

- 2-1. Water at 120 C and a pressure of 250 kPa passes through a pressure-reducing valve and then flows to a separating tank at standard atmospheric pressure of 101.3 kPa, as shown in Fig. 2-14.
- What is the state of the water entering the valve (subcooled liquid, saturated liquid, or vapor)?
  - For each kilogram that enters the pressure-reducing valve, how much leaves the separating tank as vapor?

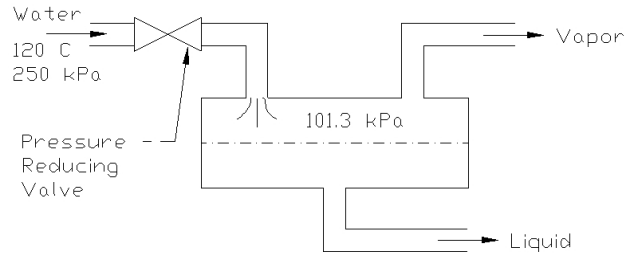


Fig. 2-14. Pressure-reducing valve in Problem 2-1

Solution:

- From Fig. 2-2, a temperature of 120 C and pressure of 250 kPa water lies in the sub-cooled region. so it is a sub-cooled liquid.
- At 120 C,  $h_1 = 503.72$  kJ/kg from Table A-1

For Pressuring Reducing Valve  $Dh = 0$

$$h_2 = h_1$$

At 101.3 kPa, Table A-1,  $h_f = 419.06$  kJ/kg

$$h_g = 2676 \text{ kJ/kg}$$

Let  $x$  be the amount of vapor leaving the separating tank.

$$h = h_f + x(h_g - h_f)$$

$$x = \frac{h - h_f}{h_g - h_f} = \frac{503.72 - 419.06}{2676 - 419.06}$$

$$x = 0.0375 \text{ kg/kg} \text{ --- Ans.}$$

- 2-2. Air flowing at a rate of 2.5 kg/s is heated in a heat exchanger from -10 to 30 C. What is the rate of heat transfer?

Solution:

$$q = mc_p(t_2 - t_1)$$

$$m = 2.5 \text{ kg/s}$$

$$c_p = 1.0 \text{ kJ/kg.K}$$

$$t_2 = 30 \text{ C}$$

$$t_1 = -10 \text{ C}$$

Then,

$$q = (2.5)(1.0)(30 + 10)$$

**q = 100 kw - - - Ans.**

2-3. One instrument for measuring the rate of airflow is a venturi, as shown in Fig. 2-15, where the cross-sectional area is reduced and the pressure difference between position A and B measured. The flow rate of air having a density of  $1.15 \text{ kg/m}^3$  is to be measured in a venturi where the area of position A is  $0.5 \text{ m}^2$  and the area at b is  $0.4 \text{ m}^2$ . The deflection of water (density =  $1000 \text{ kg/m}^3$ ) in a manometer is 20 mm. The flow between A and B can be considered to be frictionless so that Bernoulli's equation applies.

- (a) What is the pressure difference between position A and B?  
 (b) What is the airflow rate?

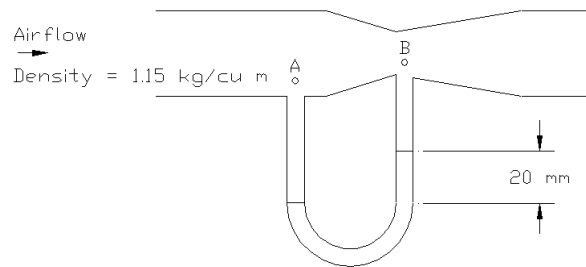


Fig. 2-15. A venturi for measuring air flow.

Solution:

- (a) Bernoulli equation for manometer

$$\frac{p_A}{\rho} + gz_A = \frac{p_B}{\rho} + gz_B$$

$$p_A - p_B = \rho g(z_B - z_A)$$

$$z_B - z_A = 20 \text{ mm} = 0.020 \text{ m}$$

$$g = 9.81 \text{ m/s}^2$$

$$\rho = 1000 \text{ kg/m}^3$$

$$p_A - p_B = (1000 \text{ kg/m}^3)(9.81 \text{ m/s}^2)(0.020 \text{ m})$$

**$p_A - p_B = 196.2 \text{ Pa}$  - - - Ans.**

- (b) Bernoulli Equation for Venturi

$$\frac{p}{\rho} + \frac{V^2}{2} = \text{constant}$$

$$\frac{p_A}{\rho} + \frac{V_A^2}{2} = \frac{p_B}{\rho} + \frac{V_B^2}{2}$$

$$p_A - p_B = \frac{1}{2}\rho(V_B^2 - V_A^2)$$

$$\text{But } m = \rho A_A V_A = \rho A_B V_B$$

$$A_A V_A = A_B V_B$$

$$A_A = 0.5 \text{ m}^2 \text{ and } A_B = 0.4 \text{ m}^2$$

Then

$$0.5V_A = 0.4V_B$$

$$V_A = 0.8V_B$$

$$p_A - p_B = 196.2 \text{ Pa} = \frac{1}{2}(1.15 \text{ kg/m}^3)[V_B^2 - (0.8V_B)^2]$$

$$V_B = 30.787 \text{ m/s}$$

$$\begin{aligned} \text{Air Flow Rate} &= A_B V_B \\ &= (0.4 \text{ m}^2)(30.787 \text{ m/s}) \\ &= \mathbf{12.32 \text{ m}^3/\text{s} \text{ --- Ans.}} \end{aligned}$$

- 2-4. Use the perfect-gas equation with  $R = 462 \text{ J/kg}\cdot\text{K}$  to compute the specific volume of saturated vapor at  $20 \text{ C}$ . Compare with data of Table A-1.

Solution:

Perfect-Gas Equation:

$$pv = RT$$

$$v = \frac{RT}{p}$$

At  $20 \text{ C}$ , Table A-1, Saturation Pressure =  $2.337 \text{ kPa} = 2337 \text{ Pa}$ .

Specific volume of saturated vapor =  $57.84 \text{ m}^3/\text{kg}$

$$T = 20 \text{ C} + 273 = 293 \text{ K}$$

$$v = \frac{(462 \text{ J/kg}\cdot\text{K})(293 \text{ K})}{2337 \text{ Pa}}$$

$$v = 57.923 \text{ m}^3/\text{kg}$$

$$\text{Deviation} = \frac{57.923 - 57.84}{57.84} (100\%)$$

$$\text{Deviation} = 0.1435 \%$$

- 2-5. Using the relationship shown on Fig. 2-6 for heat transfer when a fluid flows inside tube, what is the percentage increase or decrease in the convection heat-transfer coefficient  $h_c$  if the viscosity of the fluid is decreased 10 percent.

Solution:

Figure 2-6.

$$Nu = 0.023Re^{0.8}Pr^{0.4}$$

where:

$$Re = \frac{\rho VD}{\mu}$$

$$Pr = \frac{\mu c_p}{k}$$

$$Nu = \frac{h_c D}{k}$$

Then,

$$\frac{\left(\frac{h_{c1}D}{k}\right)}{\left(\frac{h_{c2}D}{k}\right)} = \frac{0.023\left(\frac{\rho VD}{\mu_1}\right)^{0.8}\left(\frac{\mu_1 c_p}{k}\right)^{0.4}}{0.023\left(\frac{\rho VD}{\mu_2}\right)^{0.8}\left(\frac{\mu_2 c_p}{k}\right)^{0.4}}$$

$$\frac{h_{c1}}{h_{c2}} = \left(\frac{\mu_2}{\mu_1}\right)^{0.4}$$

If viscosity is decreased by 10 %

$$\frac{\mu_2}{\mu_1} = 0.9$$

Then,

$$\frac{h_{c1}}{h_{c2}} = (0.9)^{0.4}$$

$$h_{c2} = 1.043h_{c1}$$

$$\text{Increase} = \frac{h_{c2} - h_{c1}}{h_{c1}} (100\%)$$

$$\text{Increase} = (1.043 - 1)(100 \%)$$

$$\text{Increase} = 4.3 \% \text{ --- Ans.}$$

- 2-6. What is the order of magnitude of heat release by convection from a human body when the air velocity is 0.25 m/s and its temperature is 24 C?

Solution:

Using Eq. (2-12) and Eq. (2-18)

$$C = h_c A (t_s - t_a)$$

$$h_c = 13.5V^{0.6}$$

$$V = 0.25 \text{ m/s}$$

$$h_c = 13.5(0.25)^{0.6} = 5.8762 \text{ W/m}^2 \cdot \text{K}$$

Human Body:  $A = 1.5 \text{ to } 2.5 \text{ m}^2$  use  $1.5 \text{ m}^2$   
 $t_s = 31 \text{ to } 33 \text{ C}$  use  $31 \text{ C}$

$$C = (5.8762 \text{ W/m}^2 \cdot \text{K})(1.5 \text{ m}^2)(31 \text{ C} - 24 \text{ C})$$

$$C = 61.7 \text{ W}$$

**Order of Magnitude ~ 60 W - - - Ans.**

2-7 What is the order of magnitude of radiant heat transfer from a human body in a comfort air-conditioning situation?

Solution:

Eq. 2-10.

$$q_{1-2} = \sigma A F_{\epsilon} F_A (T_1^4 - T_2^4)$$

Surface area of human body =  $1.5 \text{ to } 2.5 \text{ m}^2$  use  $1.5 \text{ m}^2$

$$A F_{\epsilon} F_A = (1.0)(0.70)(1.5 \text{ m}^2) = 1.05 \text{ m}^2$$

$$s = 5.669 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$$

$$T_1 = 31 \text{ C} + 273 = 304 \text{ K}$$

$$T_2 = 24 \text{ C} + 273 = 297 \text{ K}$$

$$q_{1-2} = (5.669 \times 10^{-8})(1.05)(304^4 - 297^4)$$

$$q_{1-2} = 45 \text{ W}$$

**Order of Magnitude ~ 40 W - - - Ans.**

2-8. What is the approximate rate of heat loss due to insensible evaporation if the skin temperature is  $32 \text{ C}$ , the vapor pressure is  $4750 \text{ Pa}$ , and the vapor pressure of air is  $1700 \text{ Pa}$ ? The latent heat of water is  $2.43 \text{ MJ/kg}$ ;  $C_{\text{diff}} = 1.2 \times 10^{-9} \text{ kg/Pa} \cdot \text{s} \cdot \text{m}^2$ .

Solution:

Equation 2-19.

$$q_{\text{ins}} = h_{\text{fg}} A C_{\text{diff}} f(p_s - p_a)$$

Where:

$A = 2.0 \text{ m}^2$  average for human body area

$h_{\text{fg}} = 2.43 \text{ MJ/kg} = 2,430,000 \text{ J/kg}$

$p_s = 4750 \text{ Pa}$

$p_a = 1700 \text{ Pa}$

$C_{\text{diff}} = 1.2 \times 10^{-9} \text{ kg/Pa} \cdot \text{s} \cdot \text{m}^2$

$$q_{\text{ins}} = (2,430,000)(2.0)(1.2 \times 10^{-9})(4750 - 1700)$$

**$q_{\text{ins}} = 18 \text{ W} - - - \text{Ans.}$**

- 0 0 0 -

- 3-1 Calculate the specific volume of an air-vapor mixture in cubic meters per kilogram of dry air when the following conditions prevail:  $t = 30\text{ C}$ ,  $W = 0.015\text{ kg/kg}$ , and  $p_t = 90\text{ kPa}$ .

Solution:

Equation 3-4.

$$v = \frac{R_a T}{p_a} = \frac{R_a T}{p_t - p_s}$$

$$T = 30\text{ C} + 273 = 303\text{ K}$$

$$R_a = 287\text{ J/kg.K}$$

$$P_t = 90\text{ kPa} = 90,000\text{ Pa}$$

Equation 3-2

$$W = \frac{0.622p_s}{p_t - p_s}$$

$$0.015 = \frac{0.622p_s}{90 - p_s}$$

$$1.35 - 0.15p_s = 0.622p_s$$

$$p_s = 2.1193\text{ kPa}$$

$$v = \frac{R_a T}{p_t - p_s} = \frac{(287)(303)}{90000 - 2119.3}$$

$$v = 0.99\text{ m}^3/\text{kg} \text{ --- Ans.}$$

- 3-2. A sample of air has a dry-bulb temperature of  $30\text{ C}$  and a wet-bulb temperature of  $25\text{ C}$ . The barometric pressure is  $101\text{ kPa}$ . Using steam tables and Eqs. (3-2), (303), and (3-5), calculate (a) the humidity ration if this air is adiabatically saturated, (b) the enthalpy of air if it is adiabatically saturated, (c) the humidity ratio of the sample using Eq. (3-5), (d) the partial pressure of water vapor in the sample, and (e) the relative humidity.

Solution:

Eq. 3-2.

$$W = \frac{0.622p_s}{p_t - p_s}$$

Eq. 3-3.

$$h = c_p t + Wh_g$$

Eq. 3-5

$$h_1 = h_2 - (W_2 - W_1)h_f$$

$$h_1 = c_p t_1 + Wh_{g1}$$

$$h_{g1} \text{ at } 30\text{ C} = 2556.4\text{ kJ/kg}$$

$$t_1 = 30\text{ C}$$

$$c_p = 1.0\text{ kJ/kg.K}$$

$$h_1 = (1)(30) + 2556.4W_1$$

$$h_1 = 30 + 2556.4W_1$$

$$h_2 = c_p t_2 + W h_{g2}$$

$$h_{g2} \text{ at } 25 \text{ C} = 2547.3 \text{ kJ/kg}$$

$$t_2 = 25 \text{ C}$$

$$c_p = 1.0 \text{ kJ/kg.K}$$

$$h_2 = (1)(25) + 2547.3W_2$$

$$h_2 = 25 + 2547.3W_2$$

$$h_f \text{ at } 25 \text{ C} = 125.66 \text{ kJ/kg}$$

Then:

$$h_1 = h_2 - (W_2 - W_1)h_f$$

$$30 + 2556.4W_1 = 25 + 2547.3W_2 - (W_2 - W_1)(125.66)$$

$$5 = 2421.64W_2 - 2430.74W_1$$

But,

$$W_2 = \frac{0.622p_s}{p_t - p_s}$$

$$p_s \text{ at } 25 \text{ C} = 3.171 \text{ kPa}$$

$$W_2 = \frac{0.622(3.171)}{101 - 3.171}$$

$$W_2 = 0.0201 \text{ kg/kg}$$

$$5 = 2421.64(0.0201) - 2430.74W_1$$

$$W_1 = 0.018 \text{ kg/kg}$$

(a) Humidity Ratio  
 **$W_2 = 0.0201 \text{ kg/kg} \text{ --- Ans.}$**

(b)  $h_2 = c_p t_2 + W_2 h_{g2}$   
 $h_2 = (1)(25) + (0.0201)(2547.3)$   
 **$h_2 = 76.2 \text{ kJ/kg} \text{ --- Ans.}$**

(c) Humidity Ratio  
 **$W_1 = 0.018 \text{ kg/kg} \text{ --- Ans.}$**

(d)  $p_{s1}$   

$$W_1 = \frac{0.622p_s}{p_t - p_s}$$

$$0.018 = \frac{0.622p_s}{101 - p_s}$$
 $p_{s1} = 2.84 \text{ kPa}$ 
 **$p_{s1} = 2840 \text{ kPa} \text{ --- Ans.}$**

(e) At 30 C,  $p_s = 4.241$  kPa

$$\text{Relative Humidity} = (2.84 \text{ kPa} / 4.241 \text{ kPa})(100\%)$$

**Relative Humidity = 67 % - - - Ans.**

3-3 Using humidity ratios from the psychrometric chart, calculate the error in considering the wet-bulb line to be the line of constant enthalpy at the point of 35 C dry-bulb temperature and 50 percent relative humidity.

Solution:

Dry-bulb Temperature = 35 C

Relative Humidity = 50 %

Fig. 3-1, Psychrometric Chart.

At constant enthalpy line: Wet-bulb = 26.04 C

At wet-bulb line = Wet-bulb = 26.17 C

$$\text{Error} = 26.17 \text{ C} - 26.04 \text{ C}$$

$$\text{Error} = 0.13 \text{ C}$$

3-4. An air-vapor mixture has a dry-bulb temperature of 30 C and a humidity ratio of 0.015. Calculate at two different barometric pressures, 85 and 101 kPa, (a) the enthalpy and (b) the dew-point temperature.

Solution:

At 30 C,  $p_s = 4.241$  kPa,  $h_g = 2556.4$  kJ/kg

$$(a) \quad h = c_p t + W h_g$$

For 85 and 101 kPa

$$c_p = 1.0$$

$$t = 30 \text{ C}$$

$$W = 0.015 \text{ kg/kg}$$

$$h_g = 2556.4 \text{ kJ/kg}$$

$$h = (1.0)(30) + (0.015)(2556.4)$$

$$h = 68.3 \text{ kJ/kg}$$

(b) For dew-point:

$$W = \frac{0.622 p_s}{p_t - p_s}$$

at 85 kPa

$$0.015 = \frac{0.622 p_s}{p_t - p_s}$$

$$p_s = 2.0016 \text{ kPa}$$

**Dew-Point = 17.5 C - - - Ans.**

at 101 kPa

$$0.015 = \frac{0.622p_s}{p_t - p_s}$$

$$p_s = 2.3783 \text{ kPa}$$

**Dew-Point = 20.3 C - - - Ans.**

- 3-5. A cooling tower is a device that cools a spray of water by passing it through a stream of air. If  $15 \text{ m}^3/\text{s}$  of air is at  $35 \text{ C}$  dry-bulb and  $24 \text{ C}$  wet-bulb temperature and an atmospheric pressure of  $101 \text{ kPa}$  enters the tower and the air leaves saturated at  $31 \text{ C}$ , (a) to what temperature can this airstream cool a spray of water entering at  $38 \text{ C}$  with a flow rate of  $20 \text{ kg/s}$  and (b) how many kilograms per second of make-up water must be added to compensate for the water that is evaporated?

Solution:

At  $35 \text{ C}$  dry-bulb,  $24 \text{ C}$  wet-bulb.

Fig. 3-1, Psychrometric Chart

$$h_1 = 71.524 \text{ kJ/kg,}$$

$$v_1 = 0.89274 \text{ m}^3/\text{kg}$$

$$W_1 = 0.0143 \text{ kg/kg}$$

At  $31 \text{ C}$  saturated, Table A-2.

$$h_2 = 105 \text{ kJ/kg}$$

$$W_2 = 0.0290 \text{ kg/kg}$$

Then;

$$m = (15 \text{ m}^3/\text{s}) / (0.89274 \text{ m}^3/\text{kg}) = 16.8022 \text{ kg/s}$$

(a)  $t_{w1} = 38 \text{ C}$   
 $m_w = 20 \text{ kg/s}$   
 $c_{pw} = 4.19 \text{ kJ/kg.K}$

$$m_w c_{pw} (t_{w1} - t_{w2}) = m(h_2 - h_1)$$

$$(20)(4.19)(38 - t_{w2}) = (16.8022)(105 - 71.524)$$

**$t_{w2} = 31.3 \text{ C} - - - \text{Ans.}$**

(b) Make-Up Water =  $m_m$

$$m_m = m(W_2 - W_1)$$

$$m_m = (16.8022)(0.0290 - 0.0143)$$

**$m_m = 0.247 \text{ kg/s} - - - \text{Ans.}$**

- 3-6. In an air-conditioning unit  $3.5 \text{ m}^3/\text{s}$  of air at  $27 \text{ C}$  dry-bulb temperature, 50 percent relative humidity, and

standard atmospheric pressure enters the unit. The leaving condition of the air is 13 C dry-bulb temperature and 90 percent relative humidity. Using properties from the psychrometric chart, (a) calculate the refrigerating capacity in kilowatts and (b) determine the rate of water removal from the air.

Solution:

At 27 C dry-bulb, 5 Percent Relative Humidity

$$h_1 = 55.311 \text{ kJ/kg,}$$

$$v_1 = 0.86527 \text{ m}^3/\text{kg}$$

$$W_1 = 0.0112 \text{ kg/kg}$$

At 13 C Dry-Bulb, 90 Percent Relative Humidity

$$h_2 = 33.956 \text{ kJ/kg}$$

$$W_2 = 0.0084 \text{ kg/kg}$$

$$m = (3.5 \text{ m}^3/\text{s}) / (0.86526 \text{ m}^3/\text{kg}) = 4.04498 \text{ kg/s}$$

$$\begin{aligned} \text{(a) Refrigerating Capacity} \\ &= m(h_1 - h_2) \\ &= (4.04498)(55.311 - 33.956) \\ &= \mathbf{86.38 \text{ kW} \text{ --- Ans.}} \end{aligned}$$

$$\begin{aligned} \text{(b) Rate of Water Removal} \\ &= m(W_1 - W_2) \\ &= (4.04498)(0.0112 - 0.0084) \\ &= \mathbf{0.0113 \text{ kg/s} \text{ --- Ans.}} \end{aligned}$$

- 3-7. A stream of outdoor air is mixed with a stream of return air in an air-conditioning system that operates at 101 kPa pressure. The flow rate of outdoor air is 2 kg/s, and its condition is 35 C dry-bulb temperature and 25 C wet-bulb temperature. The flow rate of return air is 3 kg/s, and its condition is 24 C and 50 percent relative humidity. Determine (a) the enthalpy of the mixture, (b) the humidity ratio of the mixture, (c) the dry-bulb temperature of the mixture from the properties determined in parts (a) and (b) and (d) the dry-bulb temperature by weighted average of the dry-bulb temperatures of the entering streams.

Solutions:

Use Fig. 3-1, Psychrometric Chart

At 35 C Dry-Bulb, 24 C Wet-Bulb

$$h_1 = 75.666 \text{ kJ/kg, } m_1 = 2 \text{ kg/s}$$

$$W_1 = 0.0159 \text{ kg/kg}$$

At 24 C Dry-Bulb, 50 Percent Relative Humidity

$$h_2 = 47.518 \text{ kJ/kg, } m_2 = 3 \text{ kg/s}$$

$$W_2 = 0.0093 \text{ kg/kg}$$

(a)

$$\begin{aligned} h_m &= \frac{(2)(75.666) + (3)(47.518)}{2 + 3} \\ h_m &= \mathbf{58.777 \text{ kJ/kg} \text{ --- Ans.}} \end{aligned}$$