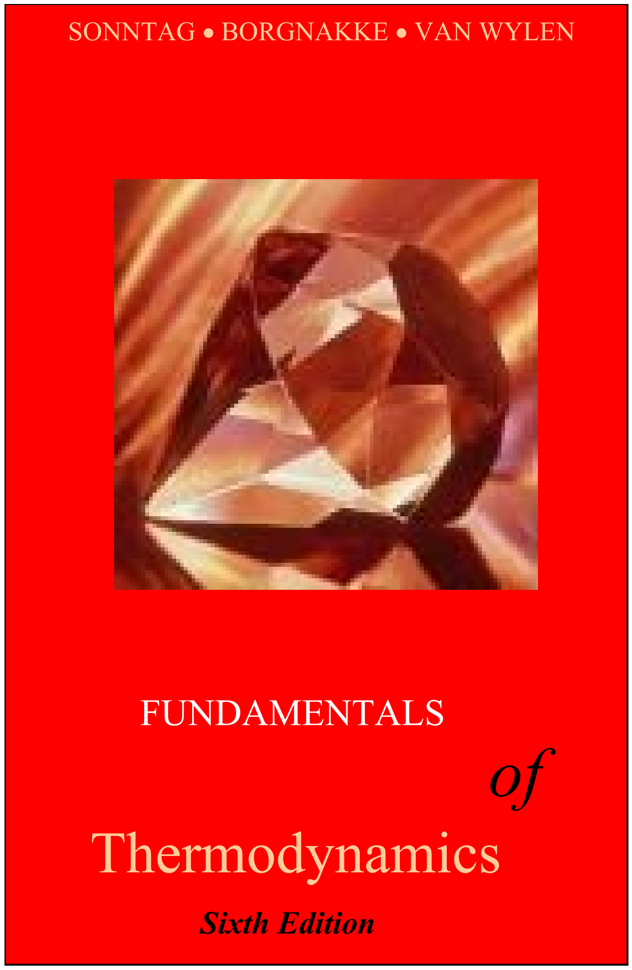
SOLUTION MANUAL
ENGLISH UNIT PROBLEMS
CHAPTER 13



CHAPTER 13

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Clapeyron Equation

13.120E

A special application requires R-22 at –150 F. It is known that the triple-point temperature is less than –150 F. Find the pressure and specific volume of the saturated vapor at the required condition.

The lowest temperature in Table F.9 for R-22 is -100 F, so it must be extended to -150 F using the Clapeyron eqn. At T_1 = -100 F = 359.7 R ,

$P_1 = 2.398 \text{ lbf/in.}^2$ and $R = \frac{1.9859}{86.469} = 0.022\,97 \text{ Btu/lbm R}$

$$\ln \frac{P}{P_1} = \frac{h_{fg}}{R} \frac{(T-T_1)}{T \times T_1} = \frac{107.9}{0.022\,97} \frac{(309.7-359.7)}{309.7 \times 359.7} = -2.1084$$

P = $\mathbf{0.2912 \text{ lbf/in.}^2}$

$$v_g = \frac{RT}{P_g} = \frac{0.022\,97 \times 778 \times 309.7}{0.2912 \times 144} = \mathbf{132 \text{ ft}^3\text{/lbm}}$$

13.121E

Ice (solid water) at 27 F, 1 atm is compressed isothermally until it becomes liquid. Find the required pressure.

Water, triple point T = 32.02 F = 491.69 R, P = 0.088 67 lbf/in.^{2}

v_f = 0.016 022 ft^3/lbm, v_i = 0.017 473 ft^3/lbm

h_f = 0.00 Btu/lbm h_i = -143.34 Btu/lbm

$$\frac{dP_{if}}{dT} = \frac{h_f - h_i}{(v_f - v_i)T} = \frac{143.34 \times 778.2}{-0.001\ 451 \times 491.69 \times 144} = -1085.8 \text{ psia/R}$$

$$\Delta P \approx \frac{dP_{if}}{dT} \Delta T = -1085.8\ (27 - 32.02) = 5450.7 \text{ lbf/in.}^2$$

$P = P_{tp} + \Delta P =$ **5451 lbf/in.^{2}**

13.122E

The saturation pressure can be approximated as $\ln P_{sat} = A – B/T$, where A and B are constants. Use the steam tables and determine A and B from properties at 70 F only. Use the equation to predict the saturation pressure at 80 F and compare to table value.

$$\ln P_{sat} = A - B/T \qquad \Rightarrow \qquad \frac{dP_{sat}}{dT} = P_{sat}\,(-B)(-T^{-2})$$

so we notice from Eq.13.7 and Table values from F.7.1 and F.4 that

$$B = \frac{h_{fg}}{R} = \frac{1053.95}{85.76 / 778} = 9561.3 \text{ R}$$

Now the constant A comes from the saturation pressure as

$$A = \ln P_{sat} + B/T = \ln 0.363 + \frac{9561.3}{459.67 + 70} = 17.038$$

Use the equation to predict the saturation pressure at 80 F as

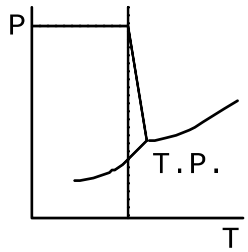
$$\ln P_{sat} = A - B/T = 17.038 - \frac{9561.3}{459.67 + 80} = -0.6789$$

$$P_{sat} = 0.5071 \text{ psia}$$

compare this with the table value of $P_{sat} = 0.507$ psia and we have a very close approximation.

13.123E

Using thermodynamic data for water from Tables C.8.1 and C.8.3, estimate the freezing temperature of liquid water at a pressure of 5000 lbf/in.^{2}.



$$H_2O \quad \frac{dP_{if}}{dT} = \frac{h_{if}}{Tv_{if}} \approx \text{constant}$$

At the triple point,

$v_{if} = v_f - v_i = 0.016\,022 - 0.017\,473$

$= -0.001\,451 \text{ ft}^3/\text{lbm}$

$h_{if} = h_f - h_i = 0.0 - (-143.34) = 143.34$ Btu/lbm

$$\frac{dP_{if}}{dT} = \frac{143.34}{491.69(-0.001\,451)} \times \frac{778.2}{144} = -1085.8 \text{ lbf/in.}^2 \text{ R}$$

$\Rightarrow$ at P = 5000 lbf/in^2,

$$T \approx 32.02 + \frac{(5000-0.09)}{(-1085.8)} = \mathbf{27.4\ F}$$

Volume Expansivity and Compressibility

13.124E

Determine the volume expansivity, α_P, and the isothermal compressibility, β_T, for water at 50 F, 500 lbf/in.^{2} and at 500 F, 1500 lbf/in.^{2} using the steam tables.

Water at 50 F, 500 lbf/in.^{2} (compressed liquid)

$$\alpha_P = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P \approx \frac{1}{v}\left(\frac{\Delta v}{\Delta T}\right)_P$$

Using values at 32 F, 50 F and 100 F

$$\alpha_P \approx \frac{1}{0.015\,998}\,\frac{0.016\,106 - 0.015\,994}{100 - 32} = \mathbf{0.000\,103\ F^{-1}}$$

$$\beta_T = -\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_T \approx -\frac{1}{v}\left(\frac{\Delta v}{\Delta P}\right)_T$$

Using values at saturation, 500 and 1000 lbf/in.^{2}

$$\beta_T \approx -\frac{1}{0.015\,998}\,\frac{0.015\,971 - 0.016\,024}{1000 - 0.178} = \mathbf{0.000\,0033\ in.^2/lbf}$$

Water at 500 F, 1500 lbf/in.^{2} (compressed liquid)

$$\alpha_P \approx \frac{1}{0.020\,245}\,\frac{0.021\,579 - 0.019\,264}{550 - 450} = \mathbf{0.001\,143\ F^{-1}}$$

$$\beta_T \approx -\frac{1}{0.020\,245}\,\frac{0.020\,139 - 0.020\,357}{2000 - 1000} = \mathbf{0.000\,0108\ in.^2/lbf}$$

13.125E

A cylinder fitted with a piston contains liquid methanol at 70 F, 15 lbf/in.^{2} and volume 1 ft^3. The piston is moved, compressing the methanol to 3000 lbf/in.^{2} at constant temperature. Calculate the work required for this process. The isothermal compressibility of liquid methanol at 70 F is 8.3×10^{-6} in.^{2}/lbf.

$$_1w_2 = \int_1^2 P dv = \int P \left(\frac{\partial v}{\partial P}\right)_T dP_T = -\int_1^2 v\beta_T P dP_T$$

For $v \approx$ const & $\beta_T \approx$ const. => $_1w_2 = -\frac{v\beta_T}{2}\left(P_2^2 - P_1^2\right)$

For liquid methanol, from Table F.3 : $\rho = 49.1$ lbm/ft^3

$V_1 = 1.0$ ft^3, $m = 1.0 \times 49.1 = 49.1$ lbm

$$_1W_2 = \frac{1.0 \times 8.3 \times 10^{-6}}{2}\left[(3000)^2 - (15)^2\right] \times 144 = 5378.4 \text{ ft lbf} = \mathbf{6.9\ Btu}$$

13.126E

Sound waves propagate through a media as pressure waves that causes the media to go through isentropic compression and expansion processes. The speed of sound c is defined by $c^2 = (\partial P/\partial \rho)_s$ and it can be related to the adiabatic compressibility, which for liquid ethanol at 70 F is 6.4×10^{-6} in.^{2}/lbf. Find the speed of sound at this temperature.

$$c^2 = \left(\frac{\partial P}{\partial \rho}\right)_s = -v^2\left(\frac{\partial P}{\partial v}\right)_s = \frac{1}{-\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_s \rho} = \frac{1}{\beta_s \rho}$$

From Table F.3 for ethanol, $\rho = 48.9$ lbm/ft^3

$$\Rightarrow c = \left(\frac{32.174\times 144}{6.4\times 10^{-6}\times 48.9}\right)^{1/2} = \mathbf{3848\ ft/s}$$

13.127E

Consider the speed of sound as defined in Problem 13.79. Calculate the speed of sound for liquid water at 50 F, 250 lbf/in.^{2} and for water vapor at 400 F, 80 lbf/in.^{2} using the steam tables.

From problem 13.79 : $c^2 = \left(\frac{\partial P}{\partial \rho}\right)_s = -v^2\left(\frac{\partial P}{\partial v}\right)_s$

Liquid water at 50 F, 250 lbf/in.^{2}

Assume $\left(\frac{\partial P}{\partial v}\right)_s \approx \left(\frac{\Delta P}{\Delta v}\right)_T$

Using saturated liquid at 50 F and compressed liquid at 50 F, 500 lbf/in.^{2},

$$c^2 = -\left(\frac{0.016024+0.015998}{2}\right)^2\left(\frac{(500-0.18)\times 144\times 32.174}{0.015998-0.016024}\right) = 22.832\times 10^6$$

c = **4778 ft/s**

Superheated vapor water at 400 F, 80 lbf/in.^{2}

v = 6.217 ft^3/lbm, s = 1.6790 Btu/lbm R

At P = 60 lbf/in.^{2} & s = 1.6790: T = 343.8 F, v = 7.7471 ft^3/lbm

At P = 100 lbf/in.^{2} & s = 1.6790: T = 446.2 F, v = 5.2394 ft^3/lbm

$$c^2 = -(6.217)^2\left(\frac{(100-60)\times 144\times 32.174}{5.2394-7.7471}\right) = 2.856\times 10^6$$

c = **1690 ft/s**

13.128E

Liquid methanol at 77 F has an adiabatic compressibility of 7.1×10^{-6} in²/lbf. What is the speed of sound? If it is compressed from 15 psia to 1500 psia in an insulated piston/cylinder, what is the specific work?

From Eq.13.43 and Eq.13.40 and the density from table A.4

$$c^2 = \left(\frac{\partial P}{\partial \rho}\right)_s = -v^2\left(\frac{\partial P}{\partial v}\right)_s = \frac{1}{\beta_s \rho} = \frac{1}{7.1 \times 10^{-6} \times 49.1} 144 \times 32.174 \text{ ft}^2/\text{s}^2$$

$$= 13.290 \times 10^6 \text{ ft}^2/\text{s}^2$$

c = **3645 ft/s**

The specific work becomes

$$w = \int P\, dv = \int P\,(-\beta_s v)\, dP = -\int \beta_s v\, P\, dP = -\beta_s v \int_1^2 P\, dP$$

$$= -\beta_s v\, 0.5\, (P_2^2 - P_1^2)$$

$$= -7.1 \times 10^{-6} \text{ in}^2/\text{lbf} \times \frac{0.5}{49.1} \text{ ft}^3/\text{lbm} \times (1500^2 - 15^2) \text{ psi}^2$$

$$= -0.163 \text{ (ft-lbf/lbm) (ft/in)}^2 = \mathbf{-23.4 \text{ ft-lbf/lbm} = -0.03 \text{ Btu/lbm}}$$

Equations of State

13.129E

Calculate the difference in internal energy of the ideal-gas value and the real-gas value for carbon dioxide at the state 70 F, 150 lbf/in.^{2}, as determined using the virial equation of state. For carbon dioxide at 70 F,

B = -2.036 ft3/lb mol, T(dB/dT) = 4.236 ft3/lb mol

Solution: CO_2 at 70 F, 150 lbf/in^2

$$\text{virial:} \quad P = \frac{RT}{v} + \frac{BRT}{v^2} \; ; \qquad \left(\frac{\partial P}{\partial T}\right)_v = \frac{R}{v} + \frac{BR}{v^2} + \frac{RT}{v^2}\left(\frac{dB}{dT}\right)$$

$$u - u^* = -\int_v^\infty \left[T\left(\frac{\partial P}{\partial T}\right)_v - P\right] dv = -\int_v^\infty \frac{RT^2}{v^2}\left(\frac{dB}{dT}\right) dv = -\frac{RT^2}{v}\frac{dB}{dT}$$

$$B = -2.036 \text{ ft}^3/\text{lbmol} \qquad T\left(\frac{dB}{dT}\right) = 4.236 \text{ ft}^3/\text{lbmol}$$

Solution of virial equation (quadratic formula):

$$\bar{v} = \frac{1}{2}\frac{\bar{R}T}{P}\left[1 + \sqrt{1 + 4BP/\bar{R}T}\right]$$

$$\text{But} \quad \frac{\bar{R}T}{P} = \frac{1545 \times 529.7}{150 \times 144} = 37.8883$$

$$\bar{v} = 0.5 \times 37.8883\left[1 + \sqrt{1 + 4(-2.036)/37.8883}\right] = 35.7294 \text{ ft}^3/\text{lbmol}$$

Using the minus-sign root of the quadratic formula results in a compressibility factor < 0.5, which is not consistent with such a truncated equation of state.

$$\bar{u} - \bar{u}^* = \frac{-1.9859 \times 529.7}{35.7294} 4.236 = \mathbf{-123.9\ Btu/lbmol}$$

Generalized Charts

13.130E

A 7-ft^3 rigid tank contains propane at 1300 lbf/in.^{2}, 540 F. The propane is then allowed to cool to 120 F as heat is transferred with the surroundings. Determine the quality at the final state and the mass of liquid in the tank, using the generalized compressibility charts.

Propane C_3H_8:

$V = 7.0\ ft^3$, $P_1 = 1300\ lbf/in.^2$, $T_1 = 540\ F = 1000\ R$

cool to $T_2 = 120\ F = 580\ R$

From Table F.1 : $T_C = 665.6\ R$, $P_C = 616\ lbf/in.^2$

$$P_{r1} = \frac{1300}{616} = 2.110, \quad T_{r1} = \frac{1000}{665.6} = 1.502$$

From D.1: $Z_1 = 0.83$

$$v_2 = v_1 = \frac{Z_1RT_1}{P_1} = \frac{0.83 \times 35.04 \times 1000}{1300 \times 144} = 0.1554\ ft^3/lbm$$

From D.1 at $T_{r2} = 0.871$, saturated => $P_{G2} = 0.43 \times 616 = 265\ lbf/in.^2$

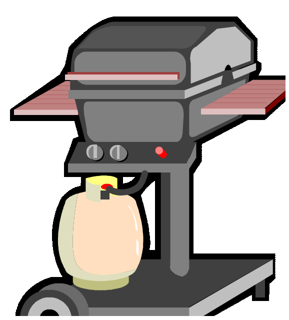
$$v_{G2} = \frac{0.715 \times 35.04 \times 580}{265 \times 144} = 0.3808\ ft^3/lbm$$

$$v_{F2} = \frac{0.075 \times 35.04 \times 580}{265 \times 144} = 0.0399\ ft^3/lbm$$

$0.1554 = 0.0399 + x_2(0.3781\text{-}0.0399)$ => $x_2 = \mathbf{0.3388}$

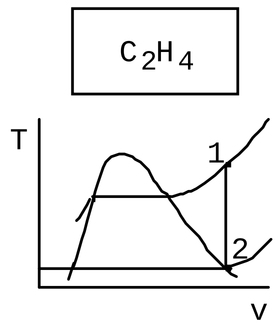
$$m_{LIQ\ 2} = (1 - 0.3388)\frac{7.0}{0.1554} = \mathbf{29.8\ lbm}$$

These tanks contain liquid propane.



13.131E

A rigid tank contains 5 lbm of ethylene at 450 lbf/in.^{2}, 90 F. It is cooled until the ethylene reaches the saturated vapor curve. What is the final temperature?



C_2H_4 m = 5 lbm

$P_1 = 450 \text{ lbf/in}^2$, $T_1 = 90 \text{ F} = 249.7 \text{ R}$

$$P_{r1} = \frac{450}{731} = 0.616, \quad T_{r1} = \frac{549.7}{508.3} = 1.082$$

Fig. D.1 $\Rightarrow$ $Z_1 = 0.82$

$$P_{r2} = P_{r1}\frac{Z_2 T_{r2}}{Z_1 T_{r1}} = 0.616\frac{Z_{G2} T_{r2}}{0.82 \times 1.082} = 0.6943\ Z_{G2} T_{r2}$$

Trial & error to match a saturated P_{r2}, T_{r2} and the Z_{G2} so Eq. is satisfied. Guess a T_{r2} and find the rest and compare with computed P_{r2} from Eq.

T_{r2}	Z_{G2}	P_{r2}	$P_{r2\ CALC}$			
0.871	0.715	0.43	0.432	~ OK	=>	T_2 = **442.7 R**

13.132E

A piston/cylinder contains 10 lbm of butane gas at 900 R, 750 lbf/in.^{2}. The butane expands in a reversible polytropic process with polytropic exponent, n = 1.05, until the final pressure is 450 lbf/in.^{2}. Determine the final temperature and the work done during the process.

C_4H_{10} , m = 10 lbm , T_1 = 900 R , P_1 = 750 lbf/in.^{2}

Rev. polytropic process (n=1.05), P_2 = 450 lbf/in.^{2}

$$T_{r1} = \frac{900}{765.4} = 1.176, \quad P_{r1} = \frac{750}{551} = 1.361 \quad => \text{ From Fig. D.1 : } \quad Z_1 = 0.67$$

$$V_1 = \frac{10 \times 0.67 \times 26.58 \times 900}{750 \times 144} = 1.484 \text{ ft}^3$$

$$P_1V_1^n = P_2V_2^n \rightarrow V_2 = 1.484 \left(\frac{750}{450}\right)^{\frac{1}{1.05}} = 2.414 \text{ ft}^3$$

$$Z_2T_{r2} = \frac{P_2V_2}{mRT_C} = \frac{450 \times 144 \times 2.414}{10 \times 26.58 \times 765.4} = 0.7688$$

at P_{r2} = 450/551 = 0.817

Trial & error: T_{r2} = 1.068, Z_2 = 0.72 => T_2 = **817.4 R**

$${}_1W_2 = \int_1^2 PdV = \frac{P_2V_2 - P_1V_1}{1-n} = \left(\frac{450 \times 2.414 - 750 \times 1.484}{1 - 1.05}\right) \times \frac{144}{778} = \mathbf{98.8\ Btu}$$

13.133E

Calculate the heat transfer during the process described in Problem 13.132E.

From solution 13.132,

$V_1 = 1.473\ ft^3$, $V_2 = 2.396\ ft^3$, ${}_1W_2 = 98.8$ Btu

$T_{r1} = 1.176$, $P_{r1} = 1.361$, $T_{r2} = 1.068$, $P_{r2} = 0.817$, $T_2 = 817.4$ R

From D.1: $\left(\frac{h^*-h}{RT_C}\right)_1 = 1.36$, $\left(\frac{h^*-h}{RT_C}\right)_2 = 0.95$

$h_2^* - h_1^* = 0.415\ (817.4 - 900) = -34.3$ Btu/lbm

$h_2 - h_1 = -34.3 + \frac{26.58\times765.4}{778}(-0.95 + 1.36) = -23.6$ Btu/lbm

$U_2 - U_1 = m(h_2-h_1) - P_2V_2 + P_1V_1$

$= 10(-23.6) - \frac{450\times144\times2.414}{778} + \frac{750\times144\times1.484}{778} = -231.1$ Btu

${}_1Q_2 = U_2 - U_1 + {}_1W_2 =$ **-132.3 Btu**

13.134E

A cylinder contains ethylene, C_2H_4, at 222.6 lbf/in.^{2}, 8 F. It is now compressed in a reversible isobaric (constant *P*) process to saturated liquid. Find the specific work and heat transfer.

Ethylene C_2H_4 P_1 = 222.6 lbf/in.^{2} = P_2, T_1 = 8 F = 467.7 R

State 2: saturated liquid, $x_2 = 0.0$

R = 55.07 ft lbf/lbm R = 0.070 78 Btu/lbm R

$$T_{r1} = \frac{467.7}{508.3} = 0.920 \quad P_{r1} = P_{r2} = \frac{222.6}{731} = 0.305$$

From D.1 and D.2: $Z_1 = 0.85$, $\left(\frac{h^*-h}{RT_C}\right)_1 = 0.40$

$$v_1 = \frac{Z_1RT_1}{P_1} = \frac{0.85 \times 55.07 \times 467.7}{222.6 \times 144} = 0.683$$

$$(h^*_1-h_1) = 0.070\ 78 \times 508.3 \times 0.40 = 14.4$$

From D.1 and D.2: $T_2 = 0.822 \times 508.3 = 417.8$ R

$$Z_2 = 0.05\ , \left(\frac{h^*-h}{RT_C}\right)_2 = 4.42$$

$$v_2 = \frac{Z_2RT_2}{P_2} = \frac{0.05 \times 55.07 \times 417.8}{222.6 \times 144} = 0.035\ 89 \ \text{ft}^3/\text{lbm}$$

$$(h^*_2-h_2) = 0.070\ 78 \times 508.3 \times 4.42 = 159.0 \text{ Btu/lbm}$$

$$(h^*_2-h^*_1) = C_{P0}(T_2-T_1) = 0.411(417.8 - 467.7) = -20.5 \text{ Btu/lbm}$$

$${}_1w_2 = \int_1^2 Pdv = P(v_2-v_1) = 222.6(0.035\ 89 - 0.683) \times \frac{144}{778} = \mathbf{-26.7\ Btu/lbm}$$

$${}_1q_2 = (u_2 - u_1) + {}_1w_2 = (h_2-h_1) = -159.0 - 20.5 + 14.4 = \mathbf{-165.1\ Btu/lbm}$$

13.135E

Carbon dioxide collected from a fermentation process at 40 F, 15 lbf/in.^{2} should be brought to 438 R, 590 lbf/in.^{2} in a steady flow process. Find the minimum amount of work required and the heat transfer. What devices are needed to accomplish this change of state?

$$R = \frac{35.1}{778} = 0.045\,12 \text{ Btu/lbm R}$$

$$T_{ri} = \frac{500}{547.4} = 0.913\,, \quad P_{ri} = \frac{15}{1070} = 0.014$$

From D.2 and D.3: $\left(\frac{h^*-h}{RT_C}\right) = 0.02, \quad \left(\frac{s^*-s}{R}\right) = 0.01 \text{ R}$

$$T_{re} = \frac{438}{547.4} = 0.80, \quad P_{re} = \frac{590}{1070} = 0.551$$

From D.2 and D.3: $h^*_e-h_e = 4.50 \text{ RT}_c, \quad s^*_e-s_e = 4.70 \text{ R}$

$$(h_i-h_e) = -(h^*_i-h_i) + (h^*_i-h^*_e) + (h^*_e-h_e)$$

$$= -0.045\,12 \times 547.4 \times 0.02 + 0.203(500 - 438) + 0.045\,12 \times 547.4 \times 4.50$$

$$= 123.2 \text{ Btu/lbm}$$

$$(s_i-s_e) = -(s^*_i-s_i) + (s^*_i-s^*_e) + (s^*_e-s_e)$$

$$= -0.045\,12{\times}0.01 + 0.203 \ln\frac{500}{438} - 0.045\,12 \ln\frac{15}{590} + 0.045\,12{\times}4.70$$

$$= 0.4042 \text{ Btu/lbm R}$$

$w^{rev} = (h_i-h_e) - T_0(s_i-s_e) = 123.2 - 500(0.4042) =$ **-78.4 Btu/lbm**

$q^{rev} = (h_e-h_i) + w^{rev} = -123.2 - 78.9 =$ **-202.1 Btu/lbm**

13.136E

Saturated vapor R-22 at 90 F is throttled to 30 lbf/in.^{2} in a steady flow process. Calculate the exit temperature assuming no changes in the kinetic energy, using the generalized charts, Fig. D.2 and repeat using the R-22 tables, Table F.9.

R-22 throttling process

$T_1 = 90$ F, $x_1 = 1.00$, $P_2 = 30$ lbf/in.^{2}

Energy Eq.: $\quad h_2 - h_1 = (h_2 - h_2^*) + (h_2^* - h_1^*) + (h_1^* - h_1) = 0$

Generalized charts, $\quad T_{r1} = \dfrac{549.7}{664.7} = 0.827$

From D.2: $\quad (h_1^* - h_1) = \dfrac{1.9859 \times 664.7}{86.469}(0.55) = 8.40$

To get C_{P0}, use h values from Table F.9 at low pressure (5 psia).

$$C_{P0} \approx \frac{121.87 - 118.72}{100 - 80} = 0.1572 \text{ Btu/lbm R}$$

Substituting into energy Eq.: $\quad (h_2 - h_2^*) + 0.1572\,(T_2 - 30) + 8.40 = 0$

at $P_{r2} = \dfrac{30}{721} = 0.042$

Assume $T_2 = 43.4$ F $= 503.1$ R $\Rightarrow$ $T_{r2} = \dfrac{503.4}{664.7} = 0.757$

$(h_2^* - h_2) = \dfrac{1.9859 \times 664.7}{86.469}(0.07) = 1.07$

Substituting,

$-1.07 + 0.1572(43.4 - 90) + 8.40 = 0.005 \approx 0$

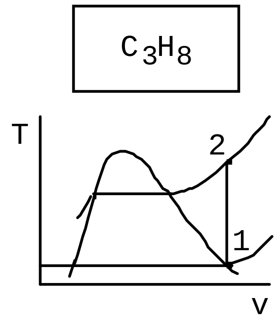
$\Rightarrow T_2 =$ **43.4 F**

b) R-22 tables, F.9: $\quad T_1 = 90$ F, $\quad x_1 = 1.0 \quad \Rightarrow \quad h_1 = 111.62$ Btu/lbm

$h_2 = h_1 = 111.62$ Btu/lbm, $\quad P_2 = 30$ lbf/in.^{2} $\Rightarrow$ $T_2 =$ **42.1 F**

13.137E

A 10-ft3 tank contains propane at 90 F, 90% quality. The tank is heated to 600 F. Calculate the heat transfer during the process.



$V = 10\ ft^3$

$T_1 = 90\ F = 549.7\ R,\ x_1 = 0.90$

Heat to $T_2 = 600\ F = 1059.7\ R$

$M = 44.094,\ T_C = 665.6\ R$

$P_C = 616\ lbf/in.^2$

$R = 35.04,\quad C_{P0} = 0.407\ Btu/lbm\ R$

$T_{r1} = 0.826$ Figs. D.1 and D.2 $\rightarrow$ $Z_1 = 0.1 \times 0.053 + 0.9 \times 0.78 = 0.707,$

$$\frac{h_1^* - h_1}{RT_c} = 0.1 \times 4.4 + 0.9 \times 0.55 = 0.935$$

$$P_r^{SAT} = 0.31\ ; \qquad P_1^{SAT} = 0.31 \times 616 = 191\ lbf/in.^2$$

$$m = \frac{PV}{ZRT} = \frac{191 \times 144 \times 10}{0.707 \times 35.04 \times 549.7} = 20.2\ lbm$$

$$P_{r2} = \frac{20.2 \times Z_2 \times 35.04 \times 1059.7}{616 \times 144 \times 10} = \frac{Z_2}{1.183} \qquad \text{at } T_{r2} = 1.592$$

$$\text{Trial \& error:} \begin{cases} P_{r2} = 0.79 & P_2 = 490\ lbf/in.^2 \\ Z_2 = 0.94 & \dfrac{h_2^* - h_2}{RT_c} = 0.36 \end{cases}$$

$$(h_2^* - h_1^*) = 0.407(600\text{-}90) = 207.6\ Btu/lbm$$

$$(h_1^* - h_1) = 0.935 \times 35.04 \times 665.9/\ 778 = 28.0$$

$$(h_2^* - h_2) = 0.36 \times 35.04 \times 665.9/\ 778 = 10.8$$

$$Q_{12} = m(h_2 - h_1) - (P_2 - P_1)V$$

$$= 20.2\ (-10.8 + 207.6 + 28.0) - (490 - 191) \times \frac{144 \times 10}{778}$$

$$= +4541 - 553 = \mathbf{3988\ Btu}$$

13.138E

A cylinder contains ethylene, C_2H_4, at 222.6 lbf/in.^{2}, 8 F. It is now compressed isothermally in a reversible process to 742 lbf/in.^{2}. Find the specific work and heat transfer.

Ethylene C_2H_4 , $R = 55.07$ ft lbf/lbm R = 0.070 78 Btu/lbm R

State 1: $P_1 = 222.6$ lbf/in.^{2}, $T_2 = T_1 = 8$ F = 467.7 R

State 2: $P_2 = 742$ lbf/in.^{2}

$$T_{r2} = T_{r1} = \frac{467.7}{508.3} = 0.920; \quad P_{r1} = \frac{222.6}{731} = 0.305$$

From D.1, D.2 and D.3: $Z_1 = 0.85$, $\left(\frac{h^*-h}{RT_C}\right)_1 = 0.40$

$$(h^*_1-h_1) = 0.070\ 78 \times 508.3 \times 0.40 = 14.4 \text{ Btu/lbm}$$

$$(s^*_1-s_1) = 0.070\ 78 \times 0.30 = 0.0212 \text{ Btu/lbm R}$$

$$P_{r2} = \frac{742}{731} = 1.015 \text{ (comp. liquid)}$$

From D.1, D.2 and D.3: $Z_2 = 0.17$

$$(h^*_2-h_2) = 0.070\ 78 \times 508.3 \times 4.0 = 143.9$$

$$(s^*_2-s_2) = 0.070\ 78 \times 3.6 = 0.2548$$

$$(h^*_2-h^*_1) = 0$$

$$(s^*_2-s^*_1) = 0 - 0.070\ 78 \ln \frac{742}{222.6} = -0.0852$$

${}_1q_2 = T(s_2-s_1) = 467.7(-0.2548 - 0.0852 + 0.0212) =$ **-149.1 Btu/lbm**

$(h_2-h_1) = -143.9 + 0 + 14.4 = -129.5$

$(u_2-u_1) = (h_2-h_1) - RT(Z_2-Z_1)$

$= -129.5 - 0.070\ 78 \times 467.7\ (0.17 - 0.85) = -107.0$

${}_1w_2 = {}_1q_2 - (u_2-u_1) = -149.1 + 107.0 =$ **-42.1 Btu/lbm**

13.139E

A geothermal power plant on the Raft river uses isobutane as the working fluid as shown in Fig. P13.42. The fluid enters the reversible adiabatic turbine at 320 F, 805 lbf/in.^{2} and the condenser exit condition is saturated liquid at 91 F. Isobutane has the properties *Tc* = 734.65 R, *Pc* = 537 lbf/in.^{2}, *Cpo* = 0.3974 Btu/lbm R and ratio of specific heats *k* = 1.094 with a molecular weight as 58.124. Find the specific turbine work and the specific pump work.

$R = 26.58$ ft lbf/lbm R $= 0.034\ 166$ Btu/lbm R

Turbine inlet: $T_{r1} = 779.7 / 734.7 = 1.061$, $P_{r1} = 805 / 537 = 1.499$

Condenser exit: $T_3 = 91$ F, $x_3 = 0.0$; $T_{r3} = 550.7 / 734.7 = 0.75$

From D.1 : $P_{r3} = 0.165$, $Z_3 = 0.0275$

$P_2 = P_3 = 0.165 \times 537 = 88.6$ lbf/in.^{2}

From D.2 and D.3,

$$(h^*_1 - h_1) = 0.034\ 166 \times 734.7 \times 2.85 = 71.5 \text{ Btu/lbm}$$

$$(s^*_1 - s_1) = 0.034\ 166 \times 2.15 = 0.0735 \text{ Btu/lbm R}$$

$$(s^*_2 - s^*_1) = 0.3974 \ln \frac{550.7}{779.7} - 0.034\ 166 \ln \frac{88.6}{805} = -0.0628 \text{ Btu/lbm R}$$

$$(s^*_2 - s_2) = (s^*_2 - s_{F2}) - x_2 s_{FG2} = 0.034\ 166 \times 6.12 - x_2 \times 0.034\ 166(6.12 - 0.29)$$

$$= 0.2090 - x_2 \times 0.1992$$

$$(s_2 - s_1) = 0 = -0.2090 + x_2 \times 0.1992 - 0.0628 + 0.0735 \quad \Rightarrow \quad x_2 = 0.9955$$

$$(h^*_2 - h^*_1) = C_{P0}(T_2 - T_1) = 0.3974(550.7 - 779.7) = -91.0 \text{ Btu/lbm}$$

From D.2,

$$(h^*_2 - h_2) = (h^*_2 - h_{F2}) - x_2 h_{FG2} = 0.034\ 166 \times 734.7[4.69 - 0.9955(4.69 - 0.32)]$$

$$= 117.7 - 0.9955 \times 109.7 = 8.5 \text{ Btu/lbm}$$

Turbine: $w_T = (h_1 - h_2) = -71.5 + 91.0 + 8.5 =$ **28.0 Btu/lbm**

Pump $$v_{F3} = \frac{Z_{F3} R T_3}{P_3} = \frac{0.0275 \times 26.58 \times 550.7}{88.6 \times 144} = 0.031\ 55 \text{ ft}^3\text{/lbm}$$

$$w_P = -\int_3^4 v dP \approx v_{F3}(P_4 - P_3) = -0.031\ 55(805 - 88.6) \times \frac{144}{778} = \mathbf{-4.2\ Btu/lbm}$$

13.140E

A line with a steady supply of octane, C_8H_{18}, is at 750 F, 440 lbf/in.^{2}. What is your best estimate for the availability in an steady flow setup where changes in potential and kinetic energies may be neglected?

Availability of Octane at $T_i = 750$ F, $P_i = 440$ lbf/in.^{2}

$R = 13.53$ ft lbf/lbm R = 0.017 39 Btu/lbm R

$$P_{ri} = \frac{440}{361} = 1.219, \quad T_{ri} = \frac{1209.7}{1023.8} = 1.182$$

From D.2 and D.3:

$$(h_1^* - h_1) = 0.017\,39 \times 1023.8 \times 1.15 = 20.5 \text{ Btu/lbm}$$

$$(s_1^* - s_1) = 0.017\,39 \times 0.71 = 0.0123 \text{ Btu/lbm R}$$

Exit state in equilibrium with the surroundings

Assume $T_0 = 77$ F, $P_0 = 14.7$ lbf/in.^{2}

$$T_{r0} = \frac{536.7}{1023.8} = 0.524\ , \ P_{r0} = \frac{14.7}{361} = 0.041$$

From D.2 and D.3:

$$(h_0^* - h_0) = RT_C \times 5.41 = 96.3 \quad \text{and} \quad (s_0^* - s_0) = R \times 10.38 = 0.1805$$

$$(h_i^* - h_0^*) = 0.409(1209.7 - 536.7) = 275.3 \text{ Btu/lbm}$$

$$(s_i^* - s_0^*) = 0.409 \ln\frac{1209.7}{536.7} - 0.017\,39 \ln\frac{440}{14.7} = 0.2733 \text{ Btu/lbm R}$$

$$(h_i - h_0) = -20.5 + 275.3 + 96.3 = 351.1 \text{ Btu/lbm}$$

$$(s_i - s_0) = -0.0123 + 0.2733 + 0.1805 = 0.4415 \text{ Btu/lbm R}$$

$$\psi_i = w^{rev} = (h_i - h_0) - T_0(s_i - s_0) = 351.1 - 536.7\ (0.4415) = \mathbf{114.1\ Btu/lbm}$$

13.141E

A control mass of 10 lbm butane gas initially at 180 F, 75 lbf/in.^{2}, is compressed in a reversible isothermal process to one-fifth of its initial volume. What is the heat transfer in the process?

Butane C_4H_{10}: m = 10 lbm, T_1 = 180 F, P_1 = 75 lbf/in.^{2}

Compressed, reversible T = const, to $V_2 = V_1/5$

$$T_{r1} = \frac{640}{765.4} = 0.836,\ P_{r1} = \frac{75}{551} = 0.136 \quad => \quad \text{From D.1 and D.3:} \quad Z_1 = 0.92$$

$$(s^*_1\text{-}s_1) = 0.16 \times \frac{26.58}{778} = 0.0055 \text{ Btu/lbm R}$$

$$v_1 = \frac{Z_1RT_1}{P_1} = \frac{0.92 \times 26.58 \times 640}{75 \times 144} = 1.449 \text{ ft}^3\text{/lbm}$$

$v_2 = v_1/5 = 0.2898$ ft^3/lbm

At $T_{r2} = T_{r1} = 0.836$

From D.1 and D.3: $P_G = 0.34 \times 551 = 187$ lbf/in.^{2}

sat. liq.: $Z_F = 0.058$; $(s^*\text{-}s_F) = R \times 5.02 = 0.1715$ Btu/lbm R

sat. vap.: $Z_G = 0.765$; $(s^*\text{-}s_G) = R \times 0.49 = 0.0167$ Btu/lbm R

Therefore

$$v_F = \frac{0.058 \times 26.58 \times 640}{187 \times 144} = 0.0366; \quad v_G = \frac{0.77 \times 26.58 \times 640}{187 \times 144} = 0.4864$$

Since $v_F < v_2 < v_G \rightarrow$ two-phase $\quad x_2 = \dfrac{v_2\text{-}v_F}{v_G\text{-}v_F} = 0.563$

$$(s^*_2\text{-}s_2) = (1\text{-}x_2)(s^*_2\text{-}s_{F2}) + x_2(s^*_2\text{-}s_{G2})$$

$$= 0.437 \times 0.1715 + 0.563 \times 0.0167 = 0.0843 \text{ Btu/lbm R}$$

$$(s^*_2\text{-}s^*_1) = C_{P0} \ln\frac{T_2}{T_1} - R \ln\frac{P_2}{P_1} = 0 - \frac{26.58}{778} \times \ln\frac{187}{75} = -0.0312 \text{ Btu/lbm R}$$

$(s_2\text{-}s_1) = -0.0843 - 0.0312 + 0.0055 = -0.110$ Btu/lbm R

${}_1Q_2 = Tm(s_2\text{-}s_1) = 640{\times}10(-0.110) =$ **-704 Btu**

13.142E

A distributor of bottled propane, C_3H_8, needs to bring propane from 630 R, 14.7 lbf/in.^{2} to saturated liquid at 520 R in a steady flow process. If this should be accomplished in a reversible setup given the surroundings at 540 R, find the ratio of the volume flow rates $\dot{V}in/\dot{V}out$, the heat transfer and the work involved in the process.

$R = 35.04/778 = 0.045\ 04$ Btu/lbm R

$T_{ri} = \frac{630}{665.6} = 0.947 \quad P_{ri} = \frac{14.7}{616} = 0.024$

From D.1, D.2 and D.3 : $Z_i = 0.99$

$(h_i^* - h_i) = 0.045\ 03 \times 665.6 \times 0.03 = 0.9$ Btu/lbm

$(s_i^* - s_i) = 0.045\ 04 \times 0.02 = 0.0009$ Btu/lbm R

$T_{re} = 520/665.6 = 0.781,$

From D.1, D.2 and D.3 :

$P_{re} = = 0.21\ , \quad P_e = 0.21 \times 616 = 129$ lbf/in.^{2}

$Z_e = 0.035$

$(h_e^* - h_e) = 0.045\ 04 \times 665.6 \times 4.58 = 137.3$ Btu/lbm

$(s_e^* - s_e) = 0.045\ 04 \times 5.72 = 0.2576$ Btu/lbm R

$(h_e^* - h_i^*) = 0.407\ (520 - 630) = -44.8$ Btu/lbm

$(s_e^* - s_i^*) = 0.407 \ln \frac{520}{630} - 0.045\ 04 \ln \frac{132}{14.7} = -0.1770$ Btu/lbm R

$(h_e - h_i) = -137.3 - 44.8 + 0.9 = -181.2$ Btu/lbm

$(s_e - s_i) = -0.2576 - 0.1759 + 0.0009 = -0.4326$ Btu/lbm R

$$\frac{\dot{V}_{in}}{\dot{V}_{out}} = \frac{Z_i T_i / P_i}{Z_e T_e / P_e} = \frac{0.99}{0.035} \times \frac{630}{520} \times \frac{129}{14.7} = \mathbf{300.7}$$

$w^{rev} = (h_i - h_e) - T_0(s_i - s_e) = 181.2 - 540(0.4326) = \mathbf{-52.4\ Btu/lbm}$

$q^{rev} = (h_e - h_i) + w^{rev} = -181.2 - 52.4 = \mathbf{-233.6\ Btu/lbm}$

Mixtures

13.143E

A 4 lbm mixture of 50% argon and 50% nitrogen by mole is in a tank at 300 psia, 320 R. How large is the volume using a model of (a) ideal gas and (b) Kays rule with generalized compressibility charts.

a) Ideal gas mixture

Eq.12.5: $M_{mix} = \sum y_i M_i = 0.5 \times 39.948 + 0.5 \times 28.013 = 33.981$

$$V = \frac{m\bar{R}T}{M_{mix}P} = \frac{4 \times 1545.36 \times 320}{33.981 \times 300 \times 144} = \mathbf{1.347\ ft^3}$$

b) Kay's rule Eq.13.86

$P_{c\ mix} = 0.5 \times 706 + 0.5 \times 492 = 599$ psia

$T_{c\ mix} = 0.5 \times 271.4 + 0.5 \times 227.2 = 249.3$ R

Reduced properties: $P_r = \frac{300}{599} = 0.50, \quad T_r = \frac{320}{249.3} = 1.284$

Fig. D.1: $Z = 0.92$

$$V = Z \frac{m\bar{R}T}{M_{mix}P} = 0.92 \times 1.347 = \mathbf{1.24\ ft^3}$$

Review Problems

13.144E

A 7-ft^3 rigid tank contains propane at 730 R, 500 lbf/in.^{2}. A valve is opened, and propane flows out until half the initial mass has escaped, at which point the valve is closed. During this process the mass remaining inside the tank expands according to the relation $Pv^{1.4}$ = constant. Calculate the heat transfer to the tank during the process.

C_3H_8: $V = 7.0\ \text{ft}^3$, $T_1 = 730\ \text{R}$, $P_1 = 500\ \text{lbf/in.}^2$

$$T_{r1} = \frac{730}{665.6} = 1.097,\quad P_{r1} = \frac{500}{616} = 0.812 \quad => \quad \text{From D.1:}\quad Z_1 = 0.76$$

$$v_1 = \frac{0.76 \times 35.04 \times 730}{500 \times 144} = 0.270\ \text{ft}^3/\text{lbm},\quad v_2 = 2v_1 = 0.54\ \text{ft}^3/\text{lbm}$$

$$m_1 = 7.0/0.270 = 25.92\ \text{lbm},\qquad m_2 = m_1/2 = 12.96\ \text{lbm},$$

$$P_2 = P_1\left(\frac{v_1}{v_2}\right)^{1.4} = \frac{500}{2^{1.4}} = 189.5\ \text{lbf/in.}^2$$

$$P_{r2} = \frac{189.5}{616} = 0.308,\qquad P_2v_2 = Z_2RT_2$$

Trial & error: saturated with

$$T_2 = 0.825 \times 665.6 = 549.4\ \text{R}\ \&\quad Z_2 = \frac{189.5 \times 144 \times 0.54}{35.04 \times 549.4} = 0.764$$

$$Z_2 = Z_{F2} + x_2(Z_{G2} - Z_{F2})$$

$$0.764 = 0.052 + x_2(0.78 - 0.052) \quad => \quad x_2 = 0.978$$

$$(h^*_1 - h_1) = 35.04 \times 665.6 \times 0.85 / 778 = 25.5\ \text{Btu/lbm}$$

$$(h^*_2 - h^*_1) = 0.407\ (549.4 - 730) = -73.4\ \text{Btu/lbm}$$

$$(h^*_2 - h_2) = (h^*_2 - h_{F2}) - x_2h_{FG2} = \frac{35.04 \times 665.6}{778}\Big[4.41 - 0.978(4.41 - 0.54)\Big] = 18.7$$

Energy Eq.: $Q_{CV} = m_2h_2 - m_1h_1 + (P_1 - P_2)V + m_eh_{e\ AVE}$

Let $h^*_1 = 0$ then: $h_1 = 0 + (h_1 - h^*_1) = -25.5\ \text{Btu/lbm}$

$$h_2 = h^*_1 + (h^*_2 - h^*_1) + (h_2 - h^*_2) = 0 - 73.4 - 18.7 = -92.1\ \text{Btu/lbm}$$

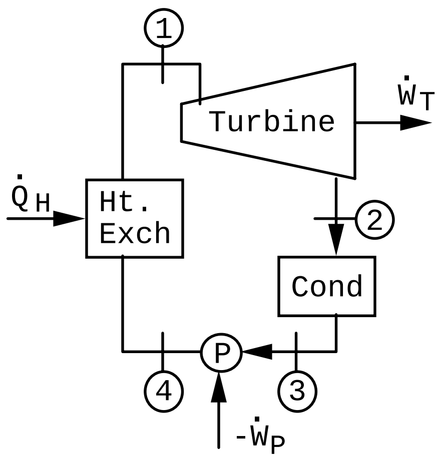
$$h_{e\ AVE} = (h_1 + h_2)/2 = -58.8\ \text{Btu/lbm}$$

$$Q_{CV} = 12.96\ (-92.1) - 25.92(-25.5) + (500-189.5)\times 7.0\times\frac{144}{778} + 12.96(-58.8)$$

$= \mathbf{-892\ Btu}$

13.145E

A newly developed compound is being considered for use as the working fluid in a small Rankine-cycle power plant driven by a supply of waste heat. Assume the cycle is ideal, with saturated vapor at 400 F entering the turbine and saturated liquid at 70 F exiting the condenser. The only properties known for this compound are molecular weight of 80 lbm/lbmol, ideal gas heat capacity *Cpo* = 0.20 Btu/lbm R and *Tc* = 900 R, *Pc* = 750 lbf/in.^{2}. Calculate the work input, per lbm, to the pump and the cycle thermal efficiency.



$T_1 = 400\text{ F} = 860\text{ R}$

$x_1 = 1.0$

$T_3 = 70\text{ F} = 530\text{ R}$

$x_3 = 0.0$

Properties known:

$M = 80,\ C_{PO} = 0.2\text{ Btu/lbm R}$

$T_C = 900\text{ R},\ P_C = 750\text{ lbf/in.}^2$

$$T_{r1} = \frac{860}{900} = 0.956,\quad T_{r3} = \frac{530}{900} = 0.589$$

From D.1: $P_{r1} = 0.76,\ P_1 = 0.76 \times 750 = 570\text{ lbf/in.}^2 = P_4$

$P_{r3} = 0.025,\quad P_3 = 19\text{ lbf/in.}^2 = P_2,\quad Z_{F3} = 0.0045$

$$v_{F3} = Z_{F3}RT_3/P_3 = \frac{0.0045 \times 1545 \times 530}{19 \times 144 \times 80} = 0.0168\text{ ft}^3/\text{lbm}$$

$$w_P = -\int_3^4 vdP \approx v_{F3}(P_4 - P_3) = -0.0168\ (570 - 19) \times \frac{144}{778} = \mathbf{-1.71\ Btu/lbm}$$

$q_H + h_4 = h_1$, but $h_3 = h_4 + w_P$ => $q_H = (h_1 - h_3) + w_P$

From D.2,

$(h_1^* - h_1) = (1.9859/80) \times 900 \times 1.34 = 30.0\text{ Btu/lbm}$

$(h_3^* - h_3) = (1.9859/80) \times 900 \times 5.2 = 116.1\text{ Btu/lbm}$

$(h_1^* - h_3^*) = C_{P0}(T_1 - T_3) = 0.2(400-70) = 66.0\text{ Btu/lbm}$

$(h_1 - h_3) = -30.0 + 66.0 + 116.1 = 152.1\text{ Btu/lbm}$

$q_H = 152.1 + (-1.71) = 150.4\text{ Btu/lbm}$

Turbine, $(s_2\text{-}s_1) = 0 = -(s_2^*\text{-}s_2)+(s_2^*\text{-}s_1^*)+(s_1^*\text{-}s_1)$

From D.3,

$(s_1^*\text{-}s_1) = (1.9859/80) \times 1.06 = 0.0263$ Btu/lbm R

$(s_2^*\text{-}s_1^*) = 0.20 \ln \frac{530}{860} - 0.024\,82 \ln \frac{19}{570} = -0.0124$ Btu/lbm R

Substituting,

$(s_2^*\text{-}s_2) = -\ 0.0124 + 0.0263 = 0.0139 = (s_2^*\text{-}s_{F2}) - x_2 s_{FG2}$

$0.0139 = 0.024\,82 \times 8.77 - x_2 \times 0.024\,82\ (8.77 - 0.075)$

$\Rightarrow\ x_2 = 0.9444$

$(h_2^*\text{-}h_2) = (h_2^*\text{-}h_{F2}) - x_2 h_{FG2}$

From D.2,

$h_{fg2} = 0.024\,82 \times 900\ (5.2 - 0.07) = 114.6$ Btu/lbm

$(h_2^*\text{-}h_2) = 116.1 - 0.9444 \times 114.6 = 7.9$ Btu/lbm

$w_T = (h_1\text{-}h_2) = -30.0 + 66.0 + 7.9 = 43.9$ Btu/lbm

$\eta_{TH} = \frac{w_{NET}}{q_H} = \frac{43.9 - 1.7}{150.4} = \mathbf{0.281}$