CAE 208 / MMAE 320: Thermodynamics

Fall 2023

November 30, 2023

Vapor compression cycles (2)

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Dr. Mohammad Heidarinejad, Ph.D., P.E.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
muh182@iit.edu

ANNOUNCEMENTS

Announcements

- Assignment 10 is posted (Due 12/01/23 for those who need to submit it).

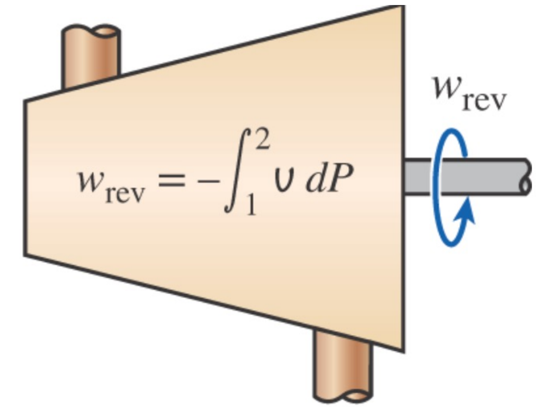
- We will talk about the bonus activity and the exam at the end of the class

RECAP

Recap

- For steady flow:

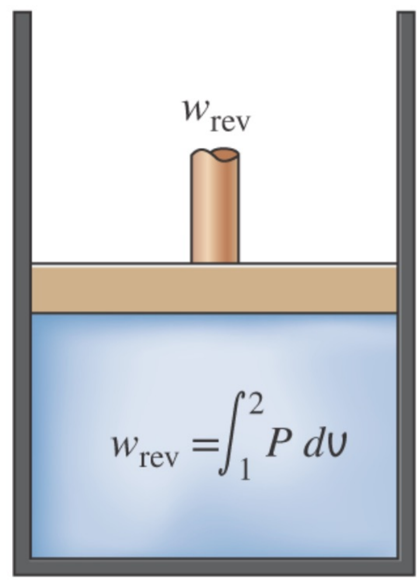
$$w_{rev} = -\int_1^2 v dP - \Delta ke - \Delta pe$$



(*a*) Steady-flow system

- For a closed system:

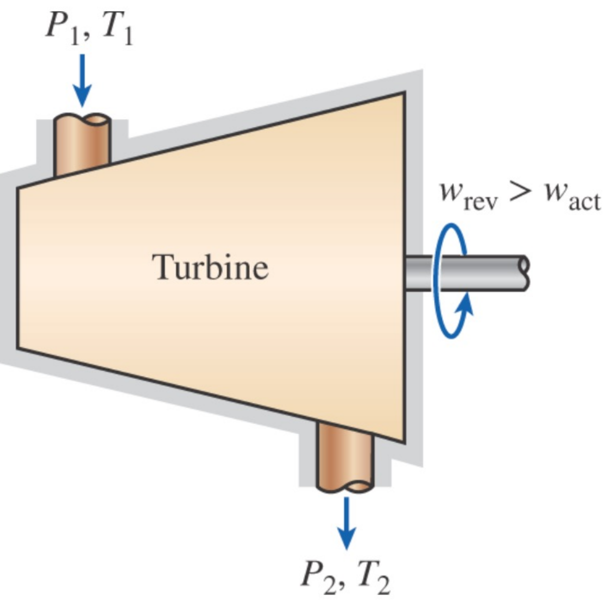
$$w_{rev} = \int_1^2 P dv$$



(*b*) Closed system

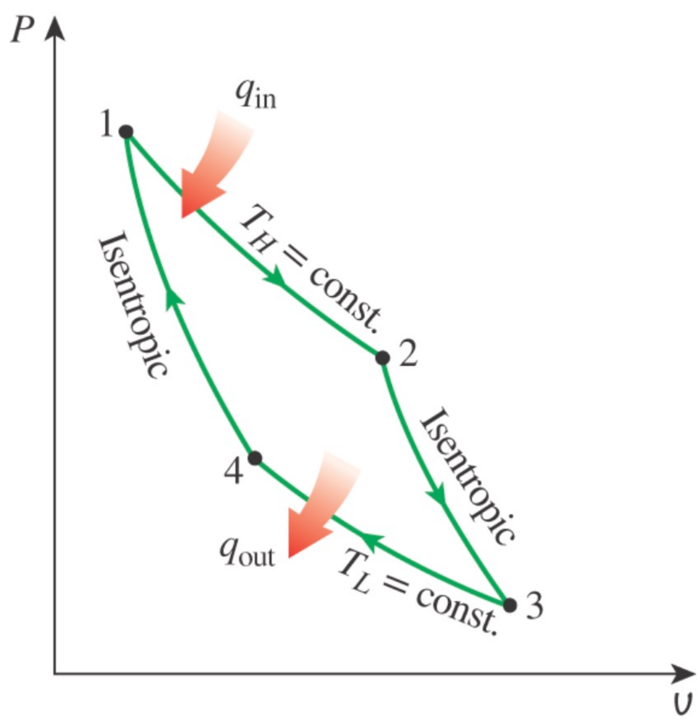
Recap

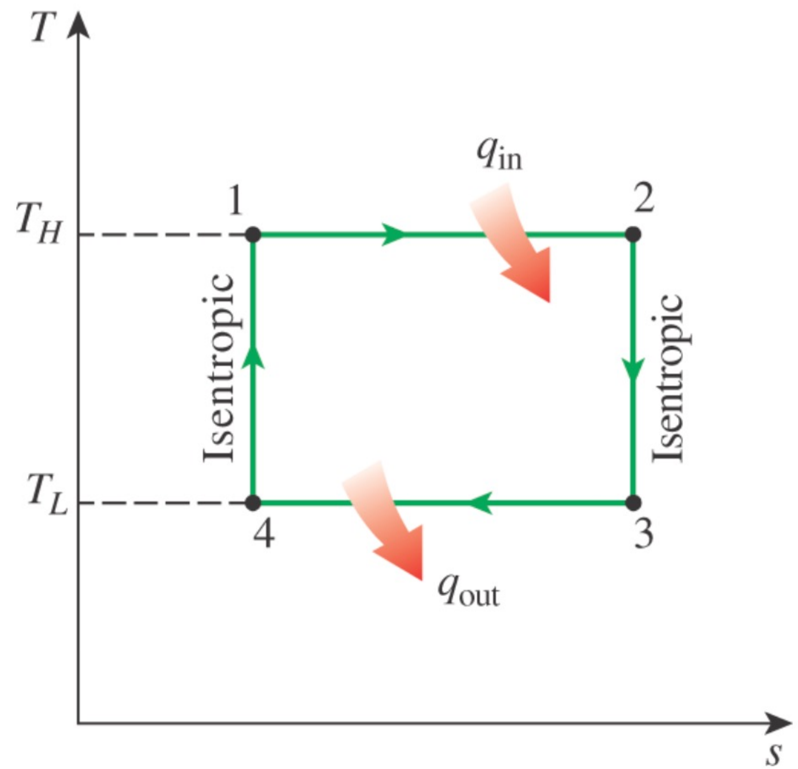
- Steady-flow devices (when the process is reversible):
  - ❑ Deliver the most work
  - ❑ Consume the least work



Recap

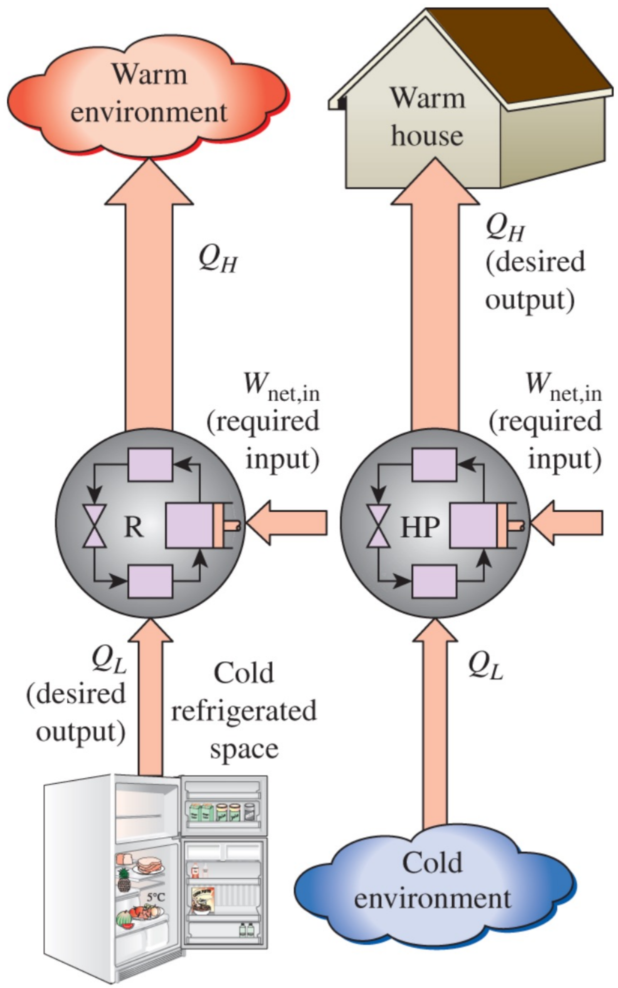
- Property diagrams such as T-s and P-V diagrams can serve as valuable aids in understanding and analysis of thermodynamics process:





Recap

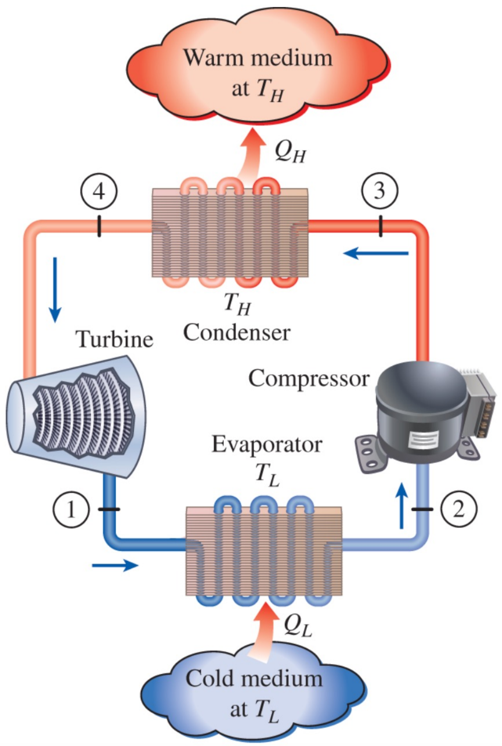
- We looked at the heat pump and vapor compression cycles:

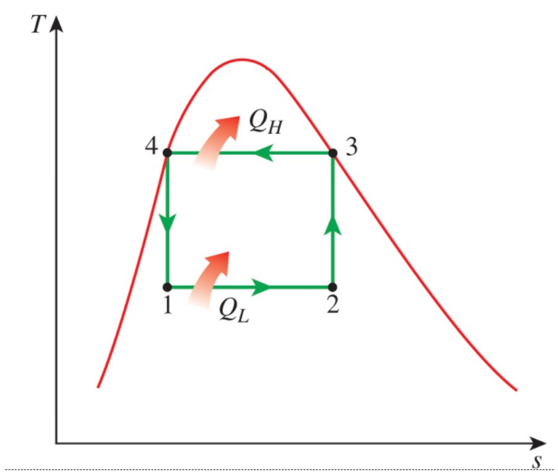


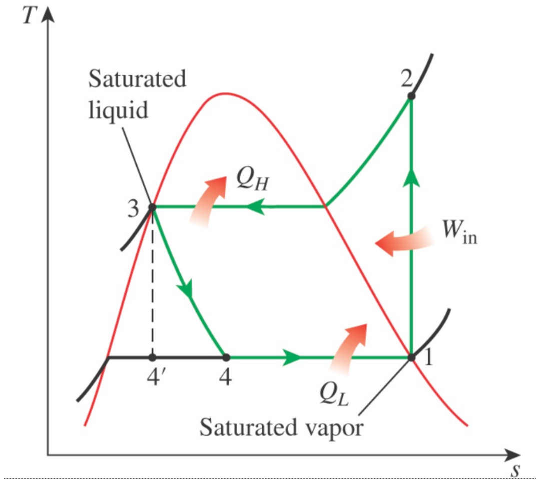
(*a*) Refrigerator (*b*) Heat pump

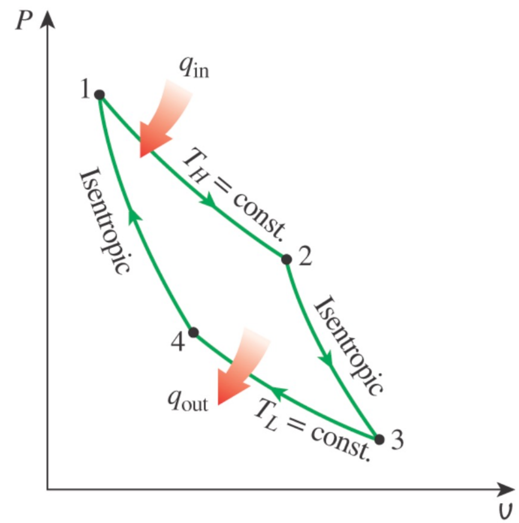
Recap

- The Carnot cycle includes:









Recap

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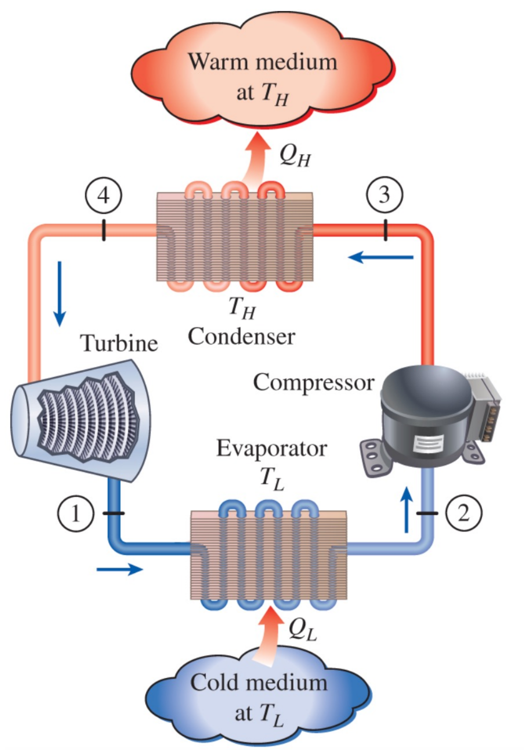
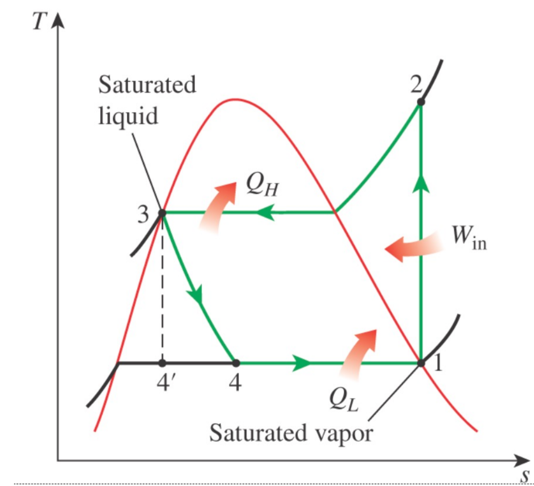
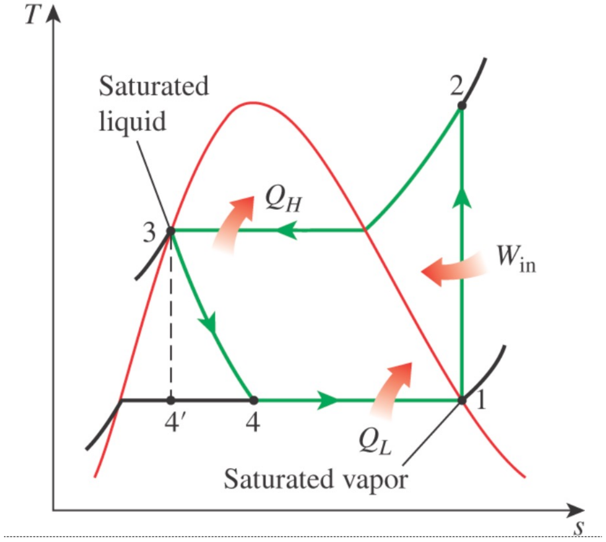
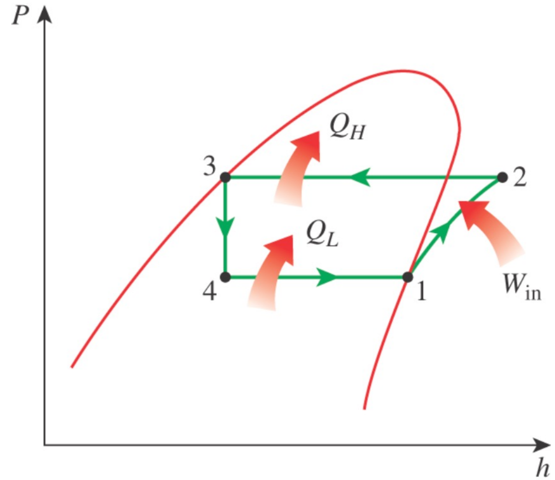




Recap

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





Recap

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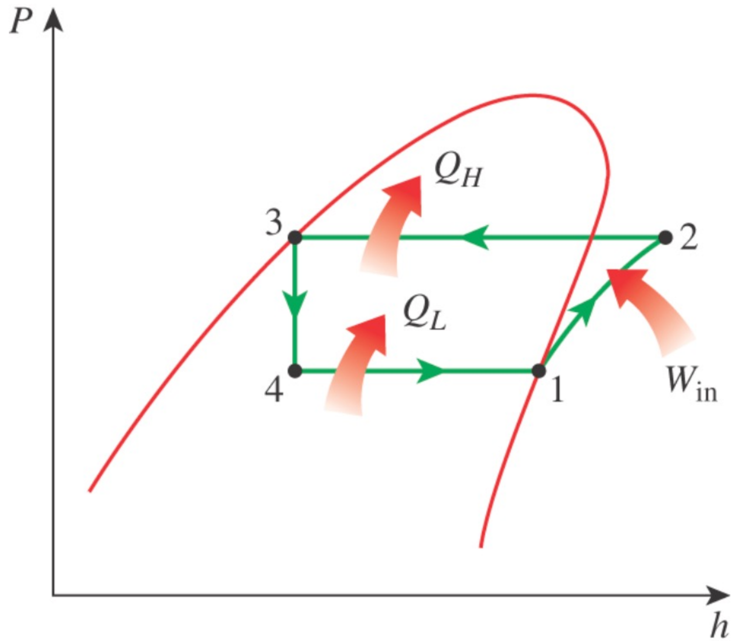


$$COP_{HP} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

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

Recap

- P-h diagram for R-134a (ASHRAE)

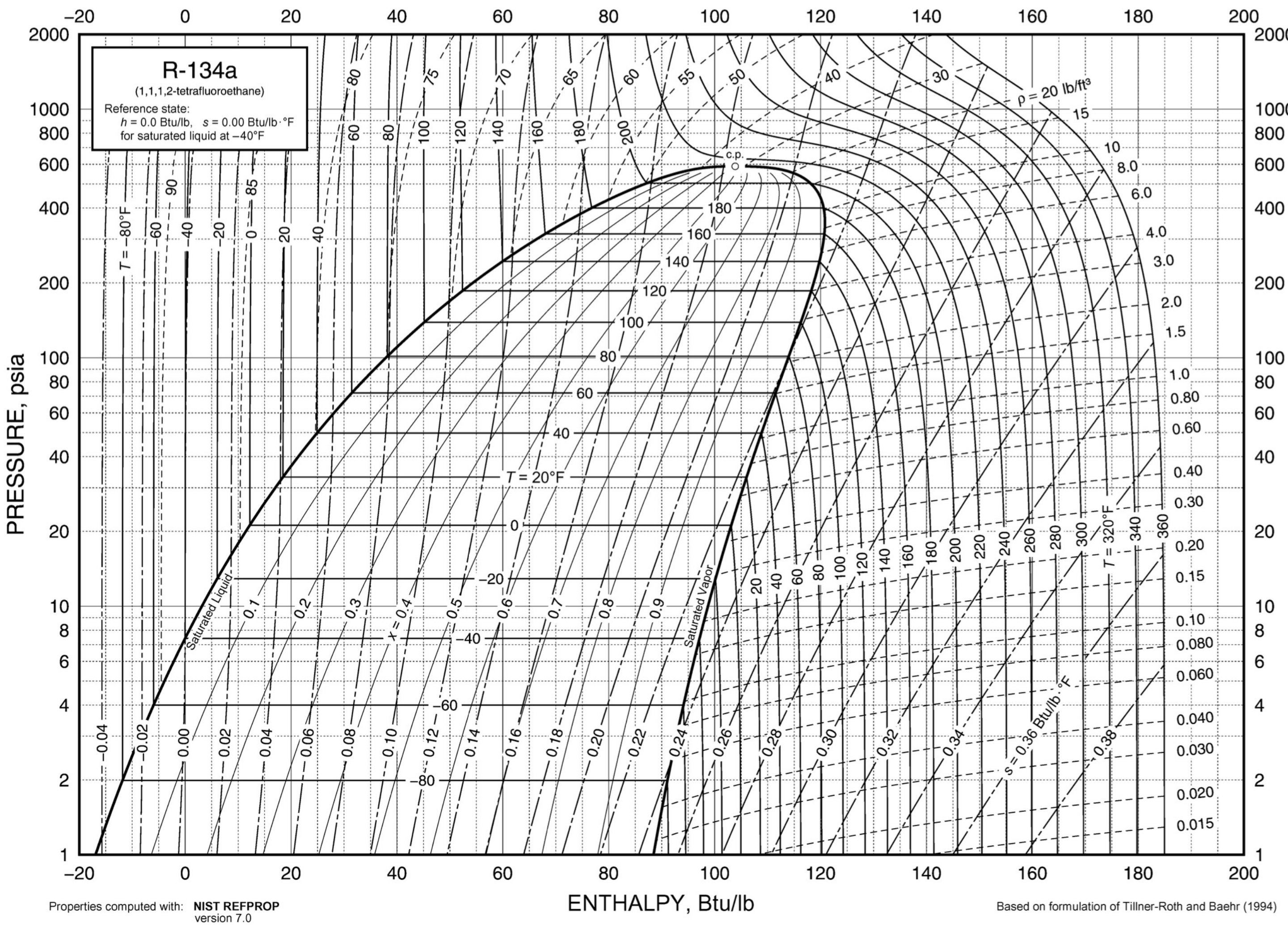


Fig. 8 Pressure-Enthalpy Diagram for Refrigerant 134a

Recap

- P-h diagram for R-134a (ASHRAE)

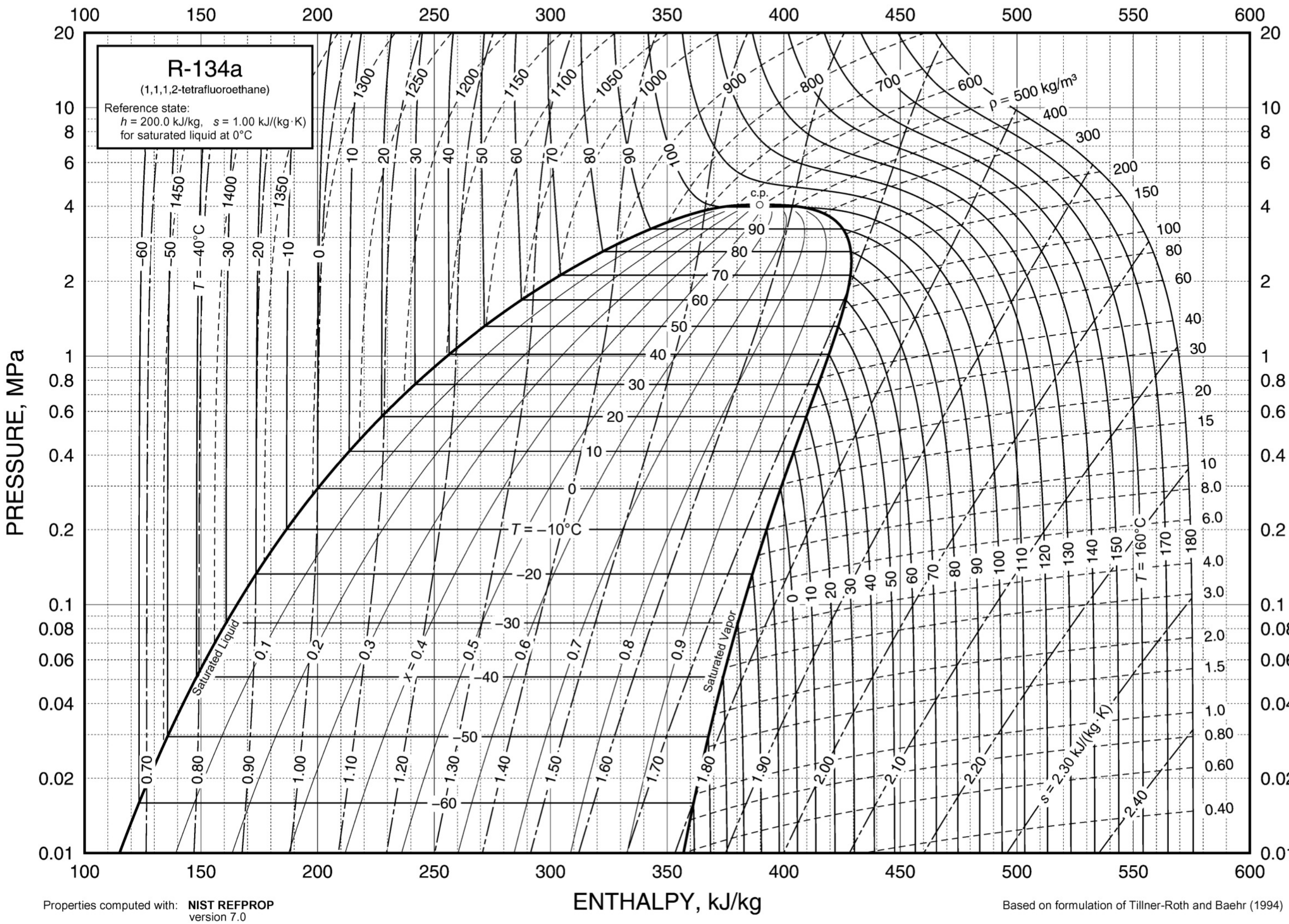
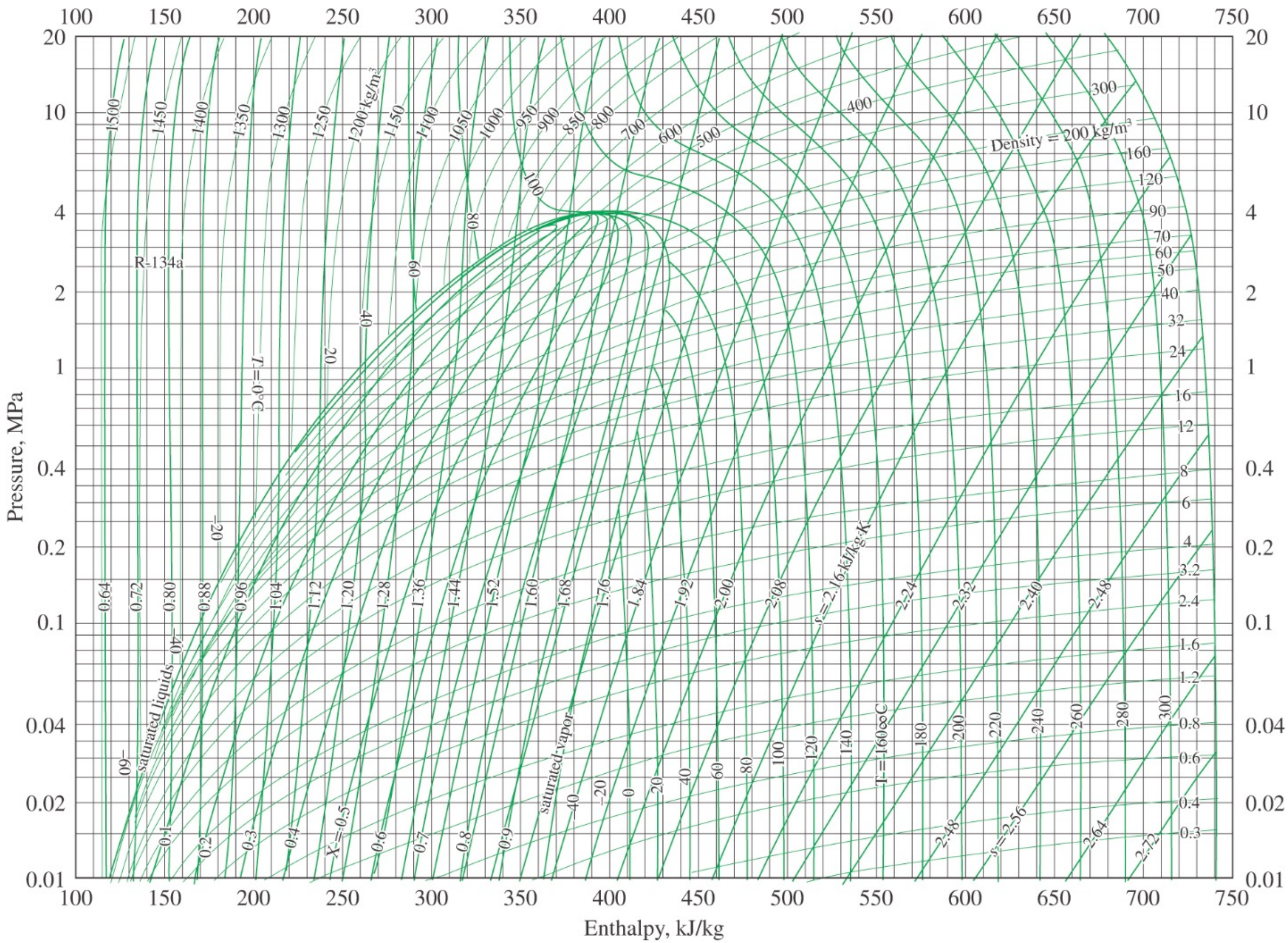


Fig. 8 Pressure-Enthalpy Diagram for Refrigerant 134a

Recap

- P-h diagram for R-134a (Figure A-14)



Recap

- Different vapor compression cycles

Ideal (Carnot)	Practical / Ideal	Actual

CLASS ACTIVITY

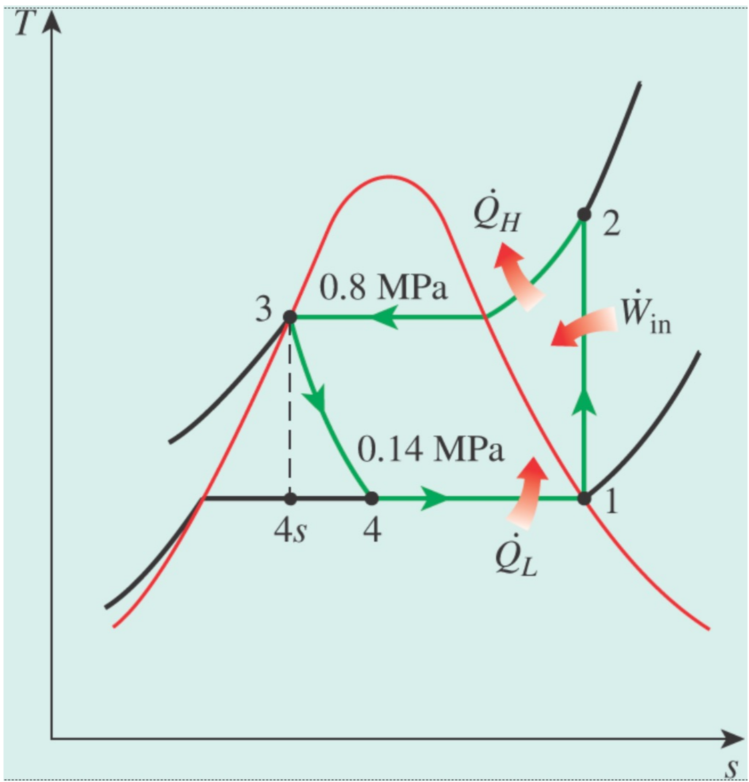
Class Activity

- A refrigerator uses refrigerant 134-a as the working fluid and operates on a practical/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:

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

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:

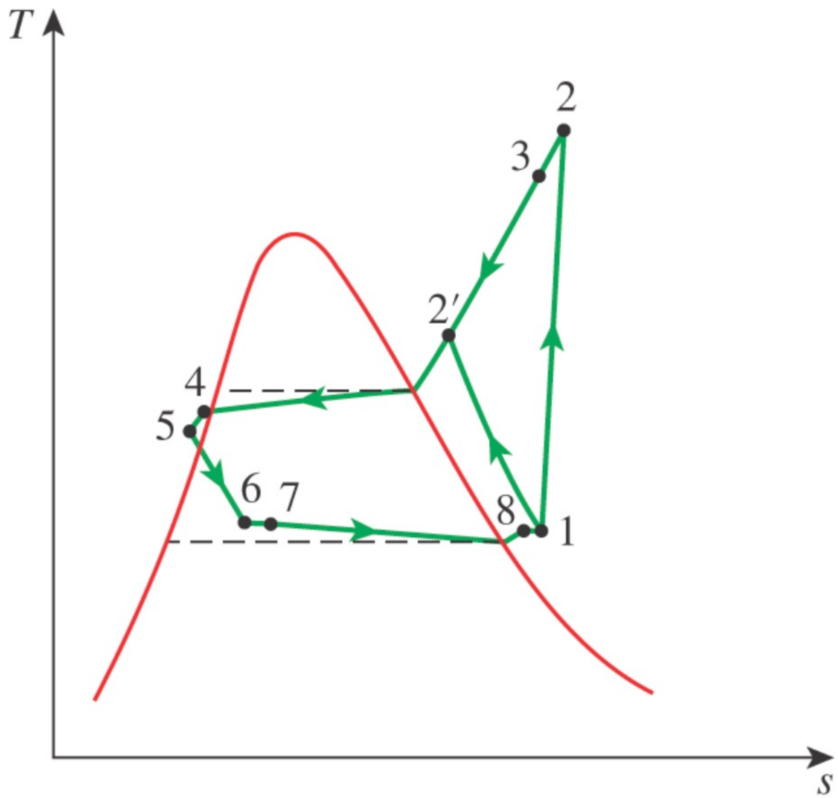
$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.19\ kW}{1.81\ kW} = 3.97$$

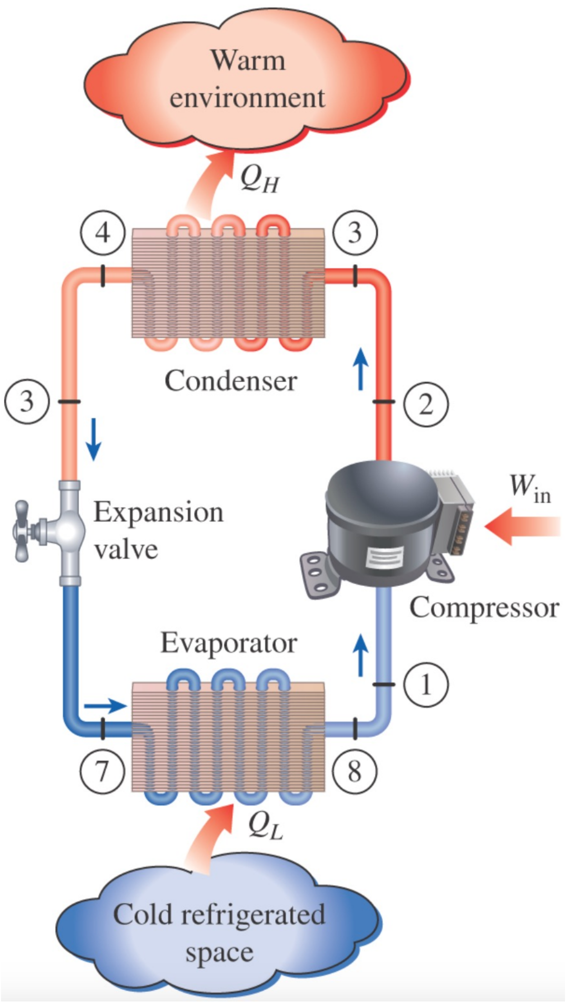
What would be the COP is the throttling process is isentropic?

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

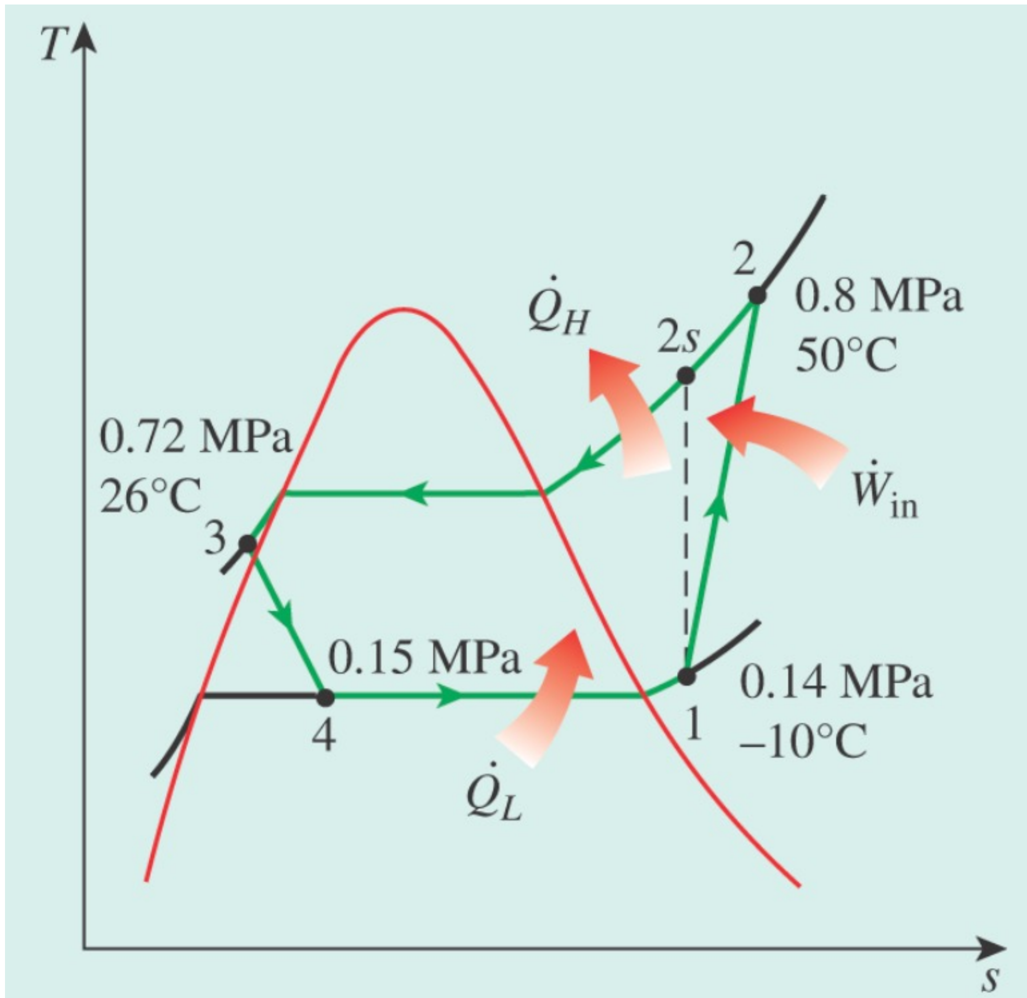
- ***(The actual vapor-compression refrigeration cycle – almost similar inputs to the previous class activity):*** Refrigerant 134-a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and -10 °C at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50 °C. The refrigerant is cooled in the condenser to 26 °C and 0.72 MPa and is 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:

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

CLASS ACTIVITY

Class Activity

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

Class Activity

- **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)

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

CLASS ACTIVITY

Class Activity

- 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.

Class Activity

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

Class Activity

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

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

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

Class Activity

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

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

$$= \quad 522{,}669.7\,\frac{Btu}{hr}$$

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

QUIZ

EXAM

Exam

- Date: December 6, 2023
- Time: 8 am to 10 am
- Location: WH 116 (Our class location)

- Review the previous final exam

- Similar to the previous midterm exams but longer since we have two hours

- Remember the best of two exams out of three will be used

Exam

- Closed Book:
  - ❑ Three papers (two papers from the first two midterms plus a new paper for the content after the midterm exam 2)
  - ❑ All the content covered in this semester
  - ❑ Calculator is also allowed

- Open Book:
  - ❑ Calculator is also allowed
  - ❑ Only the thermodynamics or thermal-science book (or the thermodynamics tables)
  - ❑ More focus on the content after exam 2 plus a detailed property table / property diagram question

BONUS ACTIVITY

Bonus Activity

- The bonus activities document is posted:
  - ❑ Please pay attention to the deadlines and also the updates about this task
  - ❑ An idea submission by the end of today – the link will disappear
  - ❑ If you need anything to purchase let me know
  - ❑ You can use the Idea Shop or the Machine Shop
  - ❑ If you are planning to write codes, no need to submit a report (Just add comments as much as possible and submit your codes or Jupiter Notebooks)
  - ❑ For the case of a hands-on activity, recording a short video would be great to demonstrate the process of you would use it and also document the process similar to these Instructable DIYs: https://www.instructables.com/

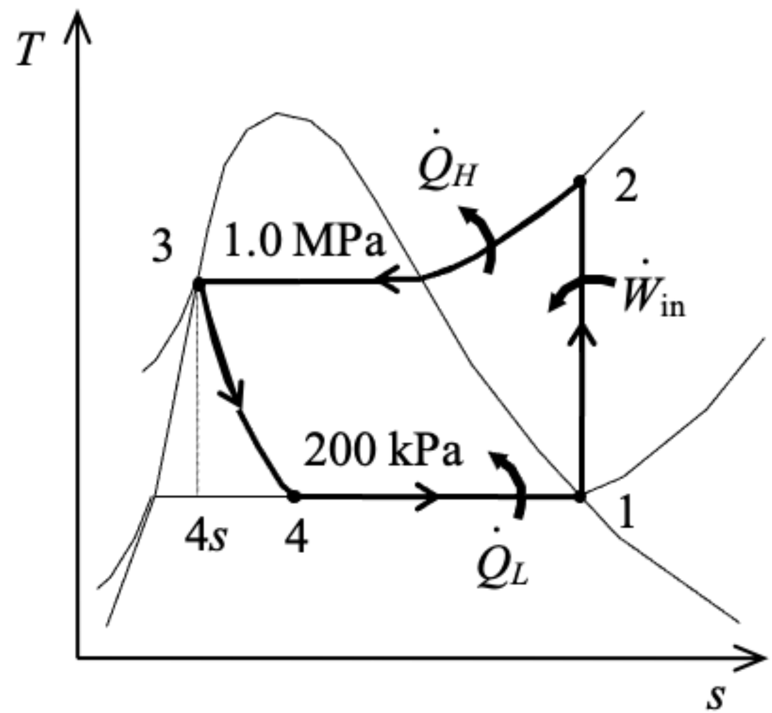
EXTRA SOLVED PROBLEM (1)

Extra Solved Problem (1)

- 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 (1)

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



Extra Solved Problem (1)

- 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 (1)

- Solution (using equations):

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

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

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

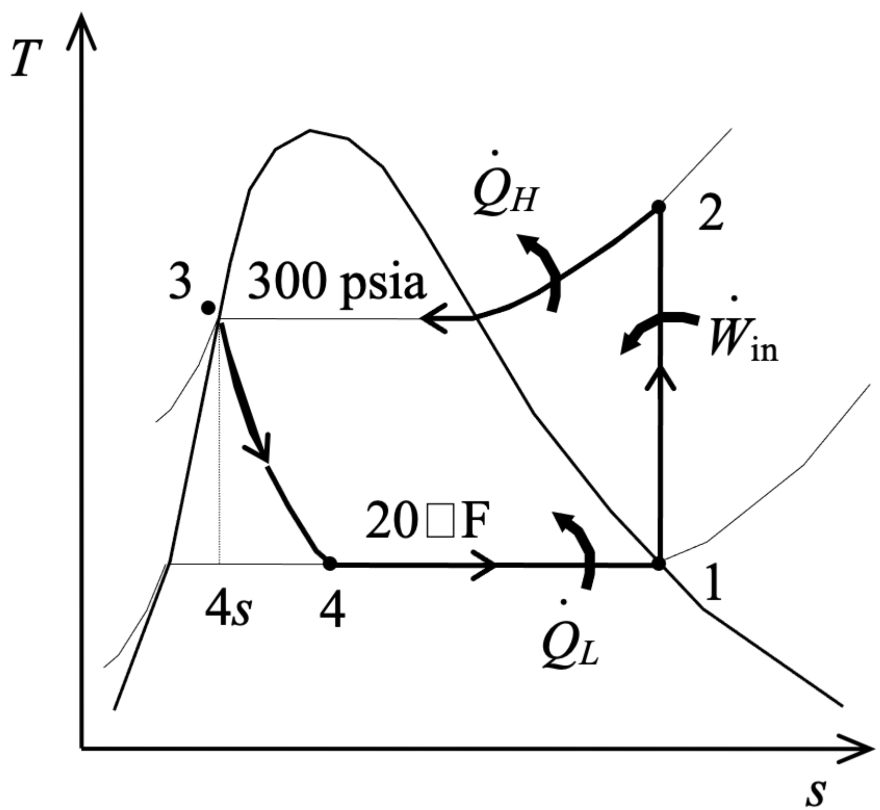
EXTRA SOLVED PROBLEM (2)

Extra Solved Problem (2)

- 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 (2)

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



Extra Solved Problem (2)

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

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

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

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

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

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- Solution (equations):

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

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

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