Quiz 6
Chemical Engineering Thermodynamics
March 9, 2015

1)PP5.1 (See figures 5.8 and 5.9 below and R134a PH chart and table.)

P5.1 An ordinary vapor compression cycle is to operate a refrigerator on R134a between –40°C and 40°C (condenser temperatures). Compute the coefficient of performance and the heat removed from the refrigerator per day if the power used by the refrigerator is 9000 J per day.

2) (See Figure 5.13 and methane PH diagram below.)

5.15 The Claude liquefaction process is to be applied to methane. Using the schematic of Fig. 5.13 on page 214 for stream numbering, the key variables depend on the fraction of stream 3 that is liquefied, $\dot{m}_8/\dot{m}_3$, and the fraction of stream 3 that is fed through the expander, $\dot{m}_5/\dot{m}_3$. Create a table listing all streams from low to high stream numbers. Fill in the table as you complete the problem sections. Attach a *P-H* diagram with your solution.

(a) Write a mass balance for the system boundary encompassing all equipment except the compressor and precooler.
(b) Write an energy balance for the same boundary described in part (a), and show

$$\frac{\dot{m}_8}{\dot{m}_3} = \frac{(H_3 - H_{12}) + (\dot{m}_5/\dot{m}_3)W_{S\ \mathrm{expander}}}{(H_8 - H_{12})}$$

(c) Stream 3 is to be 300 K and 3 MPa, stream 4 is to be 280 K and 3 MPa, stream 12 is to be 290 K and 0.1 MPa, and the flash drum is to operate at 0.1 MPa. The expander has an efficiency of 91%. The fraction liquefied is to be $\dot{m}_8/\dot{m}_3$ = 0.15. Determine how much flow to direct through the expander, $\dot{m}_5/\dot{m}_3$.
(d) Find the enthalpies of streams 3–12, and the temperatures and pressures.

3) Test yourself Chapter 6

1. What are the restrictions necessary to calculate one state property in terms of only two other state variables?

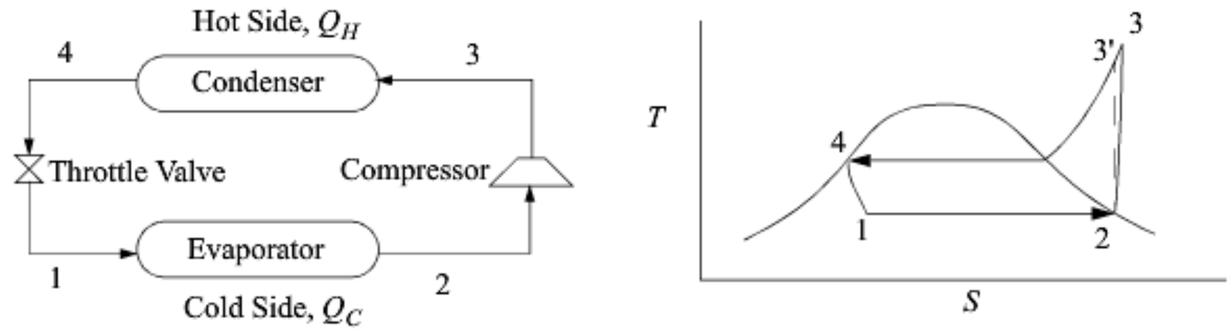
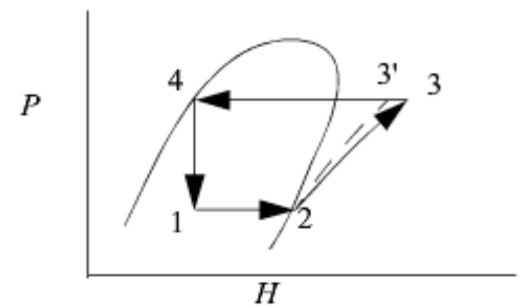


Figure 5.8 *OVC refrigeration cycle process schematic and T-S diagram.*

Figure 5.9 *OVC refrigeration cycle plotted on the more commonly used P-H diagram. State numbers correspond to Fig. 5.8.*



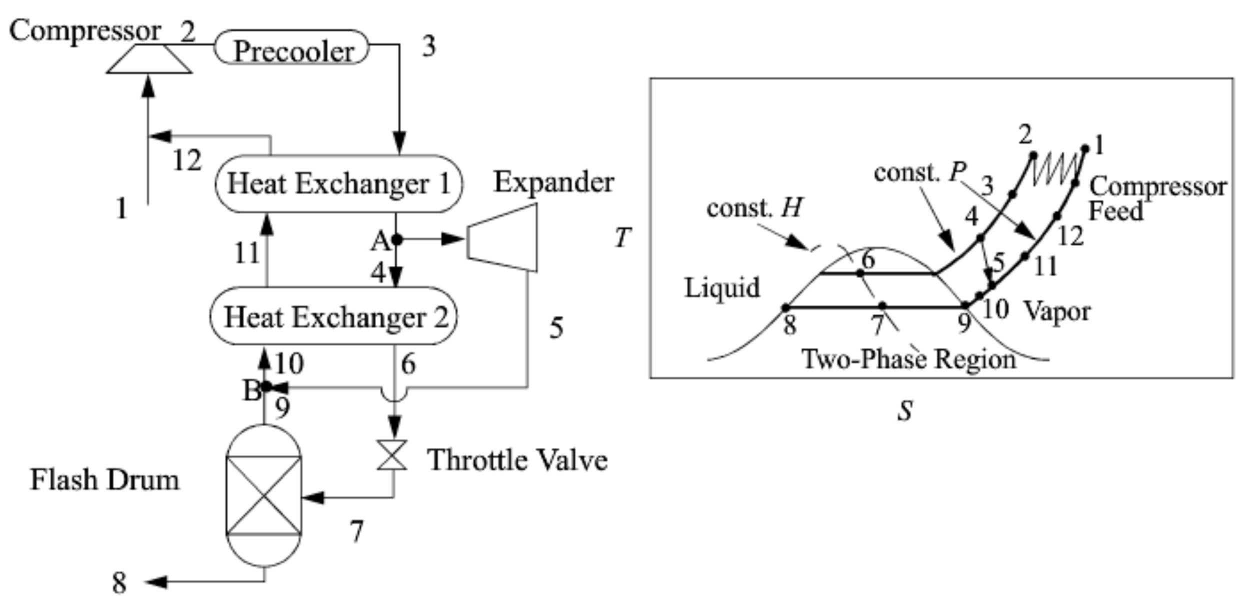


Figure 5.13 *The Claude liquefaction process.*

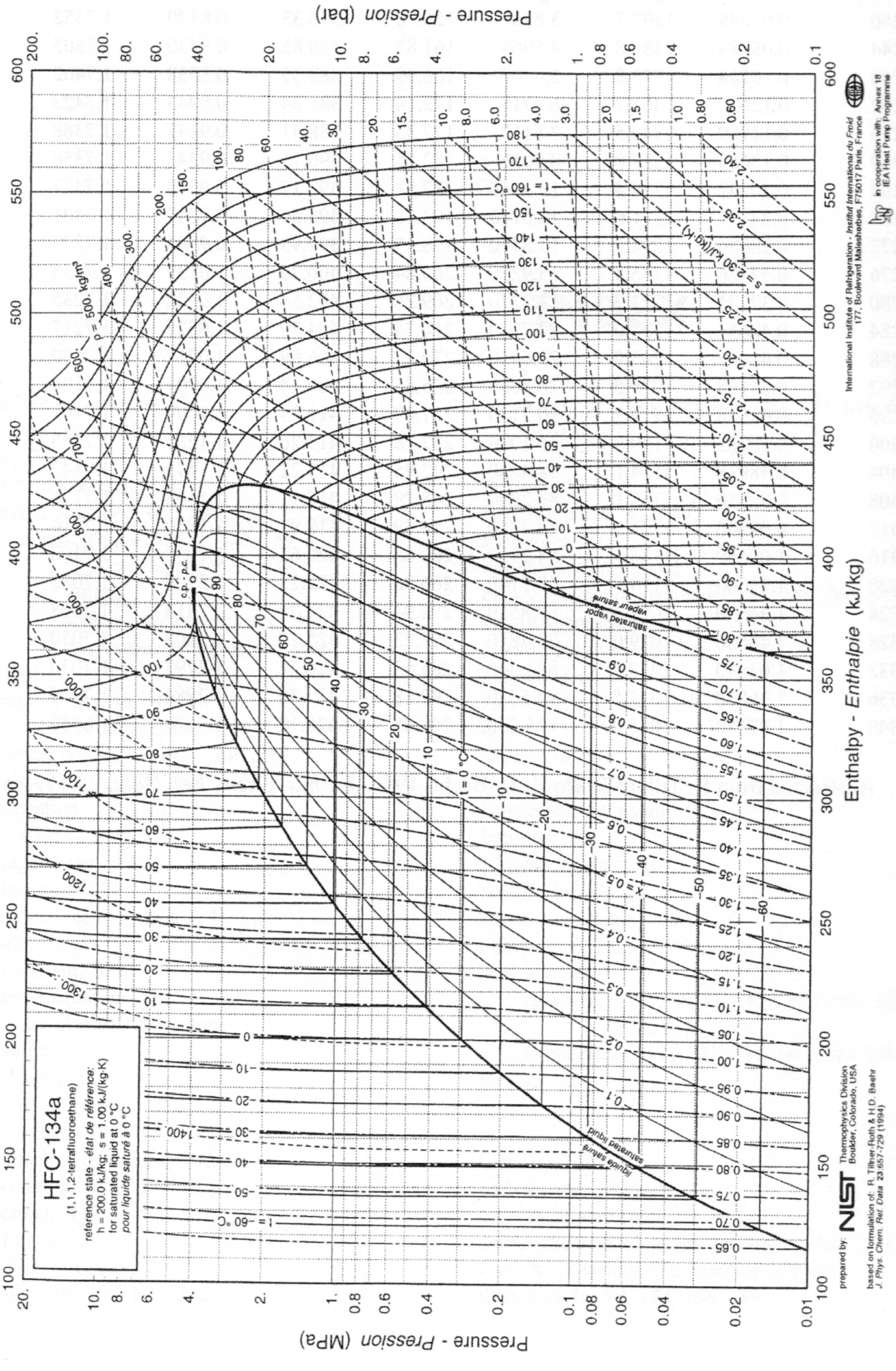
Properties of Saturated HFC-134*a*.

T	P	ρ^L	ρ^V	H^L	H^V	S^L	S^V
K	MPa	kg/m^3	kg/m^3	kJ/kg	kJ/kg	kJ/kg-K	kJ/kg-K
240	0.07248	1397.7	3.8367	156.78	378.33	0.8320	1.7552
244	0.08784	1385.8	4.5965	161.87	380.85	0.8530	1.7505
248	0.10568	1373.8	5.4707	166.99	383.35	0.8738	1.7462
252	0.12627	1361.7	6.4715	172.14	385.84	0.8943	1.7423
256	0.14989	1349.5	7.6117	177.33	388.31	0.9147	1.7388
260	0.17684	1337.0	8.9051	182.55	390.75	0.9348	1.7356
264	0.20742	1324.4	10.3660	187.81	393.17	0.9548	1.7327
268	0.24197	1311.6	12.0110	193.11	395.56	0.9747	1.7301
272	0.28080	1298.5	13.8570	198.45	397.93	0.9943	1.7277
276	0.32426	1285.3	15.9230	203.84	400.25	1.0139	1.7255
280	0.37271	1271.7	18.2270	209.26	402.54	1.0332	1.7235
284	0.42651	1258.0	20.7940	214.74	404.79	1.0525	1.7217
288	0.48603	1243.9	23.6450	220.27	406.99	1.0717	1.7200
292	0.55165	1229.5	26.8080	225.85	409.14	1.0907	1.7184
296	0.62378	1214.7	30.3130	231.49	411.23	1.1097	1.7169
300	0.70282	1199.6	34.1920	237.18	413.26	1.1286	1.7155
304	0.78918	1184.1	38.4830	242.95	415.22	1.1475	1.7142
308	0.88330	1168.1	43.2280	248.78	417.11	1.1663	1.7128
312	0.98560	1151.5	48.4750	254.69	418.92	1.1850	1.7114
316	1.09650	1134.5	54.2820	260.68	420.63	1.2038	1.7100
320	1.21660	1116.7	60.7140	266.76	422.25	1.2226	1.7085
324	1.34620	1098.3	67.8510	272.94	423.74	1.2414	1.7068
328	1.48600	1079.0	75.7890	279.23	425.10	1.2603	1.7050
332	1.63640	1058.8	84.6440	285.63	426.31	1.2793	1.7030
336	1.79810	1037.5	94.5630	292.18	427.34	1.2984	1.7007
340	1.97150	1015.0	105.7300	298.88	428.17	1.3177	1.6980

Abstracted from R. Tillner-Roth; H. D. Baehr, 1994. *J. Phys. Chem. Ref. Data*, 23:657.

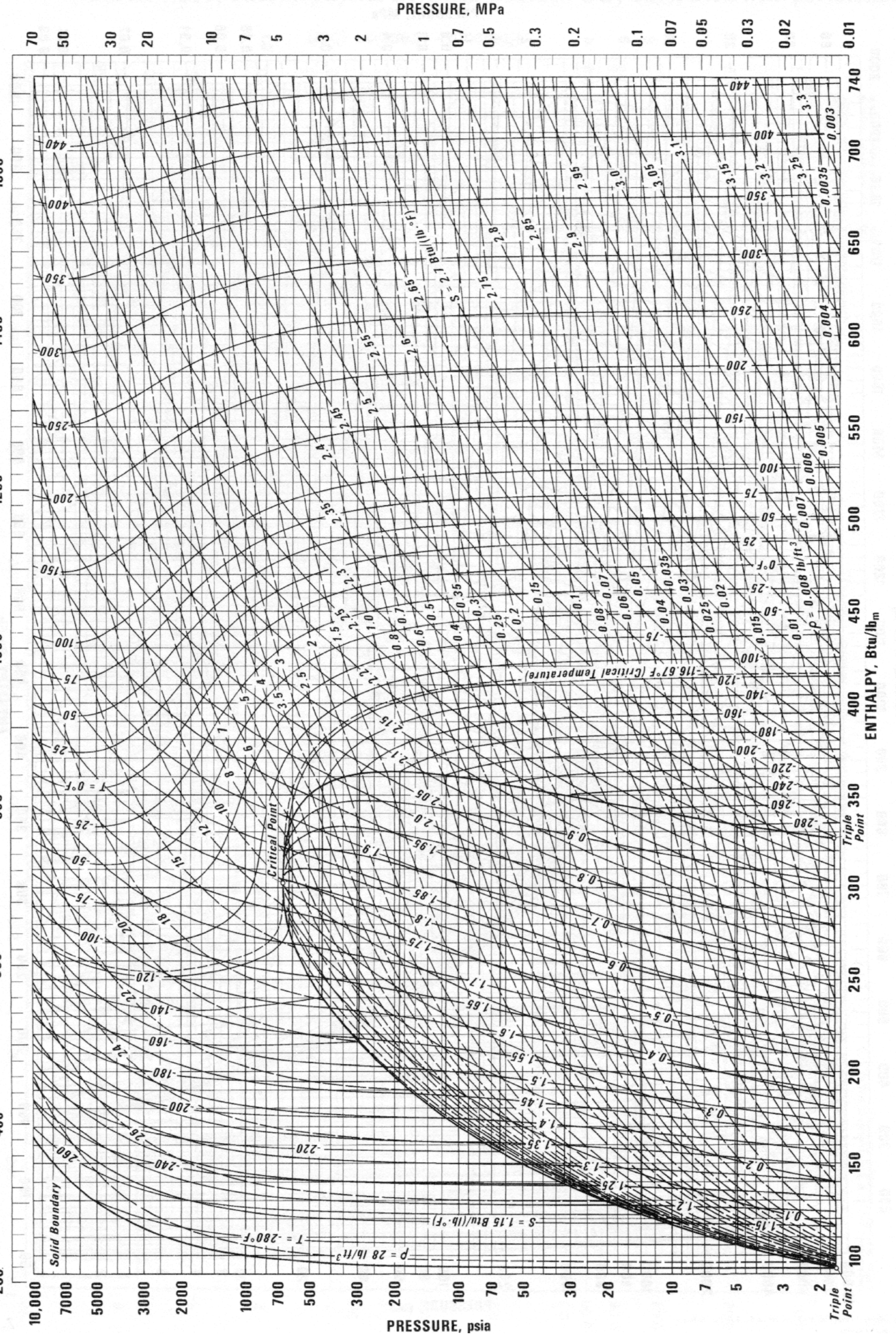
E.12 PRESSURE-ENTHALPY DIAGRAM FOR R134A (1,1,1,2-TETRAFLOUROETHANE)

(Source: NIST, Thermophysics Division, Boulder, CO, USA, used with permission.)



E.10 PRESSURE-ENTHALPY DIAGRAM FOR METHANE

(Source: NIST, Thermophysics Division, Boulder, CO, USA, used with permission.)



Answers Quiz 6
Chemical Engineering Thermodynamics
March 9, 2015

1)PP5.1

P5.1 An ordinary vapor compression cycle is to operate a refrigerator on R134a between –40°C and 40°C (condenser temperatures). Compute the coefficient of performance and the heat removed from the refrigerator per day if the power used by the refrigerator is 9000 J per day.

(P5.1) COP = coef. of performance = $\dfrac{\underline{Q}_C}{W_{S,net}}$

Using state numbers of Fig 5.8-5.9. P-H plot will look like Fig 5.9. Use P-H chart and table from Appendix E. Saturated values are from the table:

state 2 is satV at –40C → H_2 = 372 kJ/kg (chart)
state 3, outlet of the reversible compressor is found by following the isentropic line to 40C, where H_3' = 438 kJ/kg.
state 4 is satL at H_4 = 256 kJ/kg (table)
state 1, $H_1 = H_4$

$\underline{Q}_C = (H_2 - H_1) = 372 - 256 = 116 kJ/kg$
$W_S = (H_3 - H_2) = 438 - 372 = 66$ kJ/kg
$\Rightarrow COP = \dfrac{\dot{\underline{Q}}_C}{\dot{\underline{W}}_S} = \dfrac{116}{66} = 1.76$
$\underline{Q}_C$ = COP (W_S) = 1.76 (9000 J/day) = 16 kJ/day

2)

5.15 The Claude liquefaction process is to be applied to methane. Using the schematic of Fig. 5.13 on page 214 for stream numbering, the key variables depend on the fraction of stream 3 that is liquefied, $\dot{m}_8/\dot{m}_3$, and the fraction of stream 3 that is fed through the expander, $\dot{m}_5/\dot{m}_3$. Create a table listing all streams from low to high stream numbers. Fill in the table as you complete the problem sections. Attach a *P-H* diagram with your solution.

(a) Write a mass balance for the system boundary encompassing all equipment except the compressor and precooler.

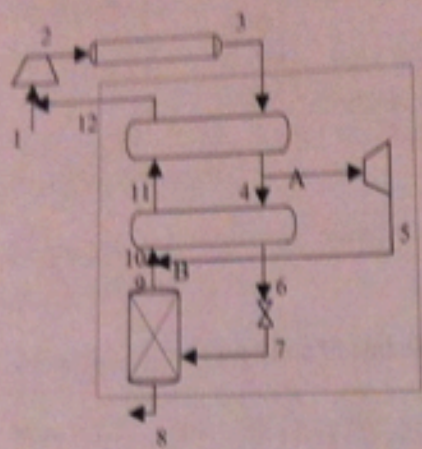
(b) Write an energy balance for the same boundary described in part (a), and show

$$\frac{\dot{m}_8}{\dot{m}_3} = \frac{(H_3 - H_{12}) + (\dot{m}_5/\dot{m}_3)W_{S\ \text{expander}}}{(H_8 - H_{12})}$$

(c) Stream 3 is to be 300 K and 3 MPa, stream 4 is to be 280 K and 3 MPa, stream 12 is to be 290 K and 0.1 MPa, and the flash drum is to operate at 0.1 MPa. The expander has an efficiency of 91%. The fraction liquefied is to be $\dot{m}_8/\dot{m}_3$ = 0.15. Determine how much flow to direct through the expander, $\dot{m}_5/\dot{m}_3$.

(d) Find the enthalpies of streams 3–12, and the temperatures and pressures.

(5.15) The Claude liquefaction...



(a) mass balance

$m_3 = m_8 + m_{12}$

(b) $0 = m_3H_3 - m_8H_8 - m_{12}H_{12} + m_5W_S$

(assumption: no heat loss across the boundary)

using m-bal from (a) to eliminate m_{12}

$0 = m_3H_3 - m_8H_8 - (m_3 - m_8)H_{12} + m_5W_S$

$(m_8/m_3)(H_8 - H_{12}) = H_3 - H_{12} + (m_5/m_3)W_S$

$(m_8/m_3) = (H_3 - H_{12} + (m_5/m_3)W_S)/(H_8 - H_{12})$

(c) The shaded values are given in the problem statement, the remaining values are determined as shown below.

Streams	Flow rate (m_i/m_3)	T K	P MPa	H Btu/lb	S Btu/lb°F
1	0.15	-	-	-	-
2	1.0	-	-	-	-
3	1.0	300(80°F)	3.0	503	
4	0.54	280(44°F)	3.0	483	2.3
5'	0.46	113(-255°F)	0.1	350	2.3
5	0.46	128(-228°F)	0.1	361	
6	0.54	178(-138°F) 2-phase	3.0	281	
7	0.54	111(-260°F) 2-phase	0.1	281	
8	0.15	111(-260°F)	0.1	122	
9	0.39	111(-260°F)	0.1	343	
10	0.85	122(-240°F)	0.1	352	
11	0.85	266(20°F)	0.1	481	
12	0.85	290(62.3°F)	0.1	505	

The expander work will be needed to solve for (m_5/m_3)

Turbine : $\Delta S' = (S_5' - S_4) = 0$ $S_5' = S_4 = 2.3$ Btu/lb°F

$H_4 = 483$ Btu/lb $H_5' = 350$ Btu/lb So $\Delta H_5' = -133$ Btu/lb

$\Delta H = W_S = 0.91 * \Delta H' = -121$ Btu/lb, so $H_5 = 361$ Btu/lb

rearranging the formula from part (b)

$0 = m_3H_3 - m_8H_8 - (m_3 - m_8)H_{12} + m_5W_S$

$(m_8/m_3)(H_8 - H_{12}) = H_3 - H_{12} + (m_5/m_3)W_S$

$(m_5/m_3) = [(m_8/m_3)(H_8 - H_{12}) - H_3 + H_{12}] / W_S$

H_8 is satL at 0.1 MPa = 122, and H_3 = 503, H_{12} = 505 found from given T,P
$(m_5/m_3) = [0.15(122 - 505) - 503 + 505]/(-121) = 0.46$
this value is very sensitive to the values read from the chart, and the rest of the problem solution depends on this number.
Increasing the amount of flow through turbine will decrease (m_5/m_3).
(d) Do a mass balance and get all the flow rates in terms of m_3

$m_4 + m_5 = m_3 \Rightarrow m_4 = (1\text{-}0.46)\, m_3 = 0.54\, m_3$
$m_4 = m_6 = m_7 = 0.54\, m_3$
$m_9 = m_4 - m_8 = (0.54 - 0.15)m_3 = 0.39\, m_3$
$m_9 + m_5 = m_{10} = m_{11} = m_{12} = (0.39 + 0.46)m_3 = 0.85\, m_3$

From the chart find the enthalpy for the streams and plug them in the mass and energy balance over each unit

The enthalpy balance around the flash drum should close using the mass flowrates above.
Flash drum: $m_7H_7 - m_8H_8 - m_9H_9 = 0 \Rightarrow m_3[0.54{*}H_7 - 0.15{*}H_8 - 0.39{*}H_9] = 0$
H_9 = enthalpy of saturated vapor at 0.1 MPa = 343 Btu/lb,
H_8 = enthalpy of saturated liquid at 0.1 MPa = 122 Btu/lb
Substituting in the balance above, we get $H_7 = H_6$ (isenthalpic throttling) = 281 Btu/lb

Mixing point B: $(m_5/m_3)H_5 + (m_9/m_3)H_9 = (m_{10}/m_3)H_{10}$
$H_{10} = [0.46(361) + 0.39(342)]/0.85 = 352$ BTU/lb

Heat Exchanger II: $(m_4H_4 + m_{10}H_{10}) - (m_{11}H_{11} + m_6H_6) = 0$

Heat Exchanger I: $(m_3H_3 + m_{11}H_{11}) - (m_3H_4 + m_{12}H_{12}) = 0$

Using either of the above two balances we can find H_{11}
Using HX I: $H_{11} = [H_4 + (m_{12}/m_3)H_{12} - H_3] / (m_{11}/m_3) =$
$[483 + 0.85(505) - 503]/0.85 = 481$ BTU /lb
Using HX II: $H_{11} = [(m_4/m_3)H_4 + (m_{10}/m_3)H_{10} - (m_6/m_3)H_6]/(m_{11}/m_3) =$
$[0.54(483) + 0.85(352) - 0.54(281)]/0.85 = 480$ BTU/lb
The rest of the states may be filled in.

turbine typically operates…

3) Test yourself Chapter 6

1. What are the restrictions necessary to calculate one state property in terms of only two other state variables?

Needs to be a simple system: Page 226-227 in book.

We restrict our treatment here to systems without internal rigid, impermeable, or adiabatic walls, no internal temperature gradients, and no external fields. These restrictions comprise what we refer to as *simple* systems. This is not a strong restriction, however. Most systems can be treated as a sum of

The energy balance for a closed simple system is

$$d(U + E_K + E_P) = dQ + dW_S + dW_{EC} \tag{6.1}$$

where E_K and E_P are the intensive kinetic and potential energies of the center of mass of the system. Eliminating all surface forces except those that cause expansion or contraction, because a simple system has no gradients or shaft work, and neglecting E_K and E_P changes by taking the system's center of mass as the frame of reference,

$$dU = dQ - PdV \tag{6.2}$$

Emphasizing the neglect of gradients, the reversible differential change between states is

$$dU_{rev} = dQ_{rev} - (PdV)_{rev} \tag{6.3}$$

but, by definition,

$$d\underline{S} = \frac{d\underline{Q}_{rev}}{T_{sys}} \qquad \Rightarrow T_{sys}d\underline{S} = d\underline{Q}_{rev} \quad (T_{sys}\text{-system temperature where } Q \text{ transferred})$$

Since the system is simple, for the process to be internally reversible, the temperature must be uniform throughout the system (no gradients). So the system temperature has a single value throughout. On a molar basis, the fundamental property relation for dU is

$$\boxed{dU = TdS - PdV} \tag{6.4}$$