CAE 208 Thermal-Fluids Engineering I
MMAE 320: Thermodynamics

Fall 2022

November 29, 2022

Entropy (iv) and power and refrigeration cycles (I)

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ANNOUNCEMENTS

Announcements

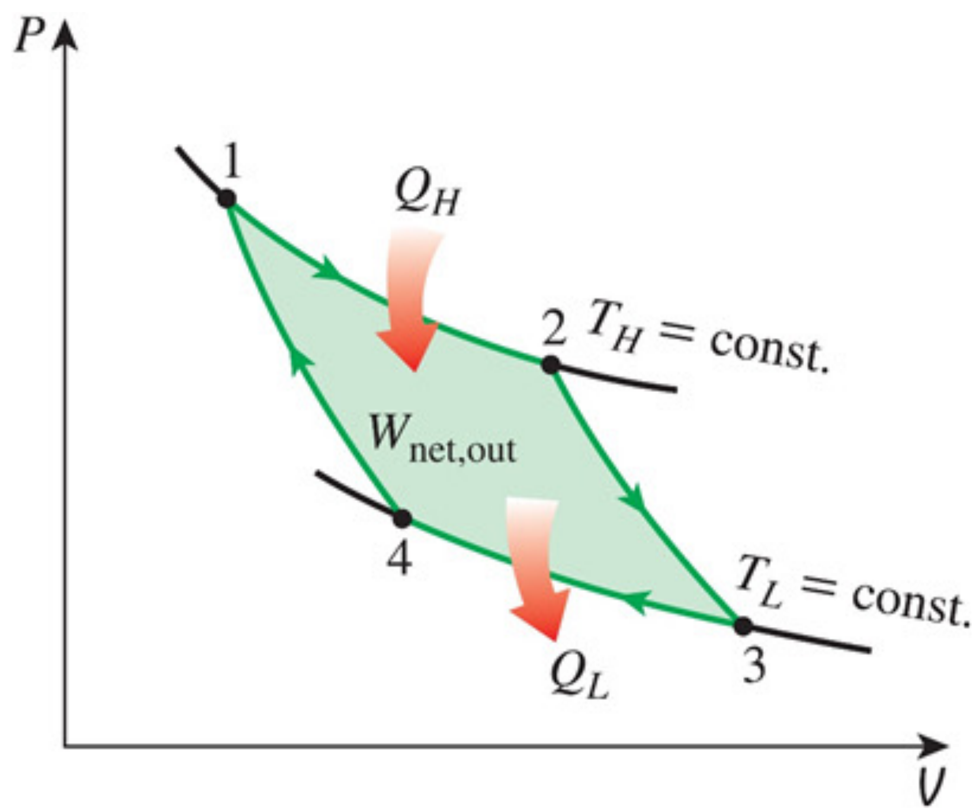
- Assignment 9 (the extra assignment) is due Thursday

- 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

RECAP

Recap

- The Reversed Carnot Cycle
  - ❑ The Carnot heat-engine cycle is a totally reversible cycle



P-V diagram of the Carnot cycle

Recap

- The equality in the *Clausius inequality* holds for totally or just internally reversible cycles and the inequality for the irreversible ones

$$\left(\oint \frac{\delta Q}{T}\right)_{int,rev} = 0$$

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{int,rev}$$

Recap

- For entropy, we can say

$$dS > \left(\frac{\delta Q}{T}\right)_{irr}$$

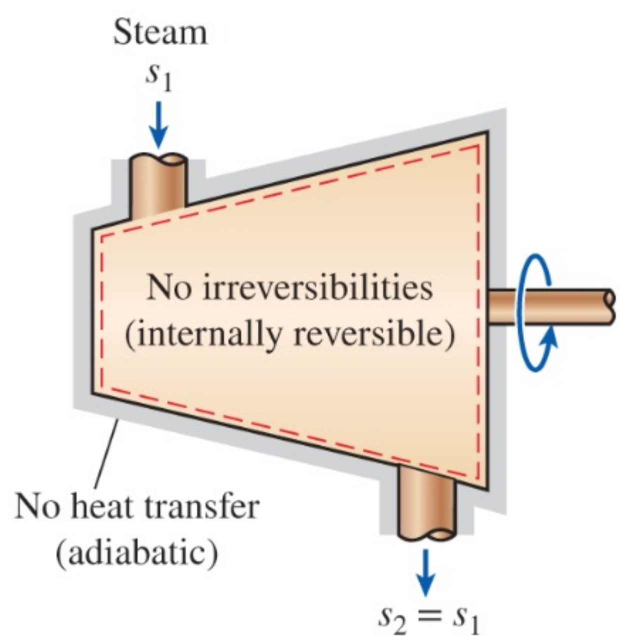
$$dS = \frac{\delta Q}{T} + \delta S_{gen}$$

Recap

- The entropy of a fixed mass can be changed by:
  - ❑ Heat Transfer
  - ❑ Irreversibilities

- Entropy of a fixed mass does not change during a process that is internally reversible and adiabatic. During this process entropy remains constant and we call it *isentropic* process

$$\Delta s = 0 \;\; or \;\; s_2 = s_1 \quad (\frac{kJ}{kg - K})$$

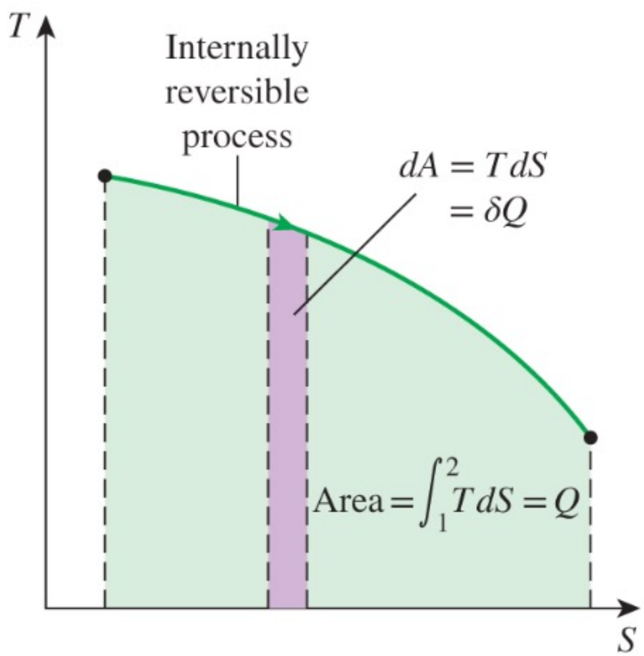


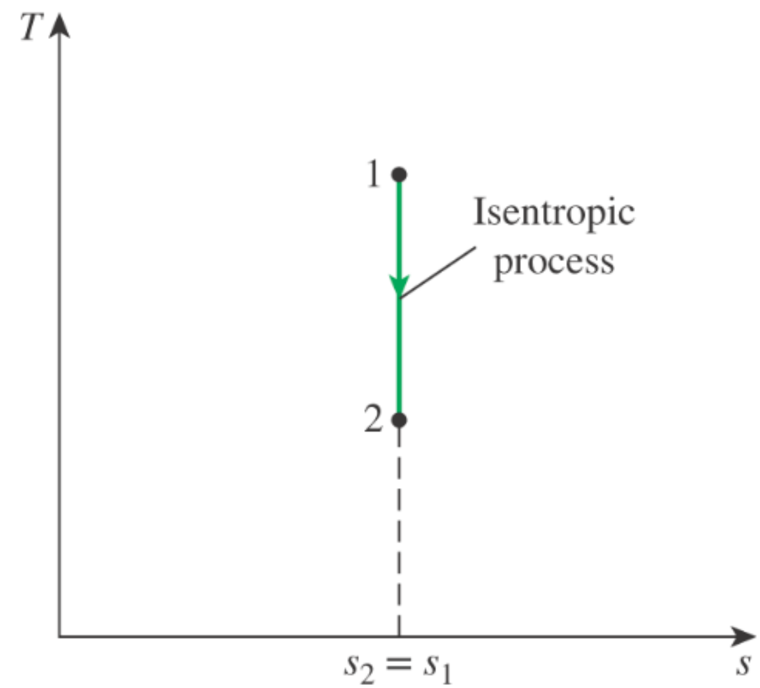
Recap

- We can rearrange our entropy equation:

$$\delta Q_{int,rev} = T\,dS$$

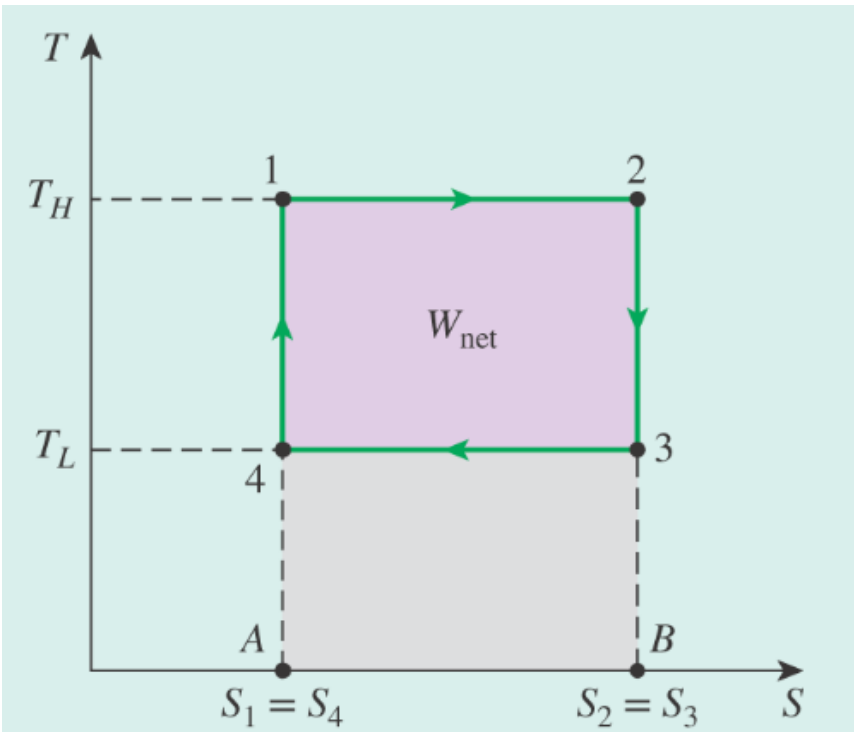
$$Q_{int,rev} = \int_1^2 T\,dS \qquad (kJ)$$





Recap

- We can find heat and work from the T-S diagram

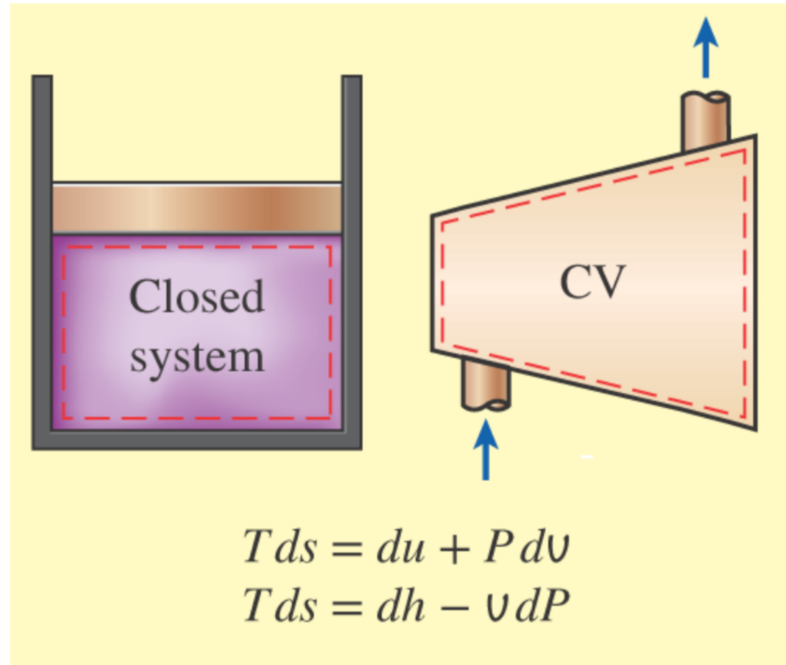


Recap

- The first T ds (or Gibbs) equation:

$$ds = \frac{du}{T} + \frac{Pdv}{T}$$

$$ds = \frac{du}{T} - \frac{vdP}{T}$$



Recap

- Liquids and solids can be approximated as incompressible substances ($dv \cong 0$ & $c_p = c_v = c_p = c$):

$$ds = \frac{du}{T} - \frac{vdP}{T}$$

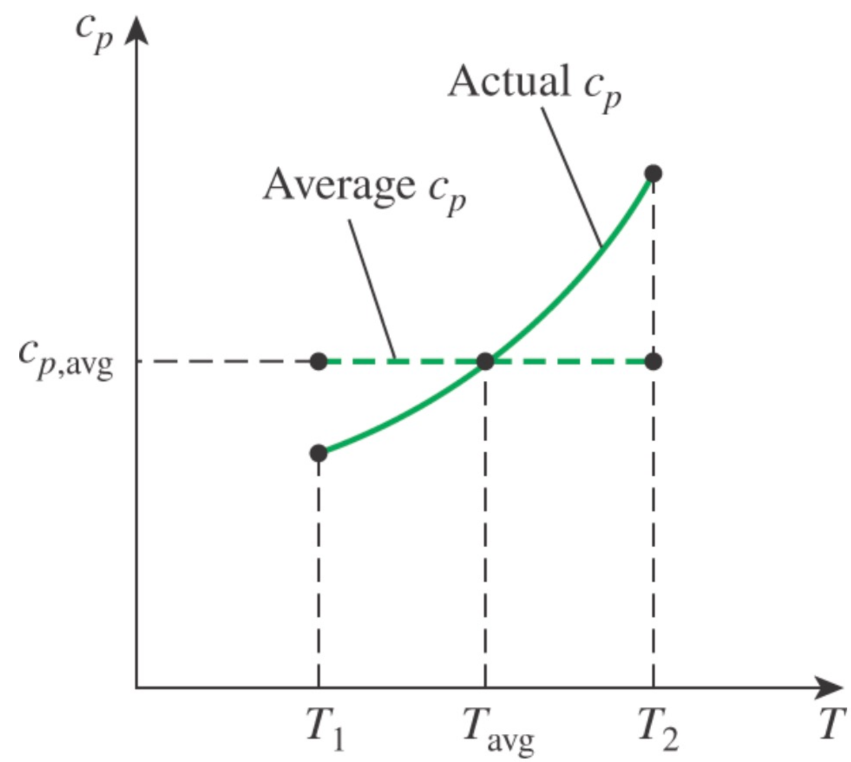
$$s_2 - s_1 = \int_1^2 c(T)\,\frac{dT}{T} \cong c_{avg}\ln(\frac{T_2}{T_1})$$

$$s_2 - s_1 = \int_1^2 c(T)\,\frac{dT}{T} \cong c_{avg}\ln\left(\frac{T_2}{T_1}\right) = 0 \quad \rightarrow \quad T_2 = T_1$$ (For isentropic)

Recap

- Approach 1: Constant Specific Heats (Approximate Analysis):

$$s_2 - s_1 = \int_1^2 c_v(T)\,\frac{dT}{T} + R\,\ln(\frac{v_2}{v_1})$$



$$s_2 - s_1 = c_{v,avg}\,\ln\left(\frac{T_2}{T_1}\right) + R \times ln\left(\frac{v_2}{v_1}\right)$$

$$s_2 - s_1 = c_{p,avg} \times \ln\left(\frac{T_2}{T_1}\right) - R \times \ln(\frac{P_2}{P_1})$$

Recap

- Approach 2: Variable Specific Heats (Exact Analysis):

$$s^0 = \int_0^T c_p(T)\frac{dT}{T}$$

$$\int_0^T c_p(T)\frac{dT}{T} = s_2^0 - s_1^0$$

$$s_2 - s_1 = s_2^0 - s_1^0 - R\times\ln(\frac{P_2}{P_1})$$

$$\overline{s_2} - \overline{s_1} = \overline{s_2^0} - \overline{s_1^0} - R_u\times\ln(\frac{P_2}{P_1})$$

T, K	s°, kJ/kg·K
⋮	⋮
300	1.70203
310	1.73498
320	1.76690
⋮	⋮

(Table A-21)

THE ENTROPY CHANGE OF IDEAL GASES

The Entropy Change of Ideal Gases

- Approach 1: Constant Specific Heats (Approximate Analysis) for Isentropic Processes of Ideal Gases

$$s_2 - s_1 = c_{v,avg} \ln\left(\frac{T_2}{T_1}\right) + R \times ln\left(\frac{v_2}{v_1}\right) \quad \rightarrow \quad \ln\left(\frac{T_2}{T_1}\right) = -\frac{R}{c_v}\ln(\frac{v_2}{v_1})$$

$$s_2 - s_1 = c_{p,avg} \times \ln\left(\frac{T_2}{T_1}\right) - R \times \ln\left(\frac{P_2}{P_1}\right) \quad \rightarrow \quad \ln\left(\frac{T_2}{T_1}\right) = \frac{R}{c_p}\ln(\frac{P_2}{P_1})$$

The Entropy Change of Ideal Gases

- Approach 1: Constant Specific Heats (Approximate Analysis) for Isentropic Processes of Ideal Gases

$$s_2 - s_1 = c_{v,avg} \ln\left(\frac{T_2}{T_1}\right) + R \times ln\left(\frac{v_2}{v_1}\right) \quad \rightarrow \quad \ln\left(\frac{T_2}{T_1}\right) = -\frac{R}{c_v}\ln(\frac{v_2}{v_1})$$

$$\ln\left(\frac{T_2}{T_1}\right) = \ln\left(\frac{v_1}{v_2}\right)^{\frac{R}{c_v}}$$

$$\begin{cases} c_p - c_v = R \\ k = \dfrac{c_p}{c_v} \end{cases} \quad \rightarrow \frac{R}{c_v} = k - 1$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

The Entropy Change of Ideal Gases

- Approach 1: Constant Specific Heats (Approximate Analysis) for Isentropic Processes of Ideal Gases

$$\left(\frac{T_2}{T_1}\right)_{s=constant} = \left(\frac{v_1}{v_2}\right)^{k-1}$$

$$\left(\frac{T_2}{T_1}\right)_{s=constant} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

$$\left(\frac{P_2}{P_1}\right)_{s=constant} = \left(\frac{v_1}{v_2}\right)^{k}$$

The Entropy Change of Ideal Gases

- Approach 1: Constant Specific Heats (Approximate Analysis) for Isentropic Processes of Ideal Gases

$$Tv^{k-1} = Constant$$

$$TP^{\frac{1-k}{k}} = Constant$$

$$Pv^{k} = Constant$$

$$\left(\frac{T_2}{T_1}\right)_{s=\text{const.}} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{\upsilon_1}{\upsilon_2}\right)^{k-1}$$

Valid for
*ideal gas
*isentropic process
*constant specific heats

The Entropy Change of Ideal Gases

- Approach 2: Variable Specific Heats (Exact Analysis) for Isentropic Processes of Ideal Gases

$$0 = s_2^0 - s_1^0 - R \times \ln(\frac{P_2}{P_1})$$

$$s_2^0 = s_1^0 + R \times \ln(\frac{P_2}{P_1})$$

$$s_2^0 = s_1^0 + R \times \ln\left(\frac{P_2}{P_1}\right) \quad \rightarrow \quad \frac{P_2}{P_1} = \exp(\frac{s_2^0 - s_1^0}{R})$$

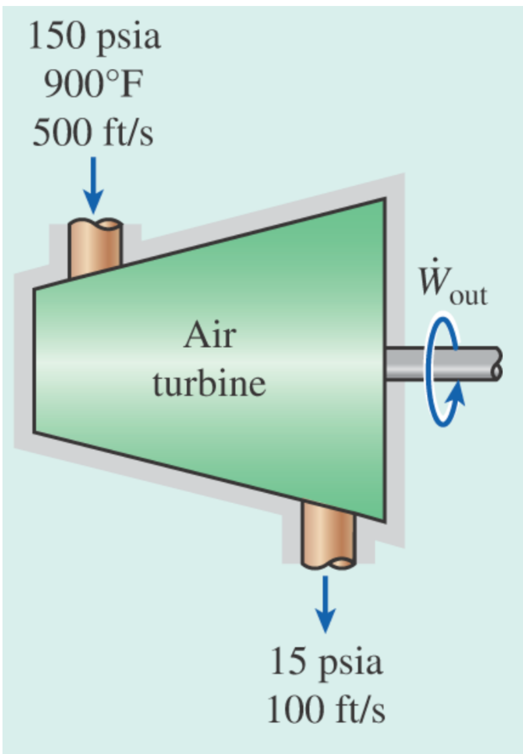
(It will not be included in the exam)

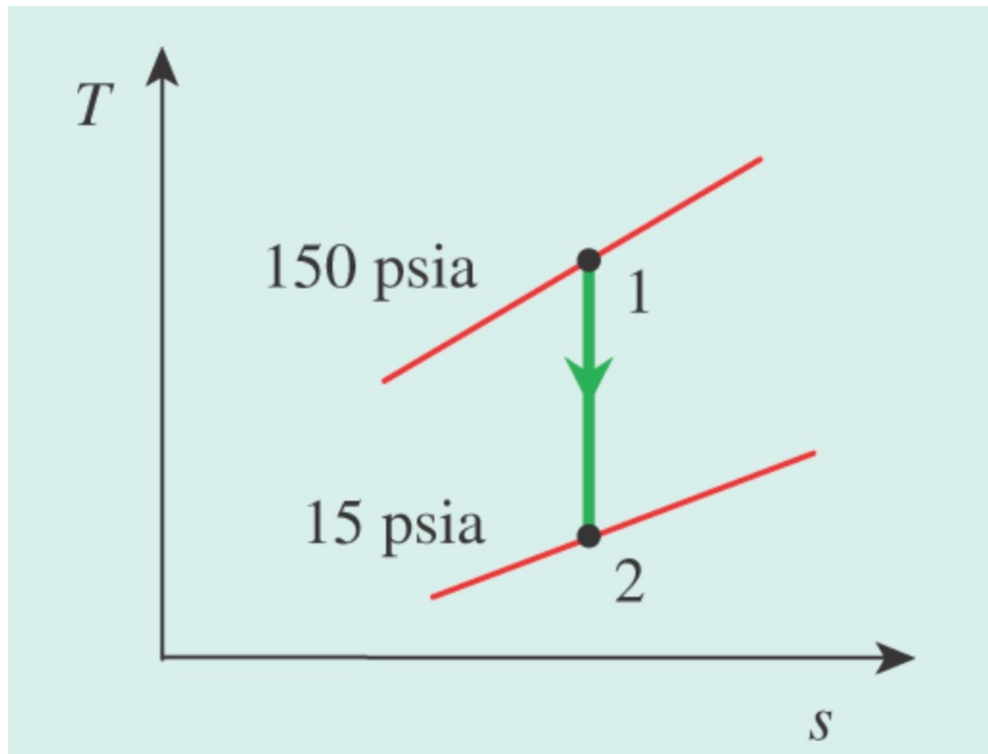
Class Activity

- Air enters an isentropic turbine at 150 psia and 900 °F through a 0.5 ft^2 inlet section with a velocity of 500 ft/s. It leaves at 15 psia with a velocity of 100 ft/s. Calculate the air temperature at the turbine exit and the power produced, in hp, by this turbine.

Class Activity

- Solution (assumptions):
  - ❑ Steady flow
  - ❑ The process is isentropic (both reversible and adiabatic)
  - ❑ Ideal gas with a constant specific heat





Class Activity

- Solution (Tables):
  - ❑ Table A-2Eb: $@600\ °F \rightarrow c_p = 0.250 \frac{Btu}{lbm-R}\ and\ k = 1.3777$

Ideal-gas specific heats of various common gases (*b*) At various temperatures

Temp., °F	c_p Btu/lbm · R	c_v Btu/lbm · R	k	c_p Btu/lbm · R	c_v Btu/lbm · R	k
	Air			*Carbon dioxide, CO_2*		
40	0.240	0.171	1.401	0.195	0.150	1.300
100	0.240	0.172	1.400	0.205	0.160	1.283
200	0.241	0.173	1.397	0.217	0.172	1.262
300	0.243	0.174	1.394	0.229	0.184	1.246
400	0.245	0.176	1.389	0.239	0.193	1.233
500	0.248	0.179	1.383	0.247	0.202	1.223
600	0.250	0.182	1.377	0.255	0.210	1.215
700	0.254	0.185	1.371	0.262	0.217	1.208
800	0.257	0.188	1.365	0.269	0.224	1.202
900	0.259	0.191	1.358	0.275	0.230	1.197
1000	0.263	0.195	1.353	0.280	0.235	1.192
1500	0.276	0.208	1.330	0.298	0.253	1.178
2000	0.286	0.217	1.312	0.312	0.267	1.169

Class Activity

- Solution (Tables):
  - ❑ Table A-1E: $R = 0.3704 \frac{psia-ft^3}{lbm-R}$

TABLE A–1E

Molar mass, gas constant, and critical-point properties

Substance	Formula	Molar mass, *M* lbm/lbmol	Gas constant, *R**		*Critical-point properties*		
			Btu/lbm · R	psia · ft^3/lbm · R	Temperature, R	Pressure, psia	Volume, ft^3/lbmol
Air	–	28.97	0.06855	0.3704	238.5	547	1.41

Class Activity

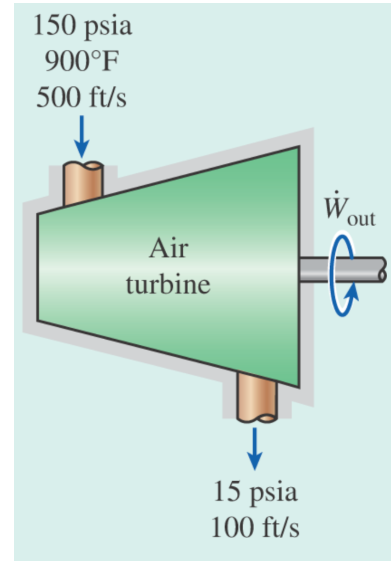
- Solution (Problem solving):

$$\dot{m} = \dot{m}_1 = \dot{m}_2$$

$$\dot{E}_{in} - \dot{E}_{out} = \frac{d\dot{E}_{system}}{dt} = 0$$

$$\dot{m}(h_1 + V_1^2) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) + \dot{W}_{out}$$

$$\dot{W}_{out} = \dot{m}\left(h_1 - h_1 + \frac{V_1^2 - V_2}{2}\right)$$



Class Activity

- Solution (Calculations):

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \rightarrow T_2 = T_1 \times \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = (900 + 460\ R)\left(\frac{15\ psia}{150\ psia}\right)^{\frac{0.3777}{1.377}} = 724\ R$$

$$v_1 = \frac{RT_1}{P_1} = \frac{\left(0.3704\,\frac{psia - ft^3}{lbm - R}\right)(900 + 460\ R)}{150\ psia} = 3.358\,\frac{ft^3}{lbm}$$

$$\dot{m} = \frac{A_1 V_1}{v_1} = \frac{(0.5\ ft^2)\left(500\,\frac{ft}{s}\right)}{3.358\,\frac{ft^3}{lbm}} = 74.45\,\frac{lbm}{s}$$

Class Activity

- Solution (Calculations):

$$\dot{W}_{out} = \dot{m}\left(h_1 - h_1 + \frac{V_1^2 - V_2}{2}\right)$$

$$\dot{W}_{out} = \left(74.45\,\frac{lbm}{s}\right)[\left(0.250\,\frac{Btu}{lbm-R}\right)(1360-724R) + \left(\frac{\left(500\,\frac{ft}{s}\right)^2}{2} - \frac{\left(100\,\frac{ft}{s}\right)^2}{2}\right)\left(\frac{\frac{1\,\frac{Btu}{lbm}}{25.037}ft^2}{s^2}\right)$$

$$\dot{W}_{out} = 12{,}194\,\frac{Btu}{s}\left(\frac{1\ hp}{0.7068\,\frac{Btu}{s}}\right) = 17{,}250\ hp$$

Chapter 8 Summary

- We did not cover 8-10, 8-11, and 8-12

POWER AND REFRIGERATION CYCLES

Power and Refrigeration Cycles

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

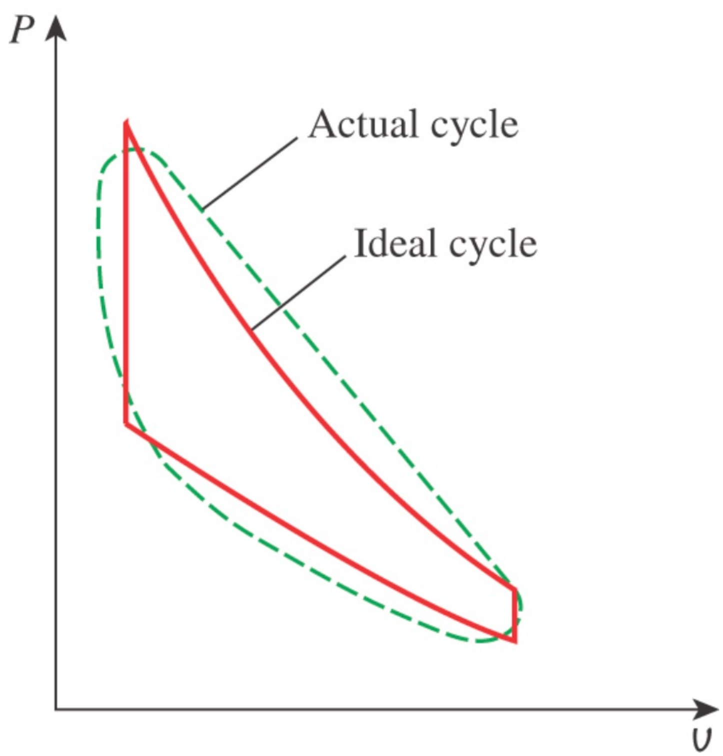
- Remember to produce work we need a cycle:
  - ❑ Power cycles for heat engines
  - ❑ Refrigeration cycles for refrigerators, heat pumps, air conditioners

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

BASIC CONSIDERATIONS IN THE ANALYSIS OF POWER CYCLES

Considerations in the Analysis of Power Cycles

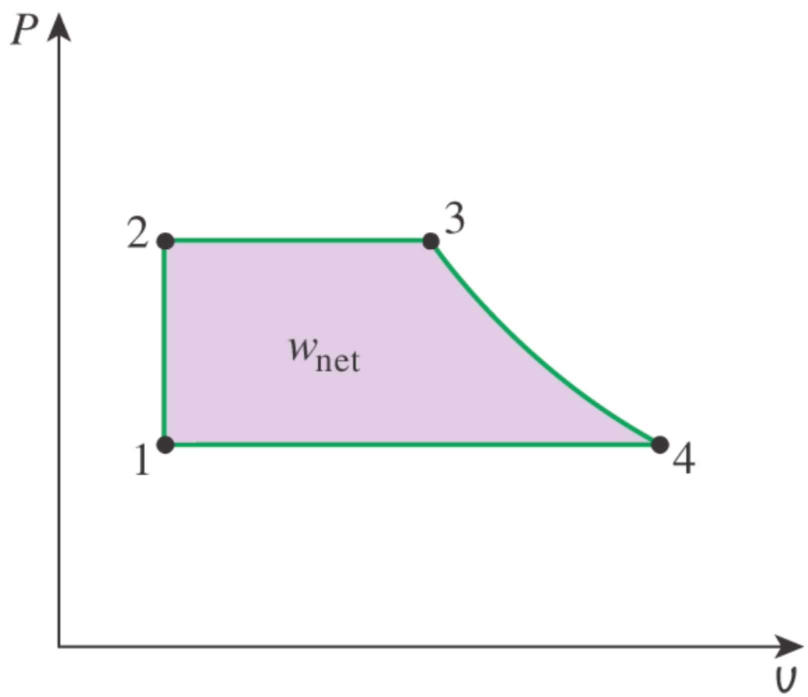
- We resemble most of actual cycles with internal irreversibilities and complexities with internal reversible cycles known as ideal cycles

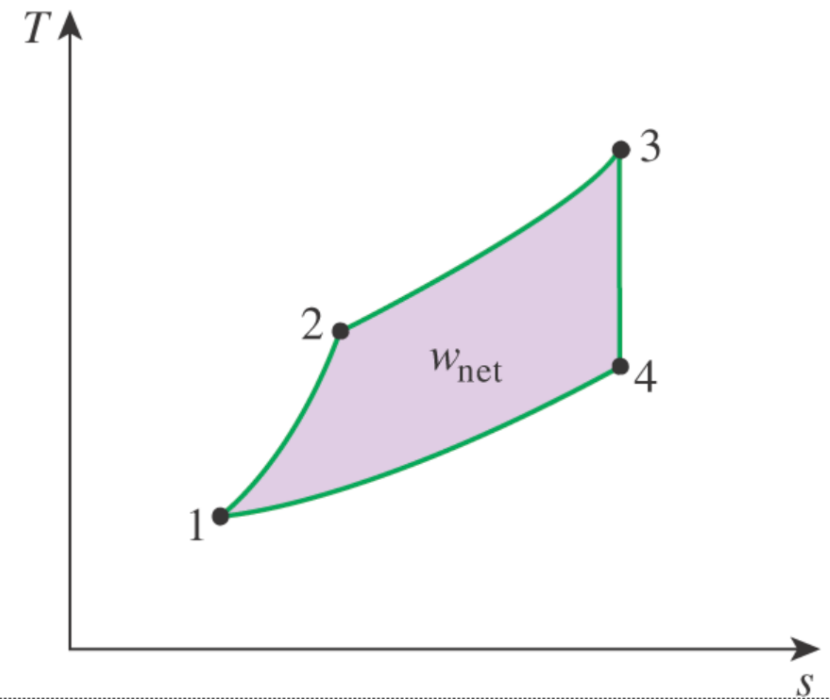


$$\eta_{thermal} = \frac{w_{net}}{q_{in}} = \frac{W_{net}}{Q_{in}}$$

Considerations in the Analysis of Power Cycles

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

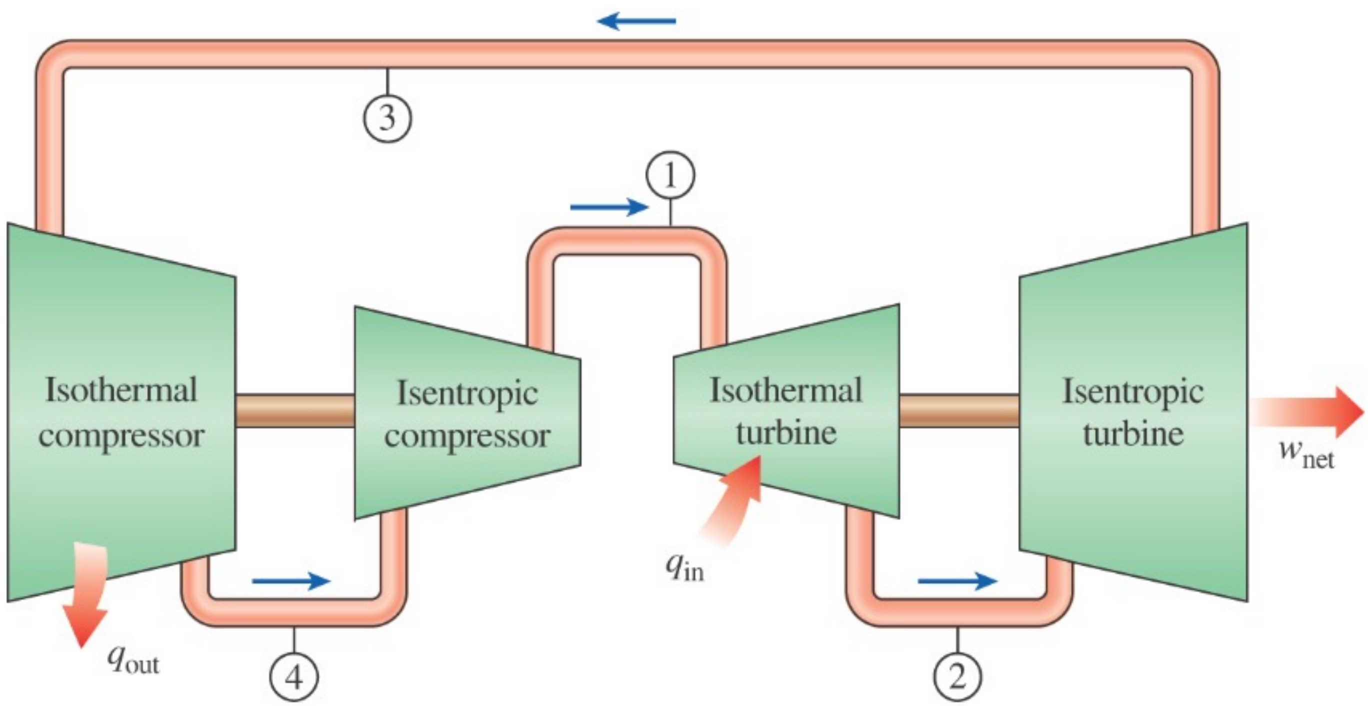




THE CARNOT CYCLE AND ITS VALUE IN ENGINEERING

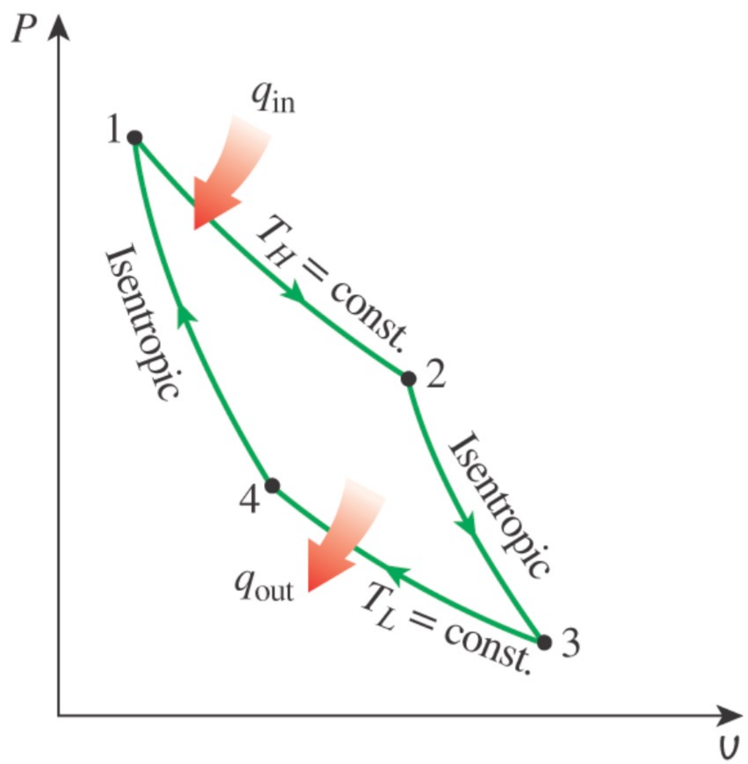
The Carnot Cycle and Its Value in Engineering

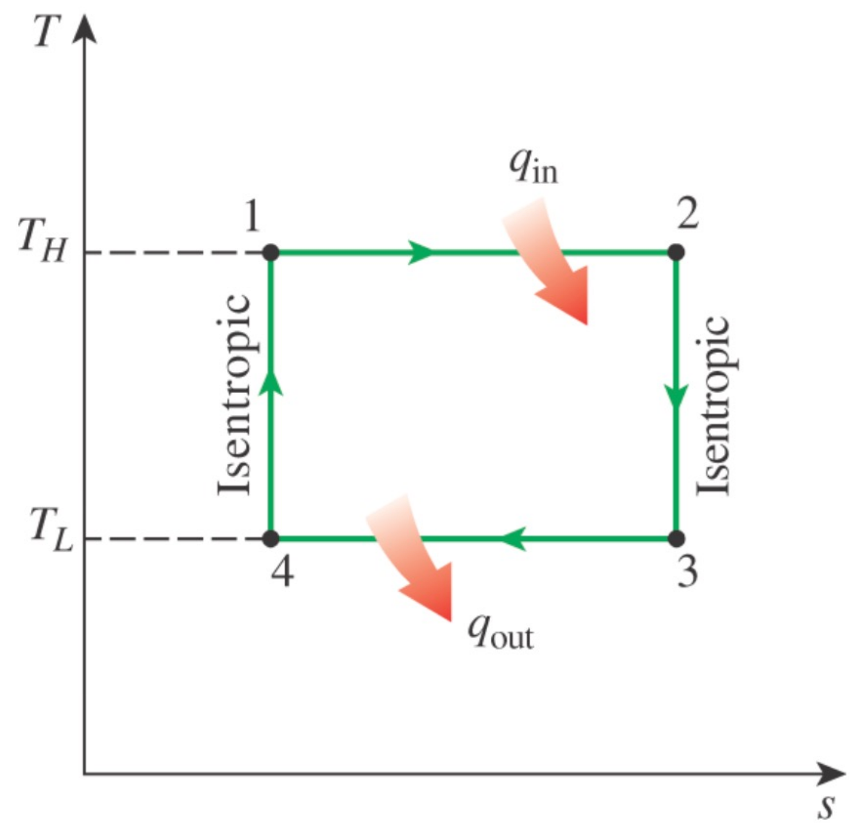
- Carnot cycle has four main processes:
  1. Isothermal heat addition
  2. Isentropic expansion
  3. Isothermal heat rejection
  4. Isentropic compression



The Carnot Cycle and Its Value in Engineering

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





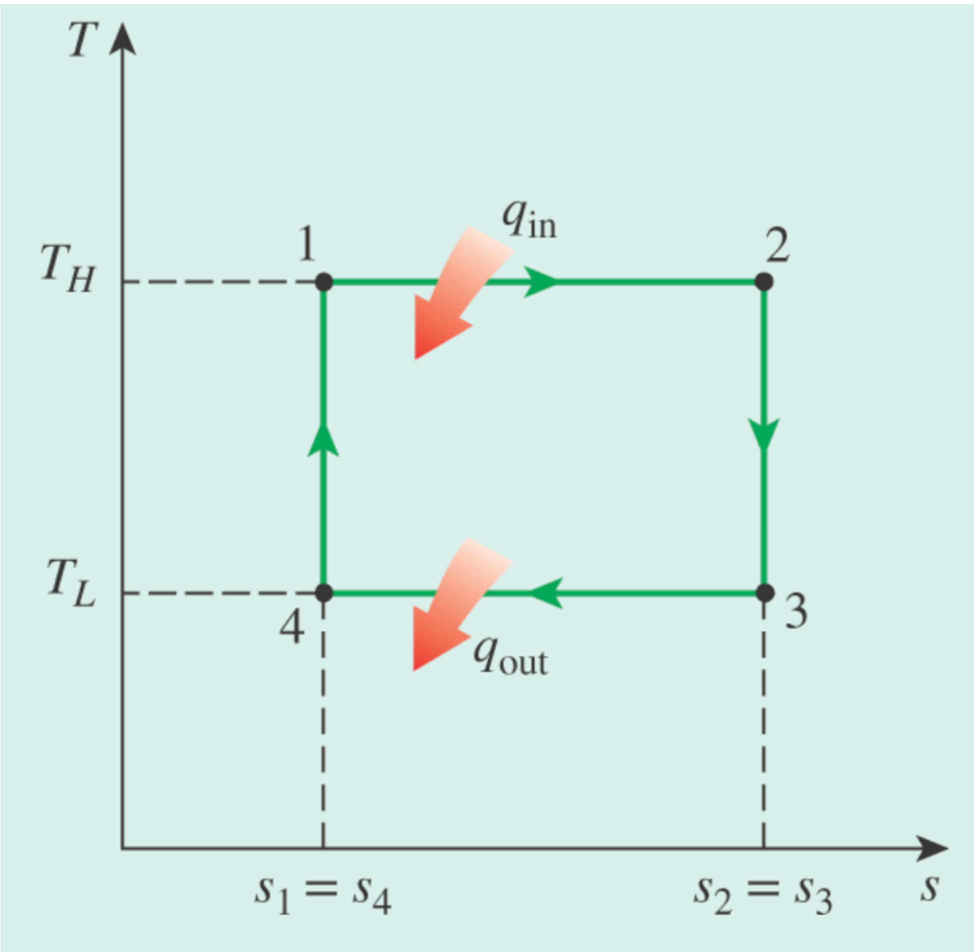
CLASS ACTIVITY

Class Activity

- ***(Derivation of the Efficiency of the Carnot Cycle):*** Show that the thermal efficiency of a Carnot cycle operating between limits of T_H and T_L is solely function of these two temperatures is equal to $\eta_{thermal,Carnot} = 1 - \frac{T_L}{T_H}$

Class Activity

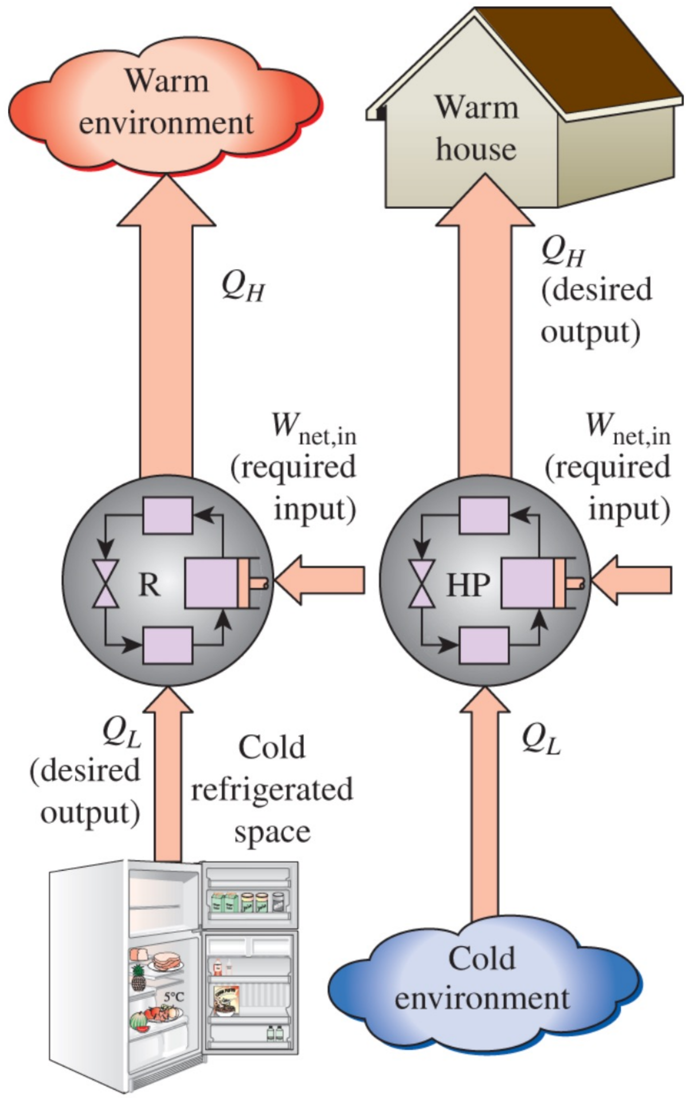
- ***Solution:***



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

Refrigerators and Heat Pumps

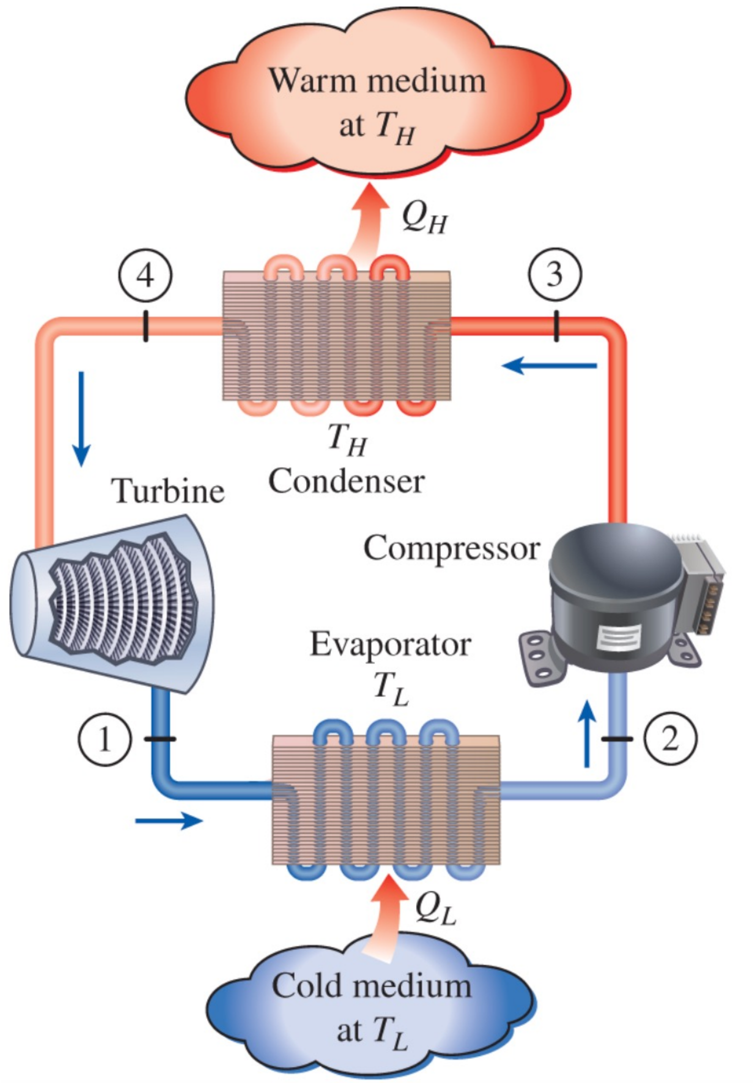
- We looked at this in Chapter 7



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

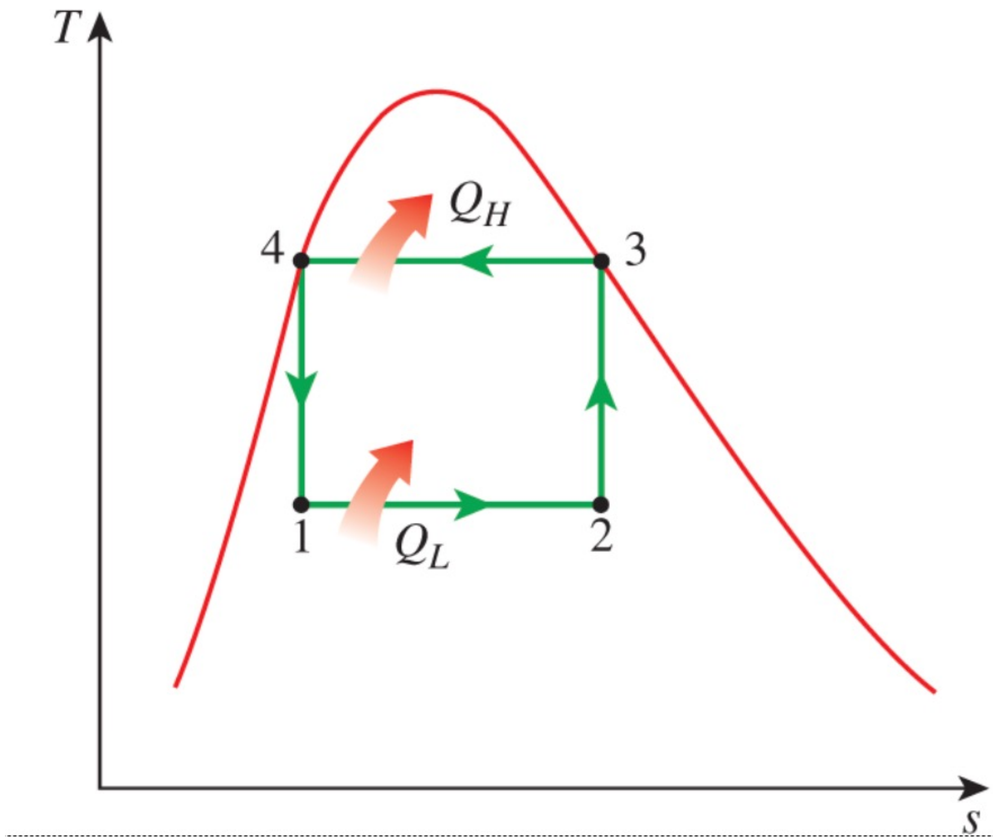
Refrigerators and Heat Pumps

- The Carnot cycle includes:



Refrigerators and Heat Pumps

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



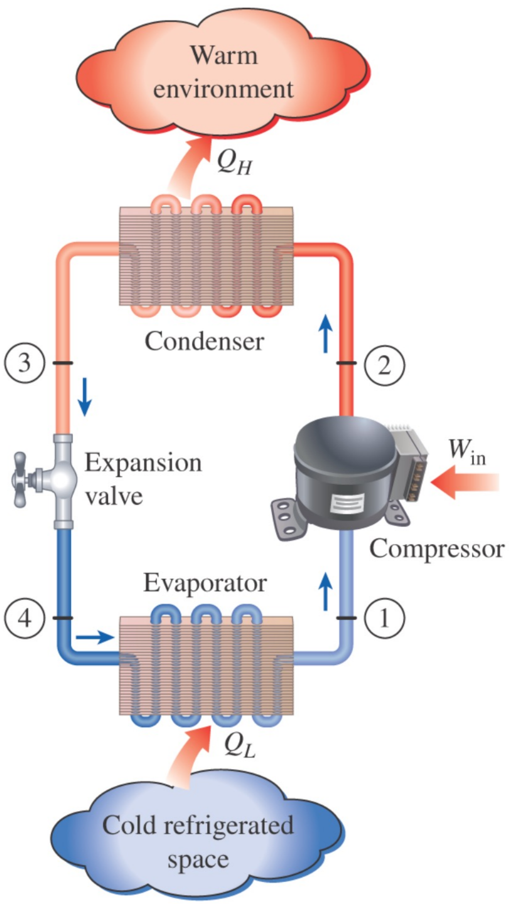
IDEAL VAPOR COMPRESSION REFRIGERATION CYCLE (SECTION 9-16)

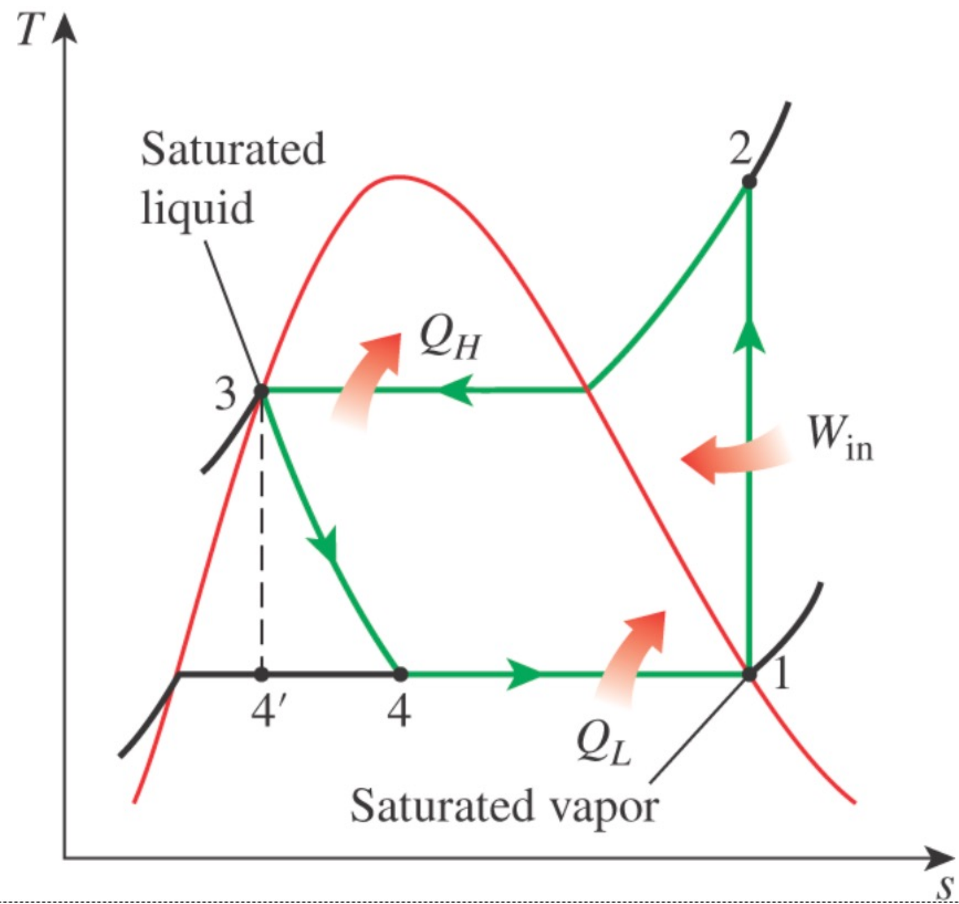
Ideal Vapor Compression Refrigeration Cycle

- 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

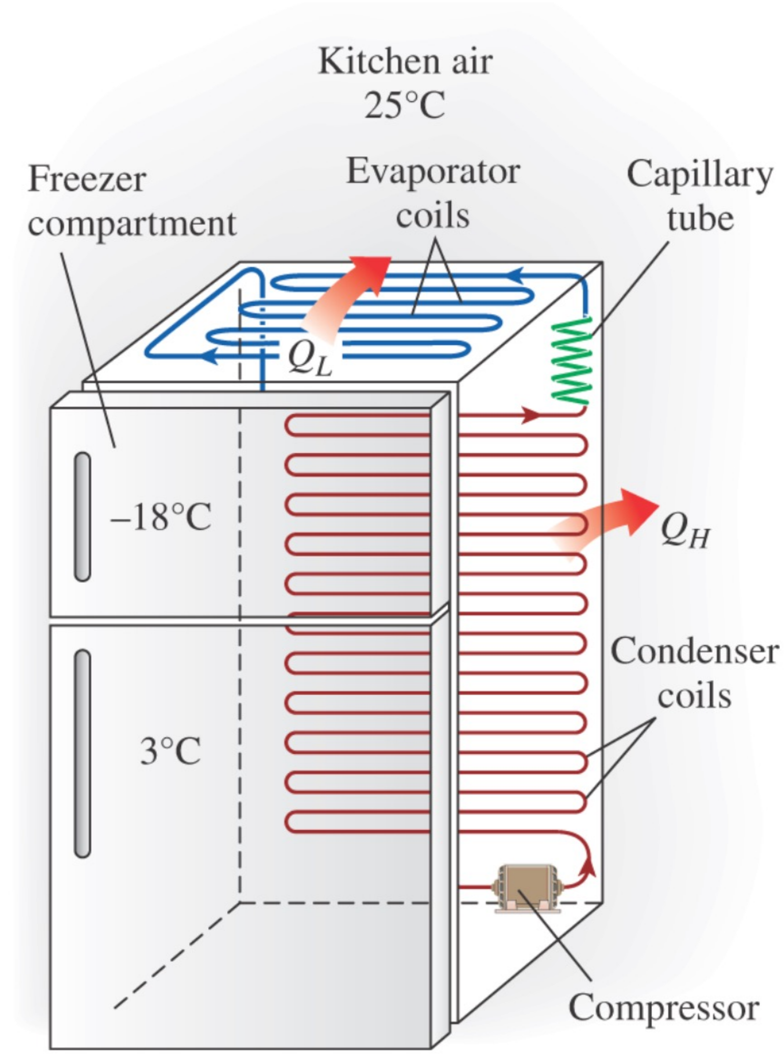
- In practice, there are several issues that limit the use of Carnot vapor compression cycle:





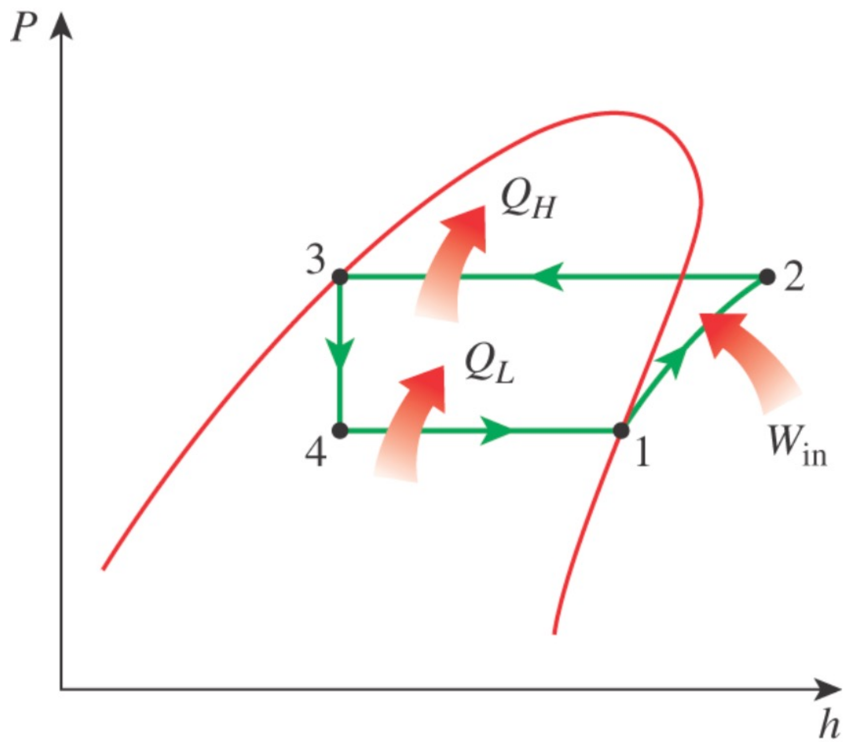
Ideal Vapor Compression Refrigeration Cycle

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



Ideal Vapor Compression Refrigeration Cycle

- P-h diagram is very helpful 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

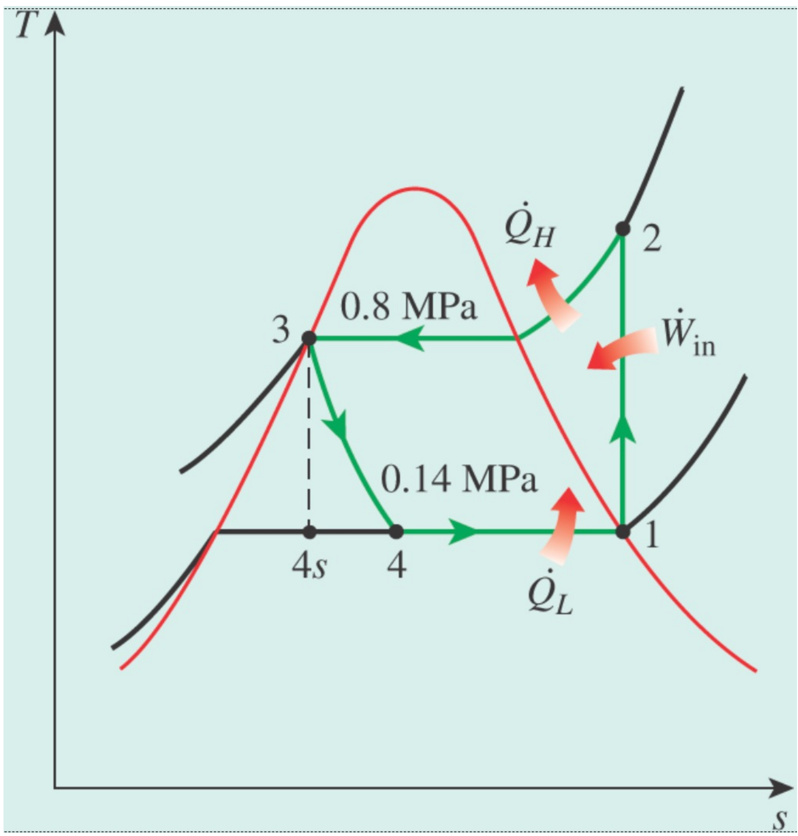
Class Activity

- 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, m³/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:

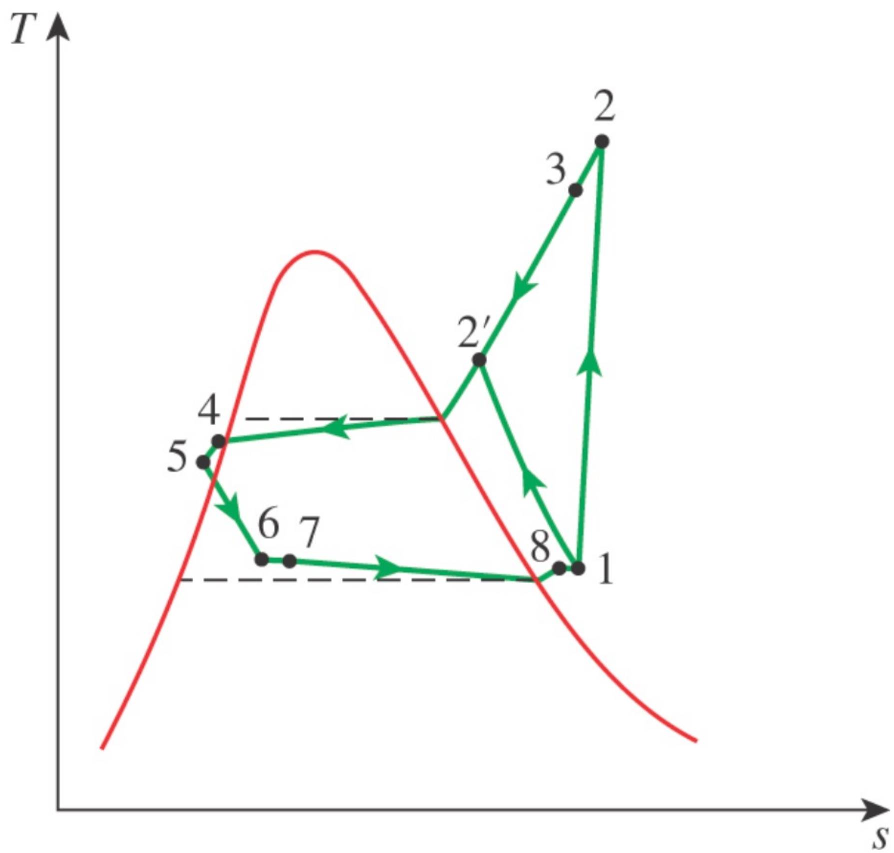
$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.19\ kW}{1.81\ kW} = 3.97$$

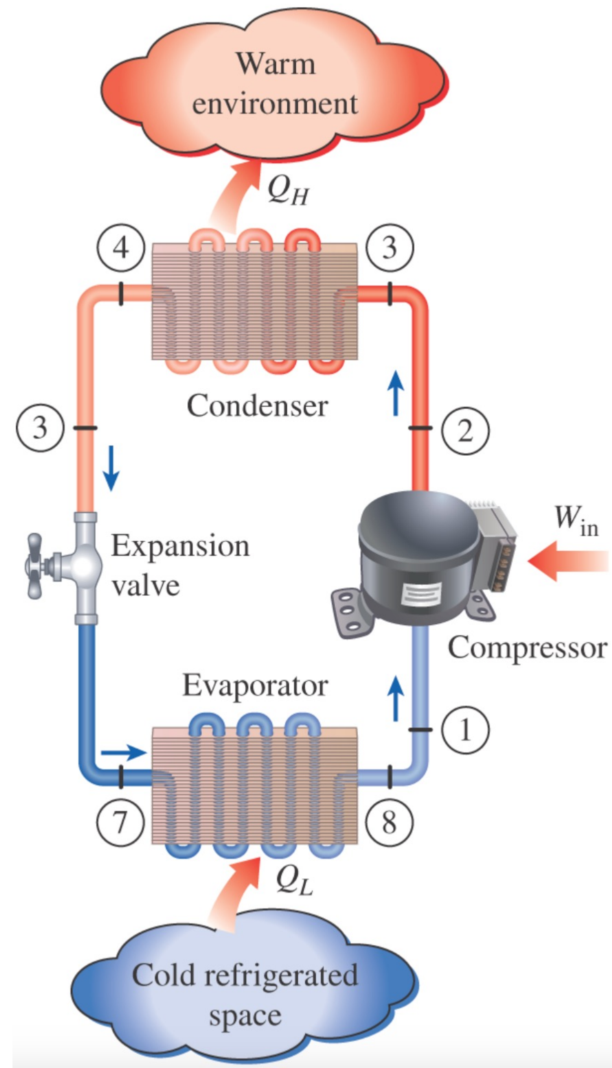
What would be the COP is the throttling process is isentropic?

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

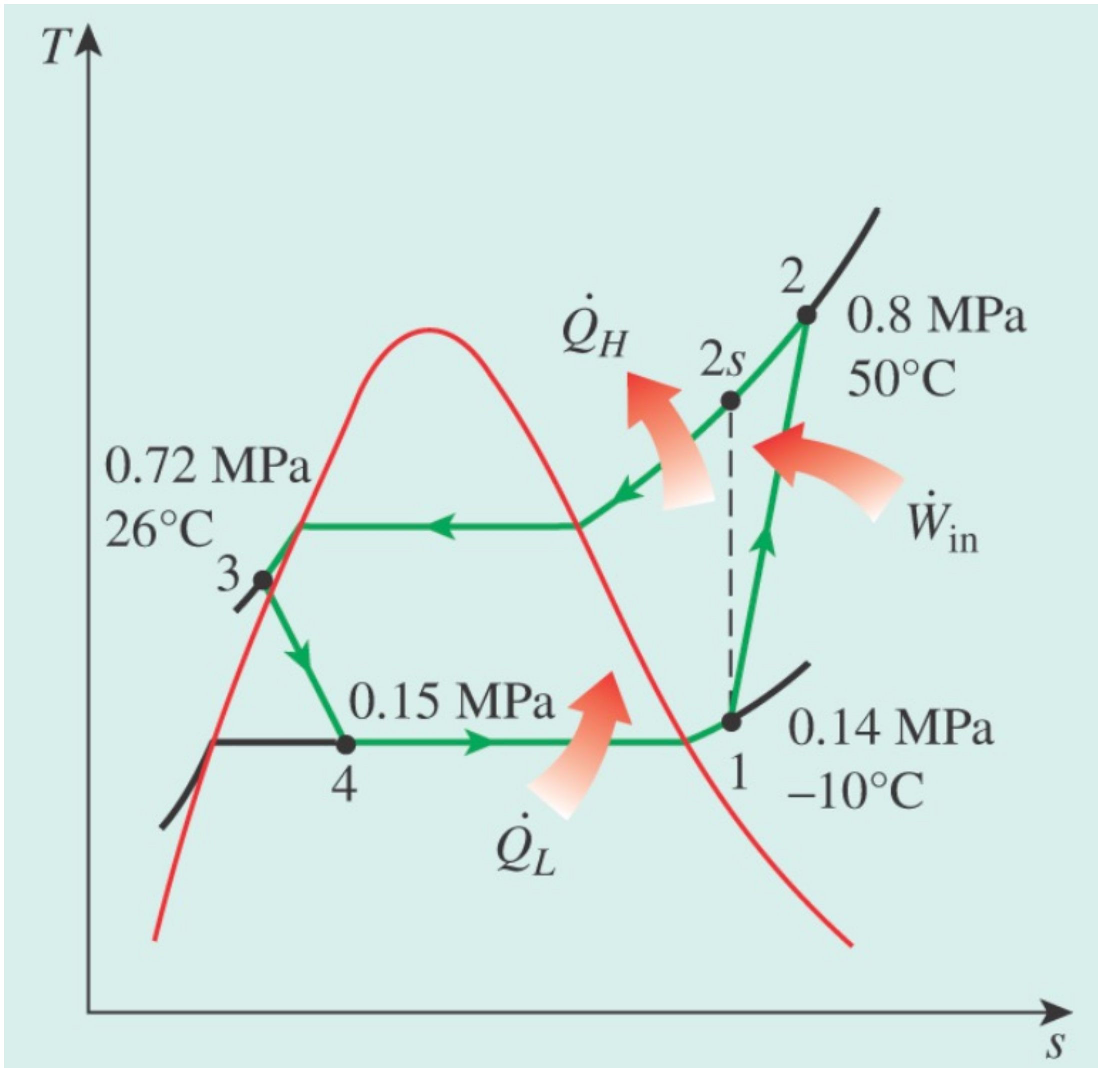
- ***(The actual vapor-compression refrigeration cycle – almost similar inputs to the previous class activity):*** Refrigerant 134-a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and -10 °C at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50 °C. The refrigerant is cooled in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

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg: 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 m³/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

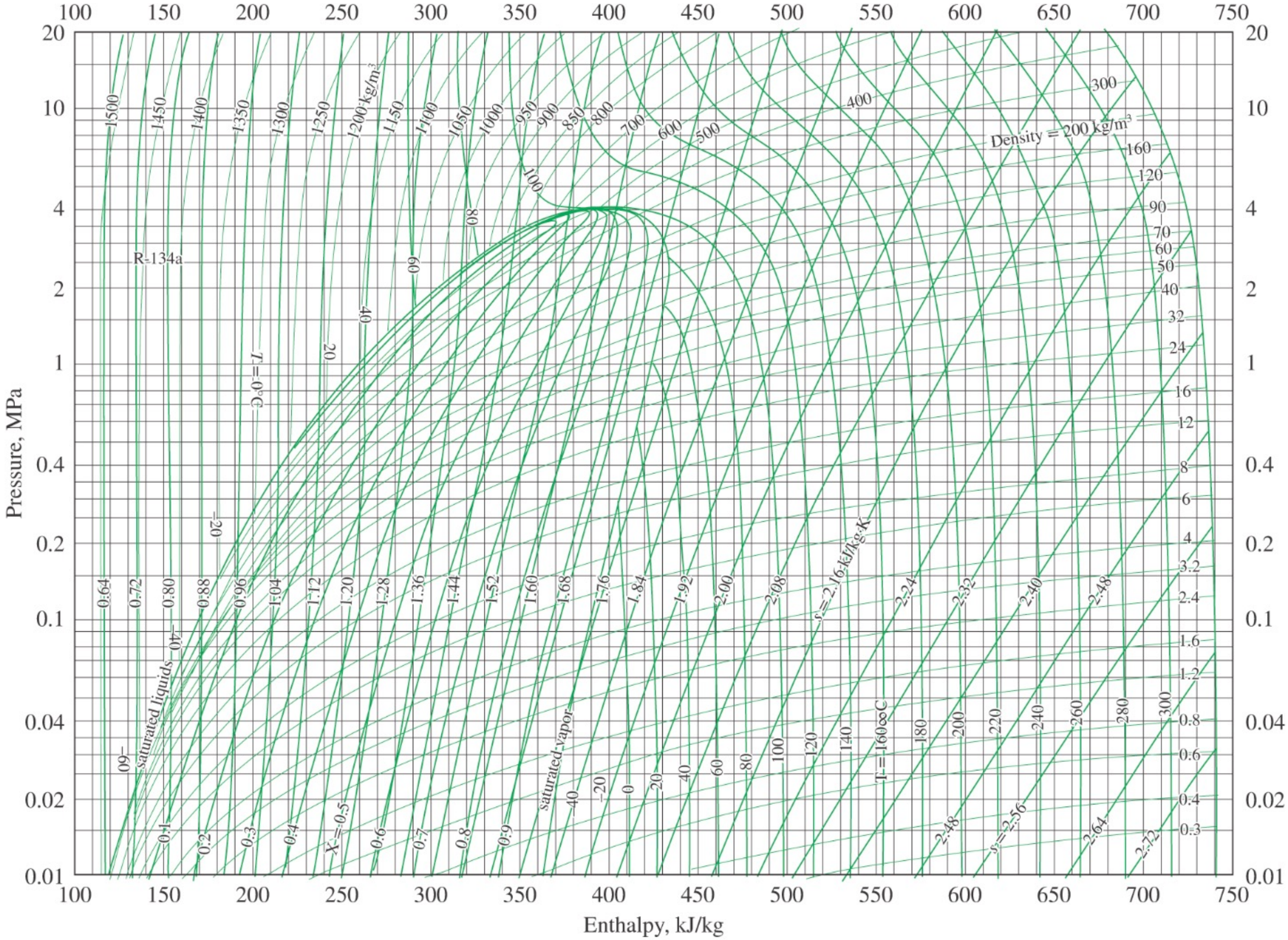
- Solution (c): The coefficient of performance of the refrigerator is:

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

CLASS ACTIVITY

Class Activity

- Solve the previous example using P-h diagram (Figure A-14)



Class Activity

- Solve the previous example using P-h diagram (ASHRAE)

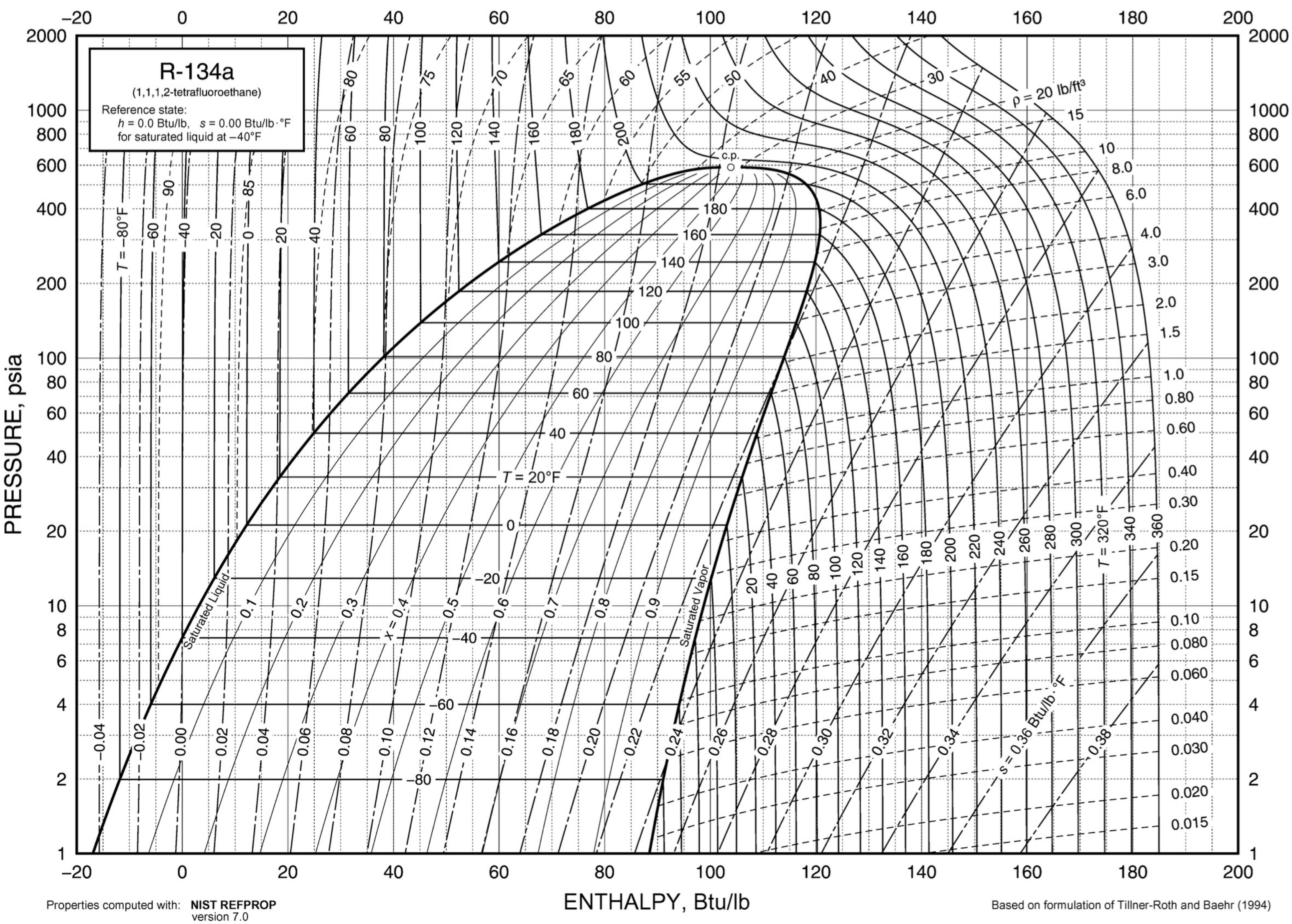


Fig. 8 Pressure-Enthalpy Diagram for Refrigerant 134a

Class Activity

- Solve the previous example using P-h diagram (ASHRAE)

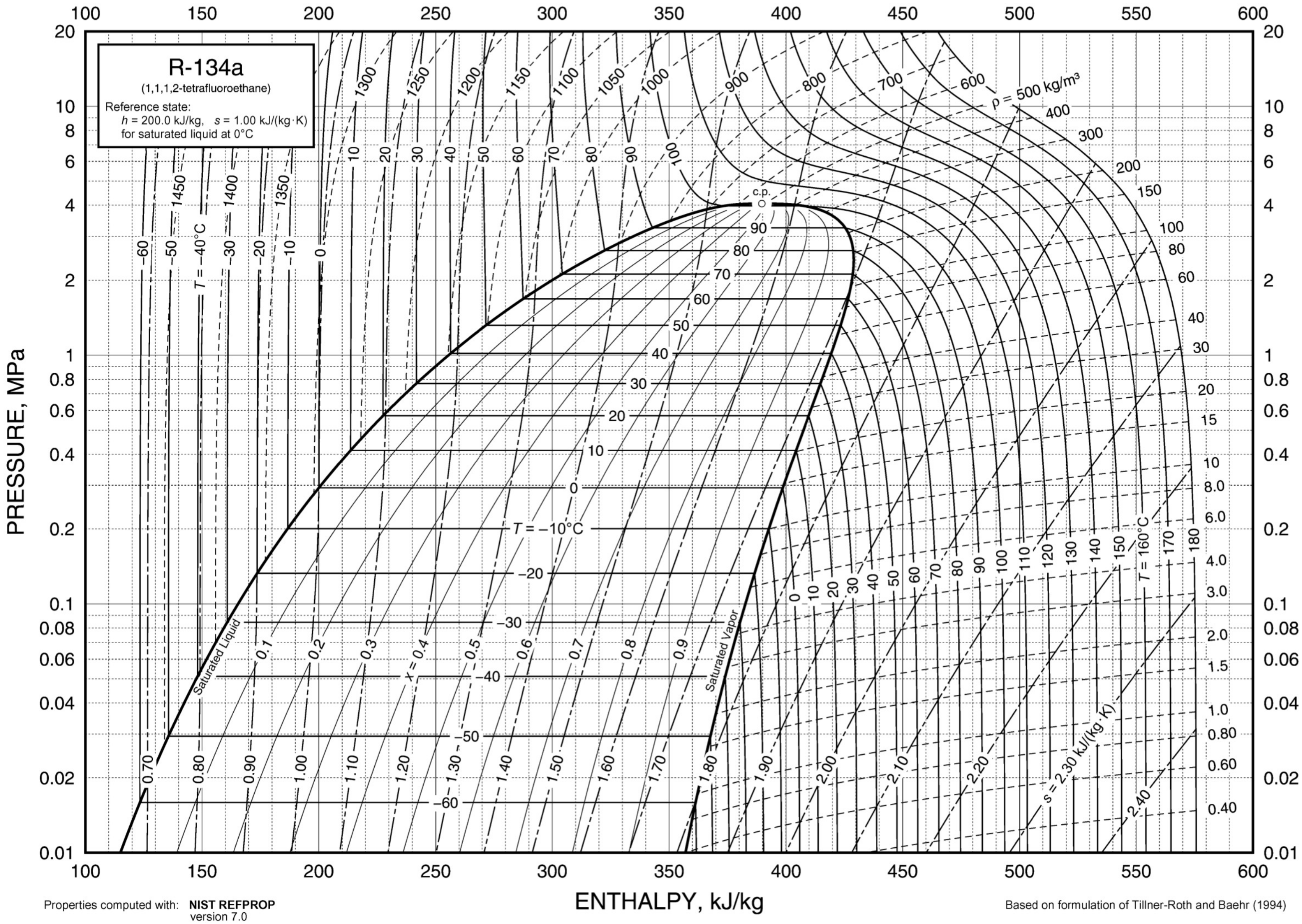


Fig. 8 Pressure-Enthalpy Diagram for Refrigerant 134a