SOLUTIONS MANUAL

THERMAL ENVIRONMENTAL ENGINEERING

THIRD EDITION

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2.1

a) $28.75 \text{ in Hg} \left(\frac{1.450 \times 10^{-4} \text{ psia}}{2.961 \times 10^{-4} \text{ in Hg}} \right) = 14.08 \text{ psia}$

b) $28.75 \text{ in Hg} \left(\frac{4.019 \times 10^{-3} \text{ in } H_2O}{2.961 \times 10^{-4} \text{ in Hg}} \right) = 390.2 \text{ in } H_2O$

c) $\frac{390.23 \text{ in } H_2O}{0.8} \left(\frac{1 \text{ m}}{39.37 \text{ in}} \right) = 12.39 \text{ m fluid}$

d) $28.75 \text{ in Hg} \left(\frac{1 \text{ Pa}}{2.961 \times 10^{-4} \text{ in Hg}} \right) = 97.10 \text{ kPa}$

2.2

a) Let x represent dry air and y represent water vapor. By Eqns.(2.18 and 2.19)

$$\frac{P_y}{P_x} = \frac{m_y}{m_x}\frac{R_y}{R_x}$$

$$m_y / m_x = 0.012$$

$$\frac{R_y}{R_x} = \frac{85.76 \text{ ft lb}_f / \text{lb}_m\,°R}{53.352 \text{ ft lb}_f / \text{lb}_m\,°R} = 1.607$$

$$P_x = P - P_y$$

Thus

$$P_y = \frac{P}{1 + \dfrac{m_x R_x}{m_y R_y}} = \frac{14.32 \text{ psia}}{1 + \dfrac{1}{(0.012)(1.607)}} = 0.27 \text{ psia}$$

b) $$\rho = \frac{m}{V} = \frac{m_x + m_y}{V} = \frac{m_x}{V}\left(1 + \frac{m_y}{m_x}\right)$$

By Eq. (2.18), $$\rho = \frac{P_x}{R_x T}\left(1 + \frac{m_y}{m_x}\right)$$

$$\rho = \frac{(14.32 - 0.27)\text{lb}_f/\text{in}^2 (144 \text{in}^2/\text{ft}^2)}{\dfrac{53.352 \text{ ft lb}_f}{\text{lb}_m\,°R}\left(70°F + 459.67°R\right)}\left(1 + 0.012\right) = 0.0725 \frac{\text{lb}_m}{\text{ft}^3}$$

c) $$R = \frac{PV}{mT} = \frac{(14.32 \text{ lb}_f/\text{in}^2)(144 \text{ in}^2/\text{ft}^2)}{(0.0725 \text{ lb}_m/\text{ft}^3)(70 + 459.67°R)} = 53.70 \frac{\text{ft lb}_f}{\text{lb}_m\,°R}$$

2.2 Cont'd

d) Based upon $m = m_x$, by Eq. (2.23)

$$c_p = c_{px} + \frac{m_y}{m_x} c_{py}$$

From Table A.5E, $c_{px} = c_{pa} = 0.2403 \ Btu/lb_{m_a}{}^\circ F$

From Table A.6E, $c_{p_y} = c_{p_v} = 0.450 \ Btu/lb_{m_v}{}^\circ F$

$$c_p = 0.2403 + (0.012)0.450 = 0.246 \ \frac{Btu}{lb_{m_a}{}^\circ F}$$

2.3

Procedure follows that outlined in Prob. 2.2

a) $m_y / m_x = 0.01 \ kg_v / kg_a$

$$P_y = \frac{95 \ kPa}{1 + \frac{1}{(0.01)(1.607)}} = 1.50 \ kPa$$

b) $$\rho = \frac{(95 - 0.01) \ kPa}{\left(0.2870 \frac{kJ}{kg \ K}\right)(20 + 273.15 K)} = 1.13 \ kg/m^3$$

c) $$R = \frac{(95 \ kPa)}{(1.13 \ kg/m^3)(20 + 273.15 K)} = 0.287 \ kJ/kg \ K$$

d) From Table A.5 SI, $c_{px} = c_{pa} = 1.006 \ kJ/kg_a \ K$

From Table A.6 SI, $c_{py} = c_{pv} = 1.882 \ kJ/kg_v \ K$

$c_p = 1.006 + (0.01)(1.882) = 1.025 \ kJ/kg_v \ K$

2.4

a) let ρ_1 be the correct density and ρ_2 the density computed using the perfect gas law

By Eq. (2.24), $\dfrac{\rho_2}{\rho_1} = Z$

By Fig. 2.1 at -20°F, 10 atm, $Z = 0.9892$

$$\text{Error} = (100)\frac{(\rho_1 - \rho_2)}{\rho_1} = 100\left(1 - 0.9892\right) = 1.08\%$$

b) $$P = 1\ \text{MPa}\left(\frac{10^3\ \text{kPa}}{1\ \text{MPa}}\right)\left(\frac{1\ \text{atm}}{101.325\ \text{kPa}}\right) = 9.87\ \text{atm}$$

By Fig. 2.1 at -30°C, 9.87 atm, $Z = 0.9895$

$$\text{Error} = 100\left(1 - 0.9895\right) = 1.05\%$$

2.5

By Table A.1E, $P = 0.95034$ psia, $v = 349.98\ ft^3/lb_m$

$$R_v = 85.76\ ft\,lb_f/lb_m\ °R$$

Thus

$$z = \frac{Pv}{RT} = \frac{(0.95034\ lb_f/in^2)(144\ in^2/ft^2)(349.98\ ft^3/lb_m)}{(85.76\ ft\,lb_f/lb_m\ °R)(100 + 459.67\ °R)}$$

$$z = 0.998$$

2.6

The energy balance on the radiator becomes

$$\left|\dot{Q}_{1-2}\right| = \dot{m}_{st}\left(h_1 - h_2\right)$$

where $\left|\dot{Q}_{1-2}\right| = 5000$ Btu/hr

at ①, by Table A.1E, $h_f = 184.64$, $h_g = 1151.89 \frac{Btu}{lbm}$

$$h_1 = h_f + x_1 (h_g - h_f) = 184.64 + 0.97(1151.89 - 184.64)$$

$$h_1 = 1122.87 \text{ Btu/lbm}$$

at ②, by Table A.1E, $h_2 = h_f(200°F) = 168.34 \frac{Btu}{lbm}$

Thus

$$\dot{m}_{st} = \frac{\left|\dot{Q}_{1-2}\right|}{h_1 - h_2} = \frac{5000 \text{ Btu/hr}}{(1122.87 - 168.34)\text{ Btu/lbm}}$$

$$\dot{m}_{st} = 5.24 \text{ lbm/hr}$$

2.7

The energy balance on the evaporator is

$$\dot{Q}_{1-2} = \dot{m}_{ref} (h_2 - h_1)$$

at ①, by Table A.2 SI, $h_f = 88.73$, $h_g = 1417.81 \frac{kJ}{kg}$

$$h_1 = 88.73 + 0.3(1417.81 - 88.73) = 487.45 \frac{kJ}{kg}$$

at ②, by Table A.2 SI, $h_2 = h_g = 1417.81 \frac{kJ}{kg}$

Thus

$$\dot{Q}_{1-2} = \frac{1 \, kg}{s}(1417.81 - 487.45)\frac{kJ}{kg} = 930.4 \, kW$$

2.8

By Eq. (2.42)

$$\dot{I} = \dot{m}_{st}(s_2 - s_1) - \frac{\dot{Q}}{T_{air}}$$

at ①, by Table A.1E, $s_f = 0.31869$, $s_g = 1.7494 \frac{Btu}{lb_m {}^\circ R}$

$$s_1 = s_f + x_1(s_g - s_f) = 0.31869 + 0.97(1.7494 - 0.31869)$$

$$s_1 = 1.7065 \ Btu/lb_m {}^\circ R$$

at ②, by Table A.1E, $s_2 = s_f(200^\circ F) = 0.29430 \frac{Btu}{lb_m {}^\circ R}$

Thus

$$\dot{I} = 5.24 \frac{lb_m}{hr}(0.29430 - 1.7065)\frac{Btu}{lb_m {}^\circ R} - \frac{(-5000)\ Btu/hr}{(70 + 459.67^\circ R)}$$

$$\dot{I} = 2.04 \frac{Btu}{hr {}^\circ R}$$

2.9

By Eq. (2.42)

$$\dot{I} = \dot{m}_{ref}(s_2 - s_1) - \frac{\dot{Q}_{1-2}}{T_{air}}$$

at ①, by Table A.2SI, $s_f = 0.3644$, $s_g = 5.6145 \frac{kJ}{kg\,K}$

$$s_1 = s_f + x_1(s_g - s_f) = 0.3644 + 0.3(5.6145 - 0.3644)$$

$$s_1 = 1.9394 \text{ kJ/kg K}$$

at ②, by Table A.2SI, $s_2 = s_g(-20°C) = 5.6145 \frac{kJ}{kg\,K}$

Thus

$$\dot{I} = 1\frac{kg}{s}\left(5.6145 - 1.9394\right)\frac{kJ}{kg\,K} - \frac{930.4\text{ kW}}{(-10 + 273.15\text{ K})}$$

$$\dot{I} = 0.1395 \text{ kW/K}$$

2.10

By Eq. (2.86)

$$R_t = R_i + \left(\frac{\ell_1}{k_1} + \frac{\ell_2}{k_2} + \frac{\ell_3}{k_3} \right) + R_o$$

$$R_i = 1/h_i = 1/1.5 \text{ Btu/hr ft}^2\text{°F} = 0.667 \frac{\text{hr ft}^2\text{°F}}{\text{Btu}}$$

$$\frac{\ell_1}{k_1} = \frac{0.5 \text{ in}}{0.1 \text{ Btu/hr ft°F}} \left(\frac{\text{ft}}{12 \text{ in}} \right) = 0.417 \frac{\text{hr ft}^2\text{°F}}{\text{Btu}}$$

$$\frac{\ell_2}{k_2} = \frac{3.5 \text{ in}}{0.03 \text{ Btu/hr ft°F}} \left(\frac{\text{ft}}{12 \text{ in}} \right) = 9.722 \frac{\text{hr ft}^2\text{°F}}{\text{Btu}}$$

$$\frac{\ell_3}{k_3} = \frac{4.0 \text{ in}}{0.75 \text{ Btu/hr ft°F}} \left(\frac{\text{ft}}{12 \text{ in}} \right) = 0.444 \frac{\text{hr ft}^2\text{°F}}{\text{Btu}}$$

$$R_o = 1/h_o = 1/6 \text{ Btu/hr ft}^2\text{°F} = 0.167 \frac{\text{hr ft}^2\text{°F}}{\text{Btu}}$$

Thus

$$R_t = 0.667 + 0.417 + 9.722 + 0.444 + 0.167 = 11.417 \frac{\text{hr ft}^2\text{°F}}{\text{Btu}}$$

$$\mathcal{U} = 1/R_t = 1/11.417 \text{ hr ft}^2\text{°F/Btu}$$

$$\mathcal{U} = 0.0876 \text{ Btu/hr ft}^2\text{°F}$$

By Eq. (2.83), $Q/A = \mathcal{U}(t_i - t_o)$

$$\frac{Q}{A} = 0.0876 \frac{\text{Btu}}{\text{hr ft}^2\text{°F}} (70 - 0)\text{°F} = 6.13 \frac{\text{Btu}}{\text{hr ft}^2}$$

2.11

We will use Eq. (2.52) to calculate h

$$\vec{V} = \frac{\dot{V}}{A} = \frac{2000\ cm^3/s}{\pi\ (3.0 cm)^2/4} = 2.83\ m/s$$

From Table A.6 SI

$k = 0.6154\ W/m\,°C$

$\mu = 797.7 \times 10^{-6}\ kg/m\,s$

$Pr = 6.24$

From Table A.1 SI

$v_f = 0.001005\ m^3/kg$

$$Re_D = \frac{(2.83\ m/s)(0.03\ m)}{(797.7 \times 10^{-6}\ kg/m\,s)(0.001005\ m^3/kg)} = 1.059 \times 10^5$$

Flow is Turbulent so Eq. (2.52) is valid with the coefficients listed

$$h = \frac{k}{D}\ c\ Re_D^{0.8}\ Pr^{0.4}$$

$$h = \frac{0.6154\ W/m°C}{0.03\ m}(0.023)(1.059 \times 10^5)^{0.8}\ (6.24)^{0.4}$$

$$h = 10,270\ W/m^2°C$$

2.12

We will use Eq. (2.54) neglecting the viscosity ratio term to determine the heat transfer coefficient

$$Re_D = \vec{V} D / \nu = \rho \vec{V} D / \mu$$

From Table A.5E at the free stream temp. of 70°F,

$\rho = 0.07493\ lb_m/ft^3$
$\mu = 0.04400\ lb_m/hr\ ft$
$k = 0.01491\ Btu/hr\ ft\ °F$
$Pr = 0.709$

$$Re_D = \frac{(0.07493\ lb_m/ft^3)(10\ ft/s)(5\ in)}{(0.04400\ lb_m/hr\ ft)(12\ in/ft)}\left(\frac{3600\ s}{hr}\right) = 2.554 \times 10^4$$

$$h = \frac{k}{D}\left(0.4\ Re_D^{0.5} + 0.06\ Re_D^{2/3}\right) Pr^{0.4}$$

$$h = \frac{0.01491\ Btu/hr\ ft\ °F}{5\ in\ (1\ ft/12\ in)}\left(0.4(2.554 \times 10^4)^{0.5} + 0.06(2.554 \times 10^4)^{2/3}\right) 0.709^{0.4}$$

$$h = 3.62\ Btu/hr\ ft^2\ °F$$

$$\dot{Q} = h A (t_p - t_{air})$$

For 1 ft of pipe

$$\frac{\dot{Q}}{ft} = \frac{3.62\ Btu}{hr\ ft^2\ °F}\left(\pi\ 5\ in\right)\left(\frac{ft}{12\ in}\right)(150 - 70)\ °F\ (1\ ft)$$

$$\frac{\dot{Q}}{ft} = 379\ Btu/hr$$

2.13

The natural convection heat transfer coefficient will be determined from Eq. (2.57)

$$Ra_D = Gr_D Pr = \frac{g \beta D^3 \Delta t}{\nu^2} Pr = \frac{g \beta D^3 \Delta t}{(\mu/\rho)^2} Pr$$

From Table A.5E at the free stream temp. 70°F

$\rho = 0.07493 \ lb_m/ft^3$

$\mu = 0.04400 \ lb_m/hr\,ft$

$k = 0.01491 \ Btu/hr\,ft\,°F$

$Pr = 0.709$

For gases, $\beta = \frac{1}{T} = 1/(70+459.67°R) = 1.888 \times 10^{-3} \ °R^{-1}$

$$Ra_D = \frac{\left(\frac{32.174 \ ft}{s^2}\right)\left(\frac{1.888 \times 10^{-3}}{°R}\right)(5 \ in)^3 (150-70)°F (0.709)}{\left(\frac{0.04400 \ lb_m/hr\,ft}{0.07493 \ lb_m/ft^3}\right)^2 \left(\frac{1728 \ in^3}{ft^3}\right)\left(\frac{hr}{3600 s}\right)^2}$$

$$Ra_D = 9.37 \times 10^6$$

By Eq. (2.57)

$$h_m = \frac{2(0.01491 \ Btu/hr\,ft°F)/(5 \ in)(ft/12 in)}{\ln\left[1 + \frac{2}{\left[\left(0.518(9.37\times10^6)^{1/4}\left[1+\left(\frac{0.559}{0.709}\right)^{3/5}\right]^{-5/12}\right)^{15} + \left(0.1(9.37\times10^6)^{1/3}\right)^{15}\right]^{1/15}}\right]}$$

$$h_m = 0.848 \ Btu/hr\,ft^2\,°F$$

$$\frac{\dot{Q}}{ft} = \frac{0.848 \ Btu}{hr\,ft°F}(\pi \, 5 \ in)(1 \ ft)\left(\frac{ft}{12 in}\right)(150-70)°F = 88.8 \ Btu/hr$$

2.14

We will use Eq. (2.60) to determine the natural convection heat transfer coefficient in the window cavity with $L = 1\text{cm}$, $H = 1\text{m}$

$$Ra_L = \frac{g L^3 \Delta t \, Pr}{T(\mu/\rho)^2}$$

From Table A.5SI at 10°C

$\rho = 1.248 \text{ kg/m}^3$

$\mu = 1.765 \times 10^{-5} \text{ kg/m s}$

$k = 0.02493 \text{ W/m K}$

$Pr = 0.712$

$$Ra_L = \frac{(9.8\text{ m/s}^2)(10^{-2}\text{m})^3(15°\text{C})(0.712)}{(283.15°\text{K})\left(\dfrac{1.765\times10^{-5}\text{ kg/m s}}{1.248 \text{ kg/m}^3}\right)^2} = 1848$$

$$Nu_{L_{conv}} = \frac{1}{2}\left[\left(0.67\left[1848(0.01)\right]^{1/4}\left[1+\left(\frac{0.559}{0.712}\right)^{3/5}\right]^{-5/12}\right)^{15} + \left(0.1\left[1848\right]^{1/3}\right)^{15}\right]^{1/15}$$

$$Nu_{L_{conv}} = 0.619$$

$$h_m = \frac{k}{L}\left[1 + \left(Nu_{L_{conv}}\right)^{15}\right]^{1/15}$$

$$= \frac{0.02493\text{ W/m K}}{0.01\text{ m}}\left[1 + (0.619)^{15}\right]^{1/15} = 2.493 \text{ W/m}^2\text{ K}$$

$$\dot{Q} = h_m A (t_h - t_c)$$

$$= 2.493\frac{\text{W}}{\text{m}^2\text{ K}}(1\text{ m}^2)(15°\text{C}) = 37.4 \text{ W}$$

2.15

From Fig. 2.8 b

150 kPa → 10 kW/m² → h

$h \cong 1500 \; W/m^2 K$

$q = h \Delta t$

$$\Delta t = q/h = \frac{10 kW/m^2}{1500 W/m^2 K} = 6.67 K$$

From Table A.2 SI, the saturation temperature at 150 kPa is −25.23 C

Therefore the surface temperature becomes

$$t_{surface} = t_{sat} + 6.67 \, C$$

$$= -25.23 + 6.67 = -18.56 \, °C$$

2.16

a) We will use Eq. (2.61) to determine the heat transfer coefficient

From Table A.8E at 10°F

$\mu_\ell = 0.581$ lbm / ft hr

$k_\ell = 0.0586$ Btu/ hr ft °F

From Table A.3E at 10°F

$h_{fg} = h_g - h_f = 105.4 - 13.1 = 92.3$ Btu/lbm

$$Re_\ell = \frac{1.0\,lbm/min}{\frac{\pi(0.5in)^2}{4}}\left(\frac{12\,in}{ft}\right)\frac{(0.5in)}{(0.581\,lb_m/ft\,hr)}\left(\frac{60\,min}{hr}\right) = 3156$$

Let $L = 10$ ft

$$K = \frac{778\,ft\,lbm}{Btu}\,\frac{0.8\,(92.3\,Btu/lbm)}{10\,ft} = 5745$$

$$h_m = \frac{(0.0586\,Btu/hr\,ft\,°F)}{(0.5in)(ft/12in)}\,0.0082\left(3156^2(5745)\right)^{0.4}$$

$h_m = 231$ Btu / hr ft² °F

(different choice of L will affect values for K and h_m)

b) The length necessary will depend on the temperature difference maintained between the tube and the fluid

For our choice of 10 ft in part a,

$$\dot{Q} = h_m A \Delta t = \dot{m} \Delta x h_{fg}$$

or $\Delta t = \dot{m} \Delta x h_{fg} / (h_m A)$

$$\Delta t = \frac{(1.0\, lb_m/min)\, 0.8\, (92.3\, Btu/lb_m)}{\left(\frac{231\, Btu}{hr\, ft^2\, °F}\right)\left(\pi\, 0.5 in\ 10\, ft\right)} \left(\frac{60\, min}{hr}\right)\left(\frac{12 in}{ft}\right)$$

$\Delta t = 15\, °F$

if the temperature difference is one-half this value, the necessary length would be doubled to 20 ft

2.17

We will use Eq. (2.63)

From Table A.8E at 100°F

$$c_{p_\ell} = 0.3162 \text{ Btu/lb}_m\text{°F}$$
$$\mu_\ell = 0.338 \text{ lb}_m\text{/ft hr}$$
$$k_\ell = 0.0466 \text{ Btu/hr ft °F}$$
$$Pr_\ell = 2.29$$

From Table A.3E at 100°F

$$\rho_\ell = 71.24 \text{ lb}_m\text{/ft}^3$$
$$\rho_v = 3.89 \text{ lb}_m\text{/ft}^3$$
$$h_{fg} = 72.80 \text{ Btu/lb}_m$$

$$Re_c = \frac{(1.0 \text{ lb}_m\text{/min})(0.5\text{in})}{\frac{\pi(0.5\text{in})^2}{4}\ \frac{0.338 \text{ lb}_m}{\text{hr ft}}}\left(\frac{71.24}{3.89}\right)^{0.5}\left(\frac{12\text{in}}{\text{ft}}\right)\left(\frac{60\text{min}}{\text{hr}}\right) = 23,214$$

$$M = \frac{72.80 \text{ Btu/lb}_m}{0.3162 \frac{\text{Btu}}{\text{lb}_m\text{°F}}(8\text{°F})} = 28.78$$

$$Nu_\ell = 0.1\,(2.29)^{1/3}(28.78)^{1/6}(23,214)^{2/3} = 188$$

$$h = \frac{188\,(0.0466 \text{ Btu/hr ft °F})}{0.5 \text{ in}}\left(\frac{12\text{in}}{\text{ft}}\right) = 210 \frac{\text{Btu}}{\text{hr ft}^2\text{°F}}$$

2.18

Using Eq. (2.74) with $\varepsilon_1 = 1$, $\varepsilon_2 = 1$, and $F_{1-2} = 1.0$

$$\frac{\dot{Q}_{1-2}}{A_1} = \sigma \left(T_1^4 - T_2^4\right)$$

$$= 0.1713 \times 10^{-8} \frac{Btu}{hr\ ft^2\ {}^\circ R^4}\left[(10 + 459.67)^4 - (-40 + 459.67)^4\right] {}^\circ R^4$$

$$\frac{\dot{Q}_{1-2}}{A_1} = 30.22 \frac{Btu}{hr\ ft^2}$$

2.19

We will use the following equation assuming the surroundings behave as a black body at 70°F

$$\dot{Q}_{1-2} = \varepsilon_1 A_1 \sigma (T_1^4 - T_2^4)$$

for a length of 1 ft

$$\frac{\dot{Q}_{1-2}}{ft} = 0.85 \frac{\pi \, 5 in \, (1 ft)}{(12 in/ft)} 0.1713 \times 10^{-8} \frac{Btu}{hr \, ft^2 \, °R^4} (609.67^4 - 529.67^4) °R$$

$$\frac{\dot{Q}_{1-2}}{ft} = 113 \frac{Btu}{hr}$$

2.20

We will use Eq. (2.74) with $F_{1-2} = 1.0$ and $A_1/A_2 = 1.0$

$$\dot{Q}_{1-2} = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

$$= \frac{1\,m^2 (5.670 \times 10^{-8} W/m^2 K^4)(288.15K^4 - 273.15K^4)}{\frac{1}{0.9} + \frac{1}{0.9} - 1}$$

$$\dot{Q}_{1-2} = 61.6\ W$$

2.21

Let the radiative heat transfer be written as

$$\dot{Q}_r = h_r A (t_1 - t_2)$$

$$h_r = \frac{\dot{Q}_r}{A(t_1 - t_2)}$$

$$= \frac{113 \text{ Btu/hr } (12 \text{ in/ft})}{\pi \text{ } 5 \text{ in } (1 \text{ ft}) (150 - 70)°F} = 1.079 \frac{\text{Btu}}{\text{hr ft}^2 °F}$$

The combined convective / radiative heat transfer coefficient becomes

$$h = h_c + h_r$$

$$= 0.848 + 1.079 = 1.927 \frac{\text{Btu}}{\text{hr ft}^2 °F}$$

2.22

Let the radiative heat transfer coefficient be written as

$$h_r = \frac{\dot{Q}_r}{A(t_1 - t_2)}$$

$$= \frac{61.6\ W}{1\ m^2\ (15-0)\ °C} = 4.11\ \frac{W}{m^2\ °C}$$

The combined convective/radiative heat transfer coefficient becomes

$$h = h_c + h_r$$

$$= 2.493 + 4.11 = 6.60\ \frac{W}{m^2\ °C}$$