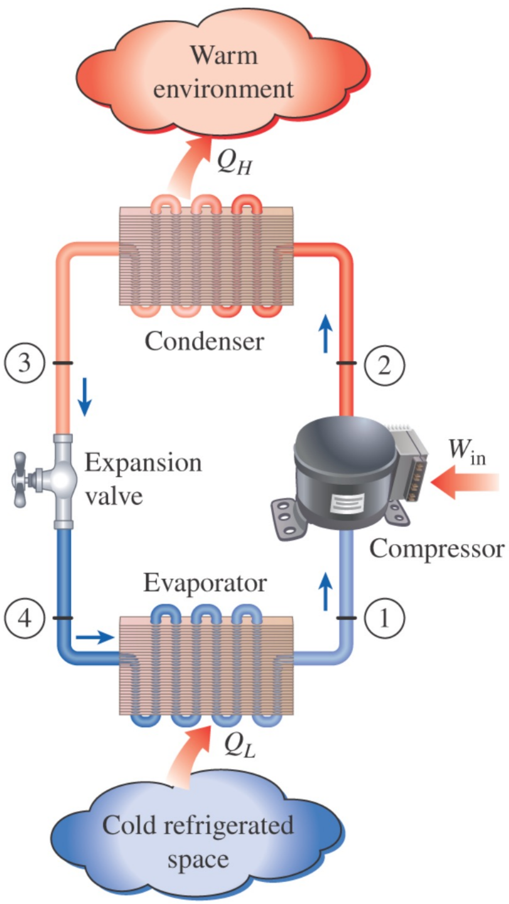
IDEAL VAPOR COMPRESSION REFRIGERATION CYCLE (SECTION 9-16)

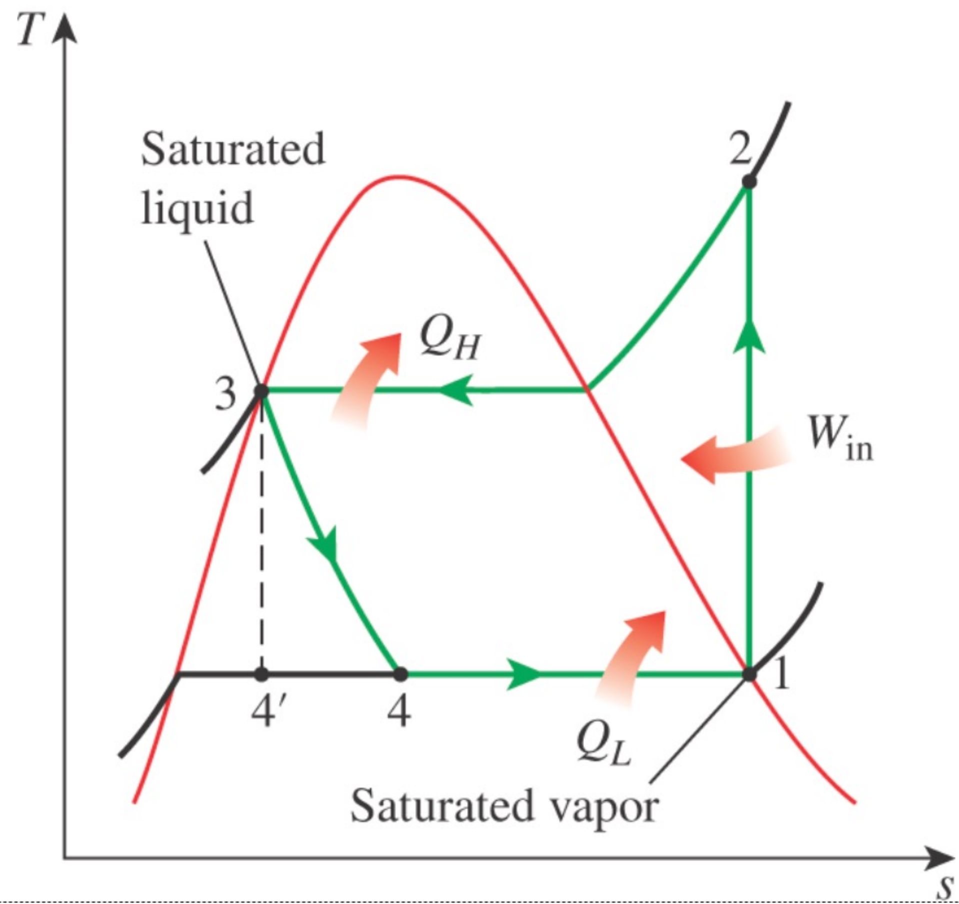
Ideal Vapor Compression Refrigeration Cycle

- In practice, there are several issues that limit the use of Carnot vapor compression cycle:
  - ❑ 1-2: Isentropic compression in a compressor
  - ❑ 2-3: Constant pressure heat rejection in a condenser
  - ❑ 3-4: Throttling in an expansion valve
  - ❑ 4-1: Constant pressure heat absorption in an evaporator

Ideal Vapor Compression Refrigeration Cycle

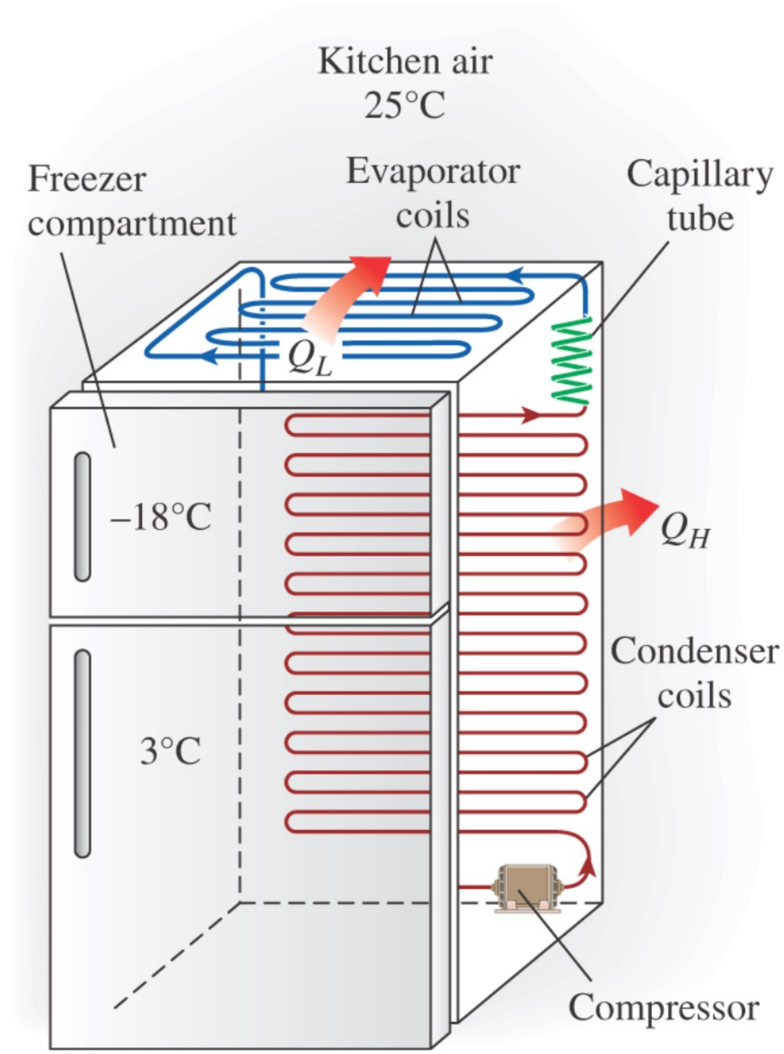
- In practice, there are several issues that limit the use of Carnot vapor compression cycle:





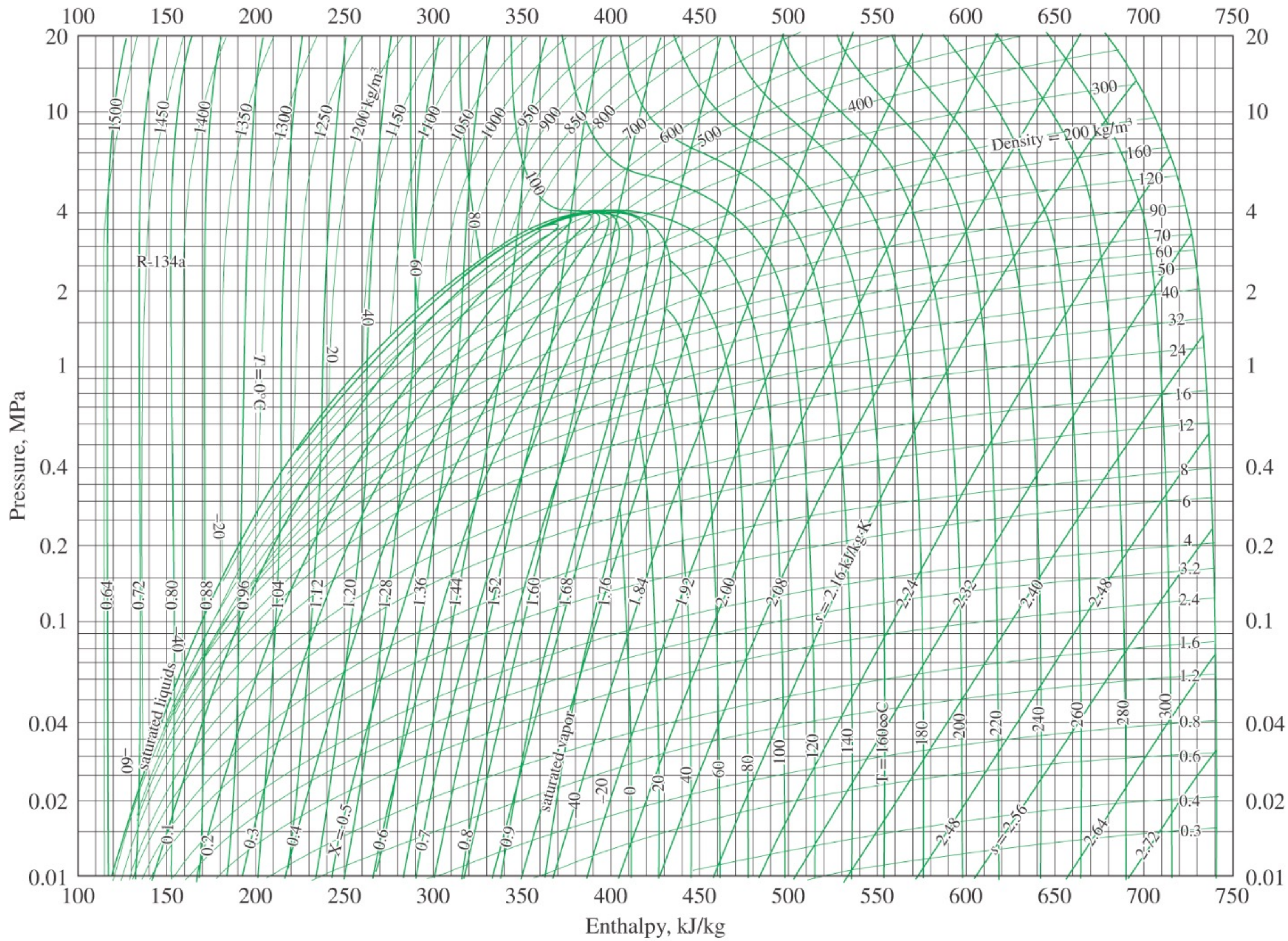
Ideal Vapor Compression Refrigeration Cycle

- An ordinary refrigerator, has all the four main components:



Ideal Vapor Compression Refrigeration Cycle

- P-h diagram is very helpful (Figure A-14)



Ideal Vapor Compression Refrigeration Cycle

- P-h diagram is very helpful (ASHRAE)

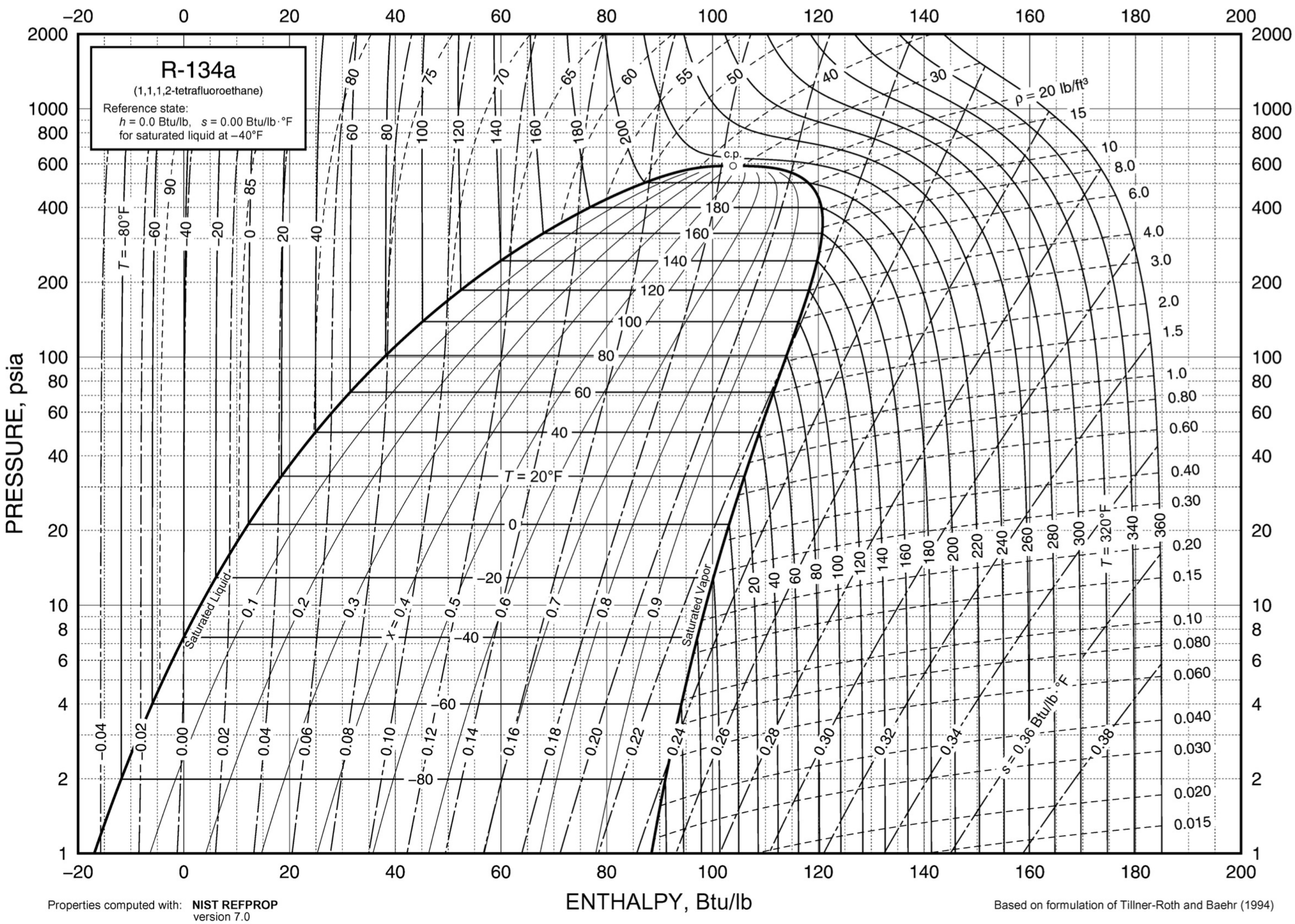


Fig. 8 Pressure-Enthalpy Diagram for Refrigerant 134a

Ideal Vapor Compression Refrigeration Cycle

- P-h diagram is very helpful (ASHRAE)

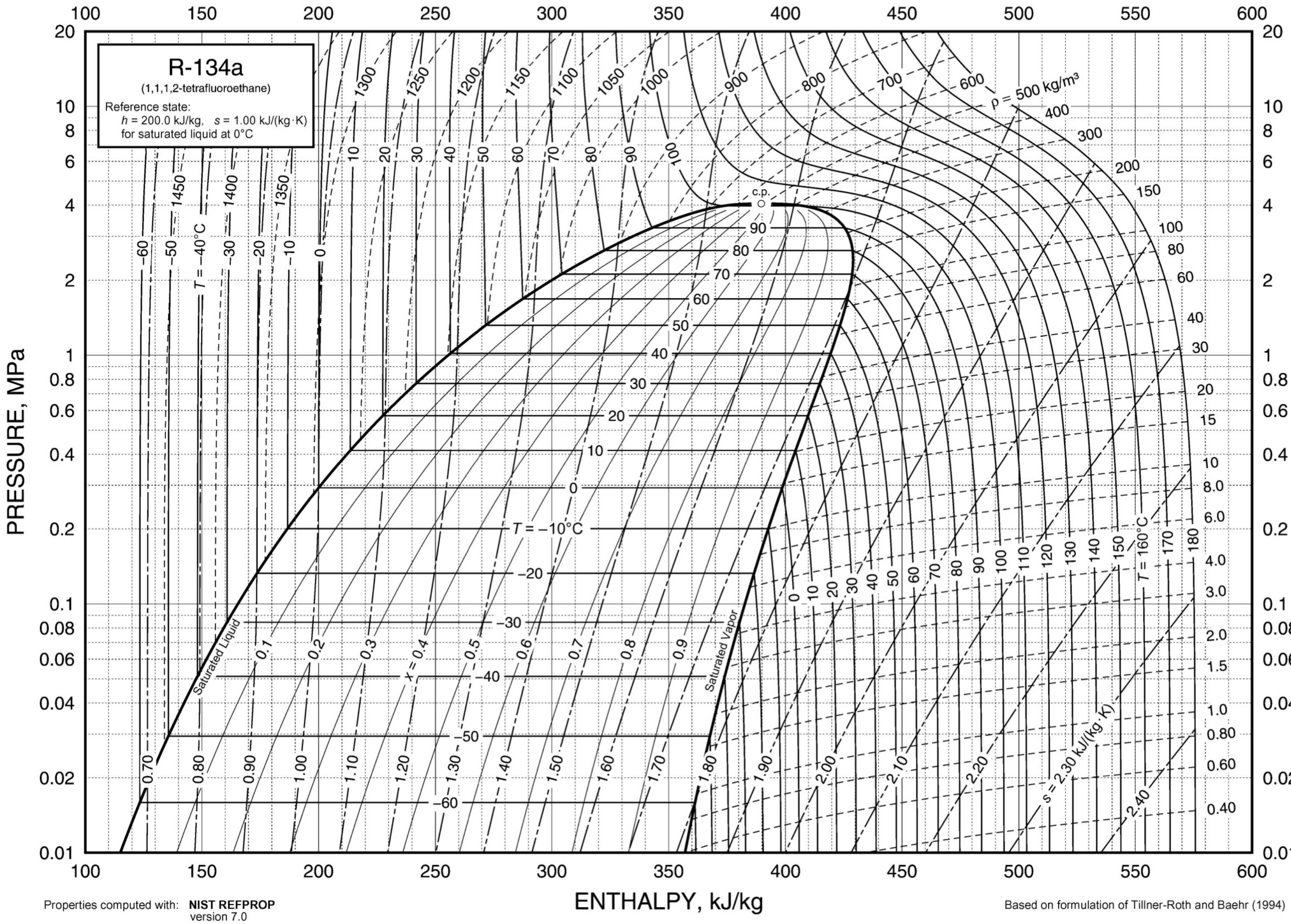
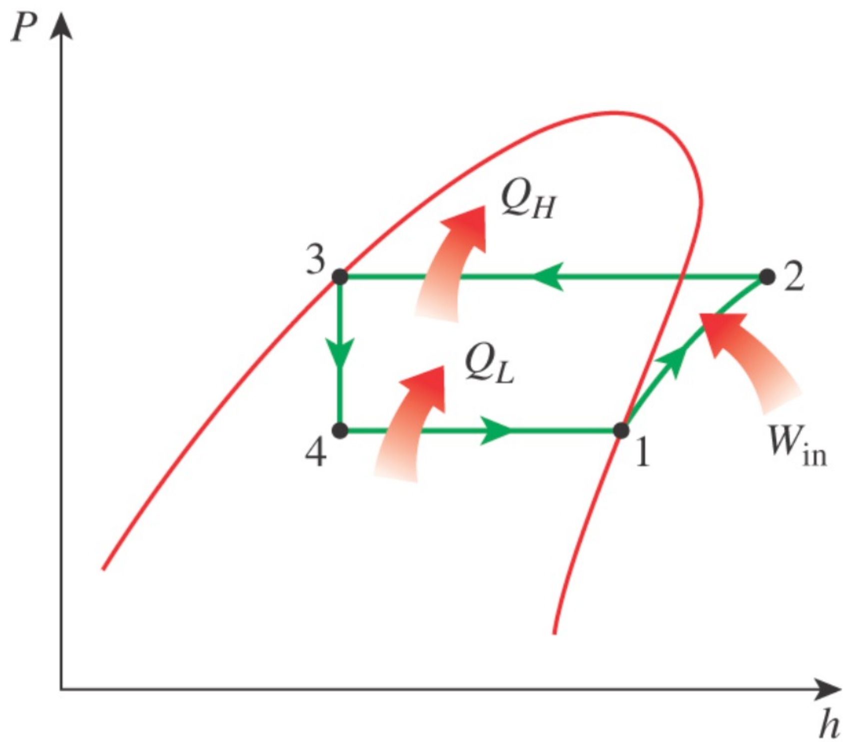


Fig. 8 Pressure-Enthalpy Diagram for Refrigerant 134a

Ideal Vapor Compression Refrigeration Cycle

- P-h diagram is very helpful in analyzing the performance:



$$COP_{HP} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

$$COP_R = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

CLASS ACTIVITY

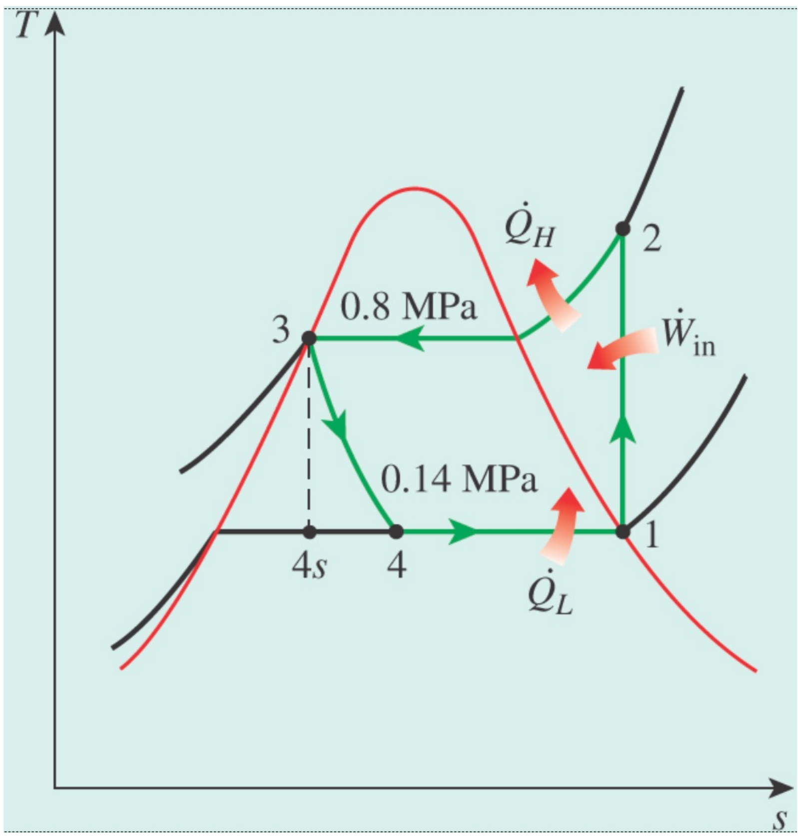
Class Activity

- A refrigerator uses refrigerant 134-a as the working fluid and operates on an ideal vapor-compression cycle between 0.14 and 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, determine
  a) The rate of heat removal from the refrigerated space and the power input to the compressor
  b) The rate of heat rejection to the environment
  c) The COP of the refrigerator

Class Activity

- Solution (assumption):
  - ❑ Steady operating condition exist
  - ❑ Kinetic and potential energy are negligible

- Understanding the states:



Class Activity

- Solution: Reading properties from the tables:

$$\begin{cases} P_1 = 0.14\ MPa \quad \rightarrow \quad h_1 = h_{g\ @\ 0.14\ MPa} = 239.19\ \dfrac{kJ}{kg} \\ s_1 = s_{g\ @\ 0.14\ MPa} = 0.94467\ \dfrac{kJ}{kg-K} \end{cases}$$

TABLE A–12

Saturated refrigerant-134a—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	−36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80	0.01633	0.94812	0.96445
70	−33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74	0.03264	0.92783	0.96047
80	−31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47	0.04707	0.91009	0.95716
90	−28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04	0.06003	0.89431	0.95434
100	−26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46	0.07182	0.88008	0.95191
120	−22.32	0.0007323	0.16216	22.38	195.15	217.53	22.47	214.52	236.99	0.09269	0.85520	0.94789
140	−18.77	0.0007381	0.14020	26.96	192.60	219.56	27.06	212.13	239.19	0.11080	0.83387	0.94467

Class Activity

- Solution: Reading properties from the tables:

$$\begin{cases} P_3 = 0.8\ MPa \\ s_2 = s_1 = 0.94467\ \dfrac{kJ}{kg-K} \end{cases} \rightarrow.\ h_2 = 275.40\ \frac{kJ}{kg}$$

TABLE A–13

Superheated refrigerant-134a

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	$P = 0.80$ MPa ($T_{sat} = 31.31$°C)			
Sat.	0.025645	246.82	267.34	0.9185
40	0.027035	254.84	276.46	0.9481
50	0.028547	263.87	286.71	0.9803
60	0.029973	272.85	296.82	1.0111
70	0.031340	281.83	306.90	1.0409

Class Activity

- Solution: Reading properties from the tables:

$$P_3 = 0.8\ MPa \quad \rightarrow \quad h_3 = h_{f\ @\ 0.8\ MPa} = 95.48\ \frac{kJ}{kg}$$

TABLE A–12

Saturated refrigerant-134a—Pressure table

		Specific volume, m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g
650	24.20	0.0008265	0.031680	84.72	158.51	243.23	85.26	178.56	263.82
700	26.69	0.0008331	0.029392	88.24	156.27	244.51	88.82	176.26	265.08
750	29.06	0.0008395	0.027398	91.59	154.11	245.70	92.22	174.03	266.25
800	31.31	0.0008457	0.025645	94.80	152.02	246.82	95.48	171.86	267.34
850	33.45	0.0008519	0.024091	97.88	150.00	247.88	98.61	169.75	268.36
900	35.51	0.0008580	0.022703	100.84	148.03	248.88	101.62	167.69	269.31

$$h_4 \cong h_3\ (throttling) \quad \rightarrow \quad h_4 = 95.48\ \frac{kJ}{kg}$$

Class Activity

- Solution (a): The rate of heat removal from the refrigerated space and the power input to the compressor is

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = \left(0.05\,\frac{kg}{s}\right)\left((239.19 - 95.48)\,\frac{kJ}{kg}\right) = 7.19\ kW$$

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = \left(0.05\,\frac{kg}{s}\right)\left((275.40 - 239.19)\,\frac{kJ}{kg}\right) = 1.18\ kW$$

Class Activity

- Solution (b): The rate of heat rejection from the refrigerant to the environment is:

$$\dot{Q}_H = \dot{m}(h_2 - h_3) = \left(0.05\,\frac{kg}{s}\right)\left((275.40 - 95.48)\,\frac{kJ}{kg}\right) = 9.00\ kW$$

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{in} = 7.19 + 1.81 = 9.00\ kW$$

Class Activity

- Solution (c): The coefficient of performance of the refrigerator is:

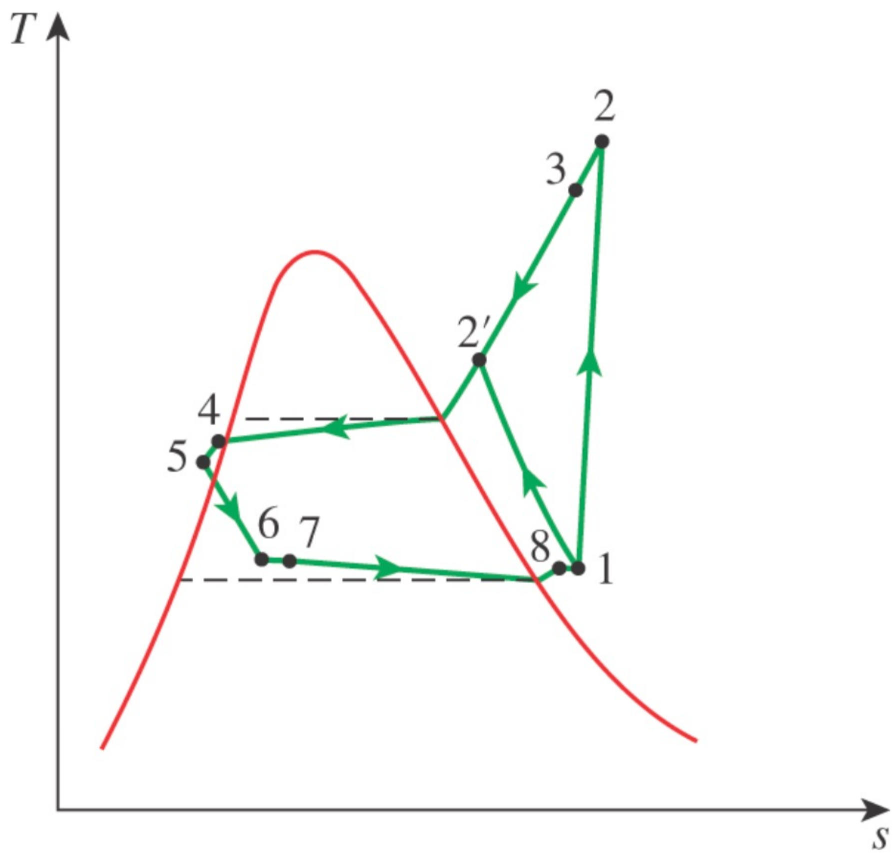
$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.19\ kW}{1.81\ kW} = 3.97$$

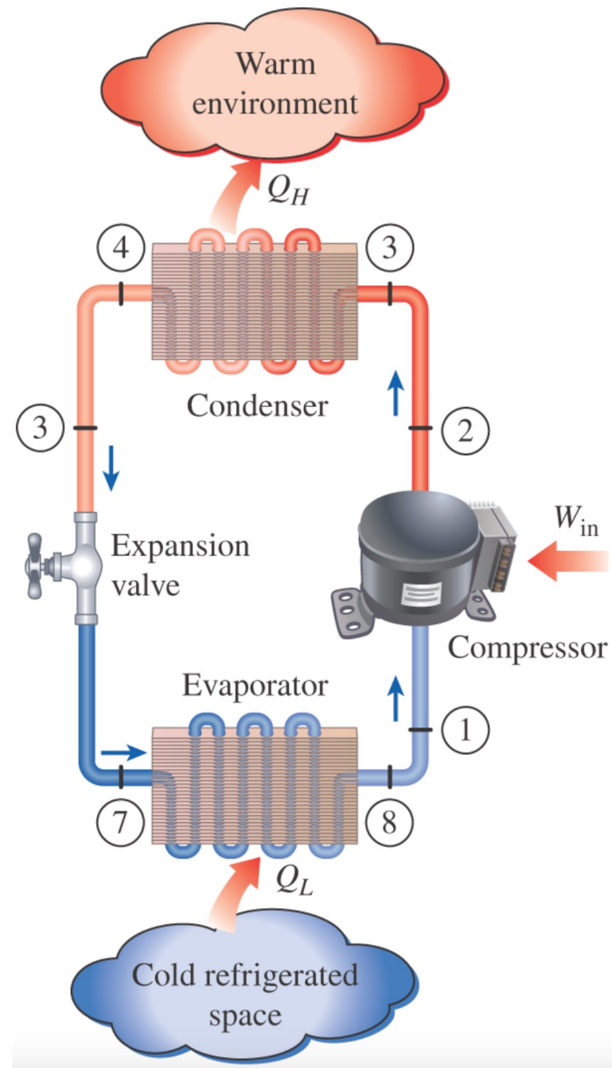
What would be the COP is the throttling process is isentropic?

ACTUAL VAPOR-COMPRESSION REFRIGERATION CYCLE (SECTION 9-17)

Actual Vapor-Compression Refrigeration Cycle

- An actual vapor-compression refrigeration cycle varies from the ideal one because of two common sources of irreversibilities:





CLASS ACTIVITY

Class Activity

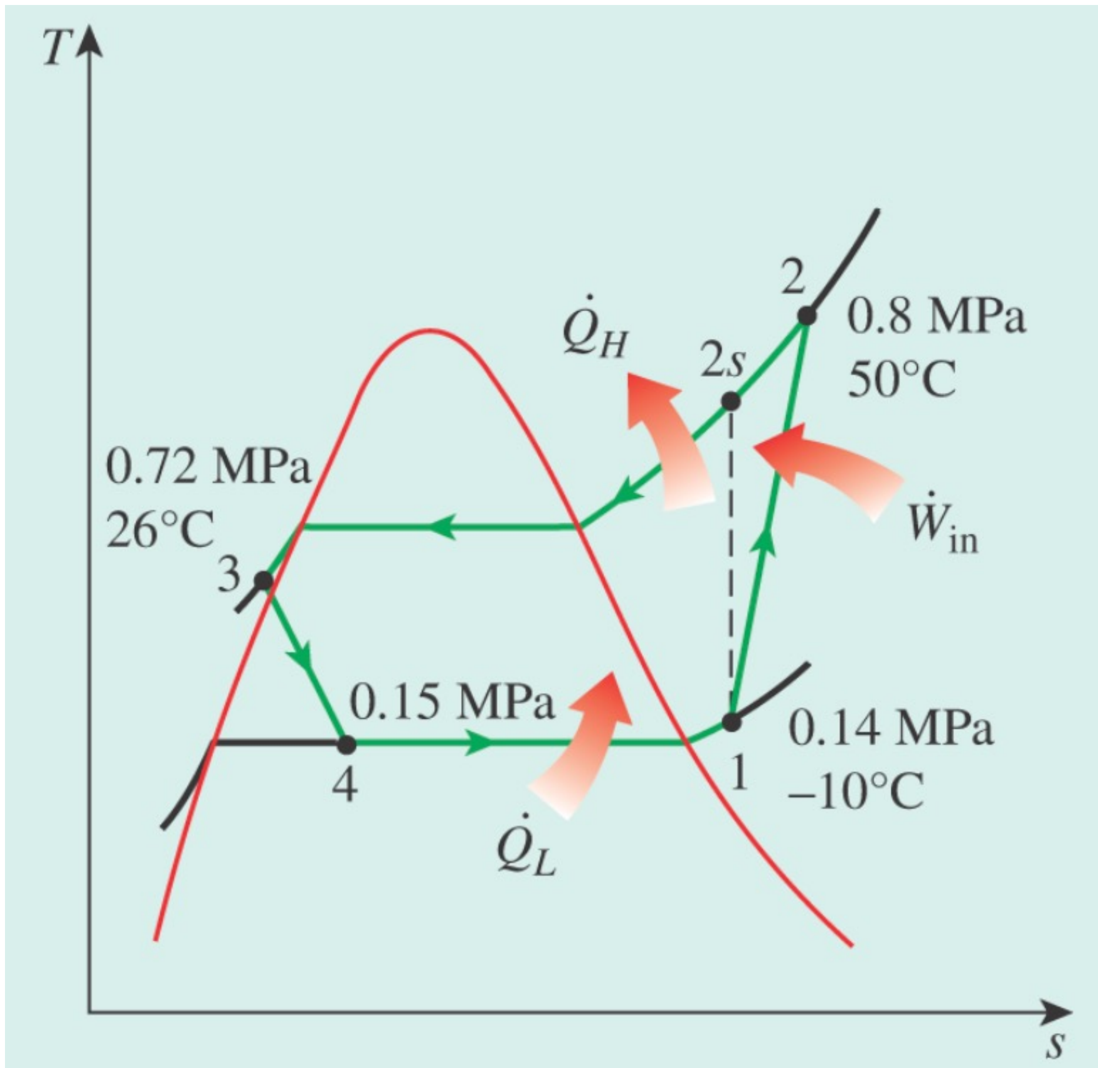
- ***(The actual vapor-compression refrigeration cycle – almost similar inputs to the previous class activity):*** Refrigerant 134-a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and -10 °C at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50 °C. The refrigerant is cooled in the condenser to 26 °C and 0.72 MPa and id throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components determine
  a) The rate of heat removal from the refrigerated space and the power pressure drops in the connecting lines between the components
  b) The isentropic efficiency of the compressor
  c) The coefficient of performance of the refrigerator

Class Activity

- Solution (assumption):
  - ❑ Steady operating condition exist
  - ❑ Kinetic and potential energy are negligible

Class Activity

- Solution (T-s diagram)



Class Activity

- Solution (Tables and Calculations):

$$\begin{cases} P_1 = 0.14\ MPa \\ T_1 = -10\ °C \end{cases} \rightarrow \quad h_1 = 246.37\ \frac{kJ}{kg}$$

TABLE A–12

Saturated refrigerant-134a—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g
60	−36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80
70	−33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74
80	−31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47
90	−28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04
100	−26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46
120	−22.32	0.0007323	0.16216	22.38	195.15	217.53	22.47	214.52	236.99
140	−18.77	0.0007381	0.14020	26.96	192.60	219.56	27.06	212.13	239.19

TABLE A–13

Superheated refrigerant-134a

	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	$P = 0.14$ MPa ($T_{sat} = -18.77$°C)			
Sat.	0.14020	219.56	239.19	0.9447
-20	0.14605	225.93	246.37	0.9724
-10	0.15263	233.25	254.61	1.0032

Class Activity

- Solution (Tables and Calculations):

$$\begin{cases} P_1 = 0.14\ MPa \\ T_1 = -10\ °C \end{cases} \rightarrow \quad h_1 = 246.37\ \frac{kJ}{kg}$$

$$\begin{cases} P_2 = 0.8\ MPa \\ T_2 = -50\ °C \end{cases} \rightarrow \quad h_2 = 286.71\ \frac{kJ}{kg}$$

$$\begin{cases} P_3 = 0.72\ MPa \\ T_3 = 26\ °C \end{cases} \rightarrow \quad h_3 \cong h_{f\ @\ 26\ °C} = 87.83\ \frac{kJ}{kg}$$

$$\begin{cases} h_4 \cong h_3 = 87.83\ \frac{kJ}{kg} \end{cases}$$

Class Activity

- Solution (a): The rate of heat removal from the refrigerated space and the power input to the compressor are:

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = \left(0.05\,\frac{kg}{s}\right)\left((246.37 - 87.83)\,\frac{kJ}{kg}\right) = 7.93\ kW$$

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = \left(0.05\,\frac{kg}{s}\right)\left((286.71 - 246.37)\,\frac{kJ}{kg}\right) = 2.02\ kW$$

Class Activity

- Solution (b): The isentropic efficiency of the compressor is determined from:

$$\eta_C \cong \frac{h_{2s} - h_1}{h_2 - h_1}$$

- Where the enthalpy at state $2s$ ($P_{2s} = 0.8\ MPa$ and $s_{2s} = s_1 = 0.9724 \frac{kJ}{kg-K}$) is $284.20 \frac{kJ}{kg}$. Thus:

$$\eta_C \cong \frac{284.20 - 246.37}{286.71 - 246.37} = 0.938\ or\ 93.8\%$$

Class Activity

- Solution (c): The coefficient of performance of the refrigerator is:

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.93\ kW}{2.02\ kW} = 3.93$$

EXTRA SOLVED PROBLEM (I)

Extra Solved Problem (I)

- What is the maximum theoretical COP of a refrigeration device operating between 0 °F and 75 °F?

Extra Solved Problem (I)

- **Solution:** The maximum theoretical Coefficient of Performance is the Carnot COP

- Make sure to use the absolute temperatures:
  - ❑ °C + 273 = K (Kelvin)
  - ❑ °F + 460 = R (Rankine)

$$COP_{carnot,cooling} = \left(\frac{T_{evap}}{T_{cond} - T_{evap}}\right) = \frac{460R}{75R} = 6.13$$

EXTRA SOLVED PROBLEM (II)

Extra Solved Problem (II)

- Refrigerant 134a enters an evaporator at -20 ºF and 0.3 quality at a mass flow rate of 1 kg/s. Compute the cooling capacity of the evaporator in kilowatts, if the refrigerant leaves as saturated vapor at -20 ºF.

Extra Solved Problem (II)

- **Solution:** From the problem statement:
  - ❑ $T_{evap} = -20\ \text{°F}$
  - ❑ $\dot{m} = 1\,\frac{kg}{s} = 132.3\,\frac{lbm}{\text{min}}$
  - ❑ $X_{evap_{in}} = 0.3$

Extra Solved Problem (II)

- **Solution:** From our knowledge of a vapor compression cycle:

  - ❑ $X_{evap_{out}} = 1$
  - ❑ $h_{evap_{out}} = 100.054\ \frac{Btu}{lbm}$

  - ❑ $h_{evap_{in}} = 0.3(100.054) + 0.7(5.991) = 34.21\ \frac{Btu}{lbm}$

Extra Solved Problem (II)

- **Solution:** Overall heat transfer of the evaporator:

$$\dot{Q}_{evap} = \dot{m}\left(h_{evap,out} - h_{evap,in}\right)$$
$$= 132.3\ \frac{lbm}{min}\left(65.844\ \frac{Btu}{lbm}\right)\left(60\ \frac{min}{hr}\right)$$
$$= \quad 522{,}669.7\ \frac{Btu}{hr}$$

$$3{,}412\ \frac{Btu}{hr} = 1\ kW$$

$$\dot{Q}_{evap} = 522{,}669.7\ \frac{Btu}{hr} \times \frac{1\ kW}{3{,}412\ \frac{Btu}{hr}} = 153.2\ kW$$

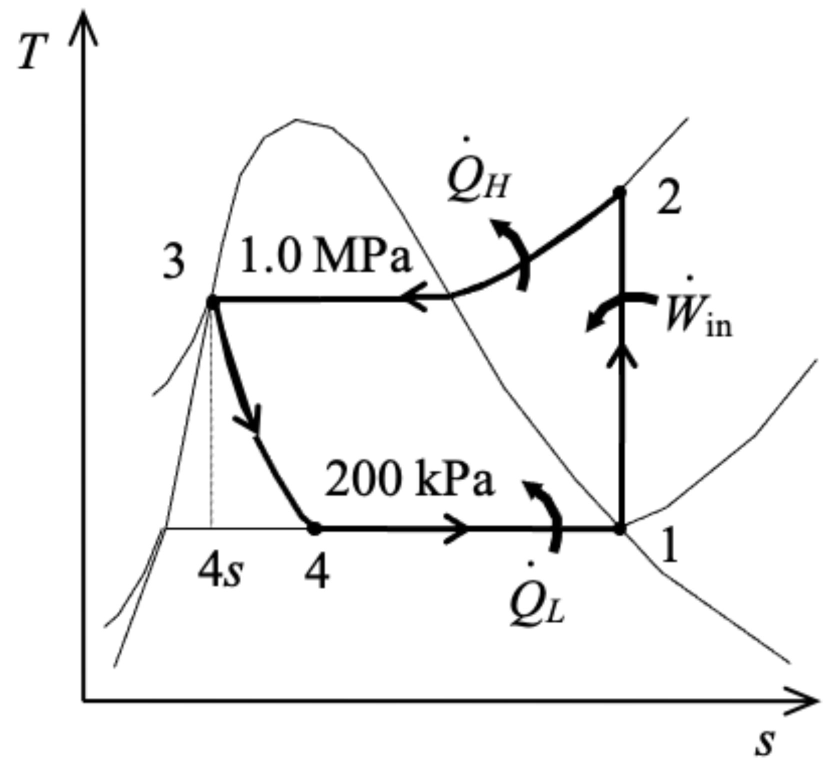
EXTRA SOLVED PROBLEM (III)

Extra Solved Problem (III)

- A heat pump operates on the ideal vapor-compression refrigeration cycle and uses refrigerant-134a as the working fluid. The condenser operates at 1000 kPa and the evaporator at 200 kPa. Determine this system's COP and the rate of heat supplied to the evaporator when the compressor consumes 6 kW.

Extra Solved Problem (III)

- Solution (assumptions):
  - ❑ Steady operating conditions exist
  - ❑ Kinetic and potential energy changes are negligible



Extra Solved Problem (III)

- Solution (using Tables A-11, A-12, and A-13):

$$\begin{cases} P_1 = 200\ kPa \\ sat.\ vapor \end{cases} \rightarrow \begin{array}{l} h_1 = h_{g\ @\ 200\ kPa} = 244.50\ \dfrac{kJ}{kg} \\ s_1 = s_{g\ @\ 200\ kPa} = 0.93788\ \dfrac{kj}{kg-K} \end{array}$$

$$\begin{cases} P_2 = 1000\ kPa \\ s_1 = s_2 \end{cases} \rightarrow \quad h_2 = 278.07\ \frac{kJ}{kg}$$

$$\begin{cases} P_3 = 1000\ kPa \\ sat.\ liquid \end{cases} \rightarrow \quad h_3 = h_{f\ @\ 1000\ kPa} = 107.34\ \frac{kJ}{kg}$$

$$h_4 = h_3 = 107.34\ \frac{kJ}{kg}$$

Extra Solved Problem (III)

- Solution (using equations):

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) \quad \rightarrow \quad \dot{m} = \frac{\dot{W}_{in}}{(h_2 - h_1)} = \frac{6\,\frac{kj}{s}}{(278.07 - 244.50)\,\frac{kJ}{kg}} = 0.1787\,\frac{kg}{s}$$

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = \left(0.1787\,\frac{kg}{s}\right)(244.50 - 107.34)\,\frac{kj}{kg} = 24.5\ kW$$

$$COP_{HP} = \frac{q_H}{w_{in}} = \frac{h_2 - h_3}{h_2 - h_1} = \frac{278.07 - 107.34}{278.07 - 244.50} = 5.09$$

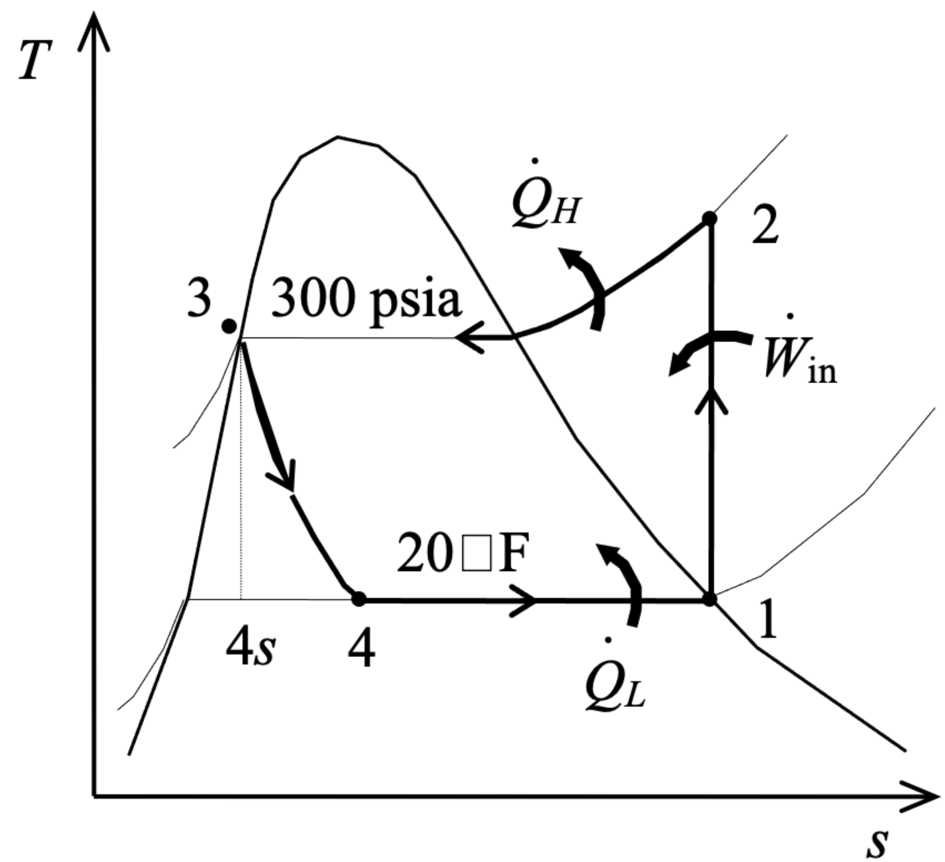
EXTRA SOLVED PROBLEM (IV)

Extra Solved Problem (IV)

- A refrigerator operates on the ideal vapor-compression refrigeration cycle and uses refrigerant-134a as the working fluid. The condenser operates at 300 psia and the evaporator at 20°F. If an adiabatic, reversible expansion device were available and used to expand the liquid leaving the condenser, how much would the COP improve by using this device instead of the throttle device?

Extra Solved Problem (IV)

- Solution (assumptions):
  - ❑ Steady operating conditions exist
  - ❑ Kinetic and potential energy changes are negligible



Extra Solved Problem (IV)

- Solution (using Tables A-11E, A-12E, and A-13E):

$$\begin{cases} T_1 = 20\ °F \\ sat.vapor \end{cases} \rightarrow \begin{matrix} h_1 = h_{g\ @\ 20\ °F} = 106.00\ \dfrac{Btu}{lbm} \\ s_1 = s_{g\ @\ 20\ °F} = 0.22345\ \dfrac{kj}{kg-K} \end{matrix}$$

$$\begin{cases} P_2 = 300\ psi \\ s_1 = s_2 \end{cases} \rightarrow \quad h_2 = 125.70\ \frac{Btu}{lbm}$$

$$\begin{cases} P_3 = 300\ psia \\ sat.liquid \end{cases} \rightarrow \begin{matrix} h_3 = h_{f\ @\ 300\ psia} = 66.347\ \dfrac{Btu}{lbm} \\ s_3 = s_{f\ @\ 300\ psia} = 0.12717\ \dfrac{Btu}{lbm-R} \end{matrix}$$

$$\begin{cases} h_4 = h_3 = 66.347\ \dfrac{Btu}{lbm} \\ T_4 = 20\ °F \ \rightarrow h_{4s} = 59.81\ \dfrac{Btu}{lbm} \\ s_4 = s_3 \quad \rightarrow \quad x_{4s} = 0.4724 \end{cases}$$

Extra Solved Problem (IV)

- Solution (equations):

$$COP_R = \frac{q_L}{w_{in}} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{106.00 - 66.347}{125.70 - 106.00} = 2.103$$

$$COP_{R\ isentropic} = \frac{q_{L\_isentropic}}{w_{in}} = \frac{h_1 - h_{4s}}{h_2 - h_1} = \frac{106.00 - 59.81}{125.70 - 106.00} = 2.344$$

$$Percent\ Increase\ in\ COP = \frac{2.344 - 3.013}{2.013} = 16.5\%$$