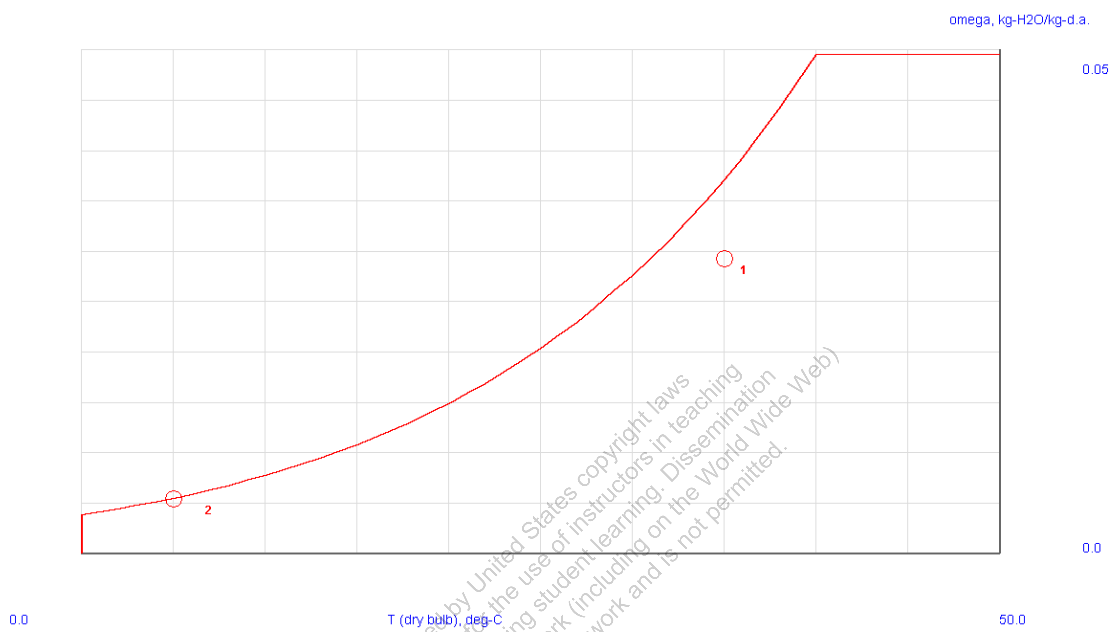
12-3-1 [OMU] Consider 100 m^3 of moist air at 100 kPa, 35°C and 80% R.H. Calculate (a) the amount of water vapor condensed if the mixture is cooled to 5°C in a constant pressure process. Also calculate (b) the heat transfer (Q). (c) What-if Scenario: What would the heat transfer be if the mixture were cooled to 15°C in a constant pressure process?

SOLUTION



Given:

$$c_{pa} = 1.005 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$R_a = 0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

State-1 (given $p_1, T_1, \cancel{V}_1, \phi_1$):

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@35°\text{C}} = (0.80)(5.6190) = 4.50 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 100 - 4.50 = 95.50 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{4.50}{95.50}\right) = 0.0293 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@35°\text{C}} = 2565.30 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(35) + (0.0293)(2565.30) = 110.34 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(308)}{95.50} = 0.9256 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$m_{a1} = \frac{\cancel{V}_1}{v_1} = \frac{100}{0.9256} = 108.04 \text{ kg}$$

State-2 (given $p_2 = p_1, T_2, \phi_2$):

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@5°\text{C}} = (1)(0.8697) = 0.87 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 100 - 0.87 = 99.13 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{0.87}{99.13}\right) = 0.0055 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@5°\text{C}} = 2510.55 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(5) + (0.0055)(2510.55) = 18.83 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(278)}{99.13} = 0.8049 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\cancel{V}_2 = m_{a2} v_2 = (108.04)(0.8049) = 86.96 \text{ m}^3$$

State-3 (given $p_3 = p_1, T_3$):

$$p_{\text{sat}@5°\text{C}} = 0.8697 \text{ kPa}$$

$$p_3 > p_{\text{sat}@5°\text{C}} \;\therefore\; \text{subcooled liquid}$$

$$u_{f@5°\text{C}} = 20.99 \frac{\text{kJ}}{\text{kg}}; \; v_{f@5°\text{C}} = 0.001000 \frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@5°\text{C}} + p_3 v_{f@5°\text{C}} = 20.99 + (100)(0.001000) = 21.09 \frac{\text{kJ}}{\text{kg}}$$

The amount of water vapor condensed

$$m_w = m_a(\omega_1 - \omega_2) = (108.04)(0.0293 - 0.0055) = 2.57 \text{ kg}$$

The boundary work (neglecting volume of condensed water)

$$W_B = p\left(\cancel{V}_2 - \cancel{V}_1\right) = (100)(86.96 - 100) = -1304 \text{ kJ}$$

The heat transfer,

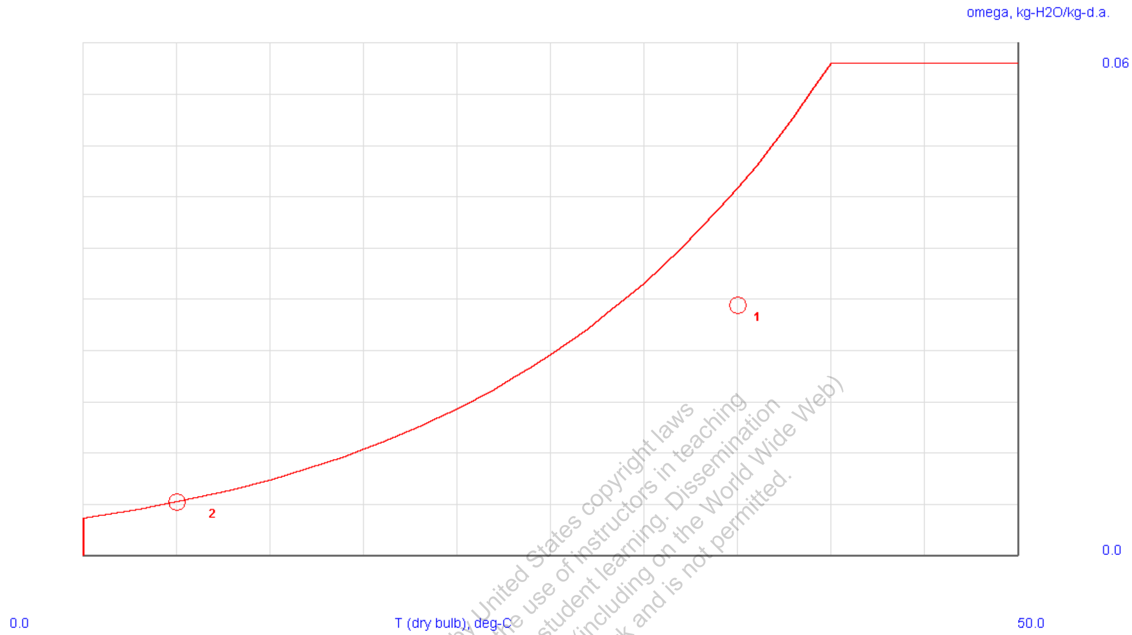
$$Q = m_a\left[\left(h_2 - h_1\right) - R_a\left(T_2 - T_1\right)\right] + m_w h_3 + W_B;$$

$$Q = (108.04)\left[(18.83 - 110.34) - (0.287)(5 - 35)\right] + (2.57)(21.09) - 1304 = -10260.52 \text{ kJ}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry closed process TESTcalc to verify the solution and perform the what-if study. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

12-3-2 [OMX] Calculate (a) the amount of water vapor condensed if the mixture in previous example is cooled to 5°C in a constant volume process. Also calculate (b) the heat transfer (Q). (c) What-if Scenario: What would the heat transfer be if the mixture were cooled to 15°C in a constant volume process?

SOLUTION



Given:

$$c_{pa} = 1.005 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$R_a = 0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

State-1 (given $p_1, T_1, \cancel{V}_1, \phi_1$):

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@35°\text{C}} = (0.80)(5.6190) = 4.50 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 100 - 4.50 = 95.50 \text{ kPa}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{4.50}{95.50}\right) = 0.0293\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@35°\text{C}} = 2565.30\frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(35) + (0.0293)(2565.30) = 110.34\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(308)}{95.50} = 0.9256\frac{\text{m}^3}{\text{kg d.a.}}$$

$$m_{a1} = \frac{V_1}{v_1} = \frac{100}{0.9256} = 108.04 \text{ kg}$$

State-2 (given $T_2, v_2 = v_1, \phi_2$):

$$p_{a2} = \frac{R_a T_2}{v_2} = \frac{(0.287)(278)}{0.9256} = 86.20 \text{ kPa}$$

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@5°\text{C}} = (1)(0.8697) = 0.87 \text{ kPa}$$

$$p_2 = p_{a2} + p_{v2} = 86.20 + 0.87 = 87.07 \text{ kPa}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{0.87}{86.20}\right) = 0.0063\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@5°\text{C}} = 2510.55\frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(5) + (0.0063)(2510.55) = 20.84\frac{\text{kJ}}{\text{kg d.a.}}$$

State-3 (given $p_3 = p_1, T_3$):

$$p_{\text{sat}@5°\text{C}} = 0.8697 \text{ kPa}$$

$$p_3 > p_{\text{sat}@5°\text{C}} \ \therefore \text{ subcooled liquid}$$

$$u_{f@5°\text{C}} = 20.99\frac{\text{kJ}}{\text{kg}}; \ v_{f@5°\text{C}} = 0.001000\frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@5°\text{C}} + p_3 v_{f@5°\text{C}} = 20.99 + (100)(0.001000) = 21.09\frac{\text{kJ}}{\text{kg}}$$

The amount of water vapor condensed

$$m_w = m_a(\omega_1 - \omega_2) = (108.04)(0.0293 - 0.0063) = 2.48 \text{ kg}$$

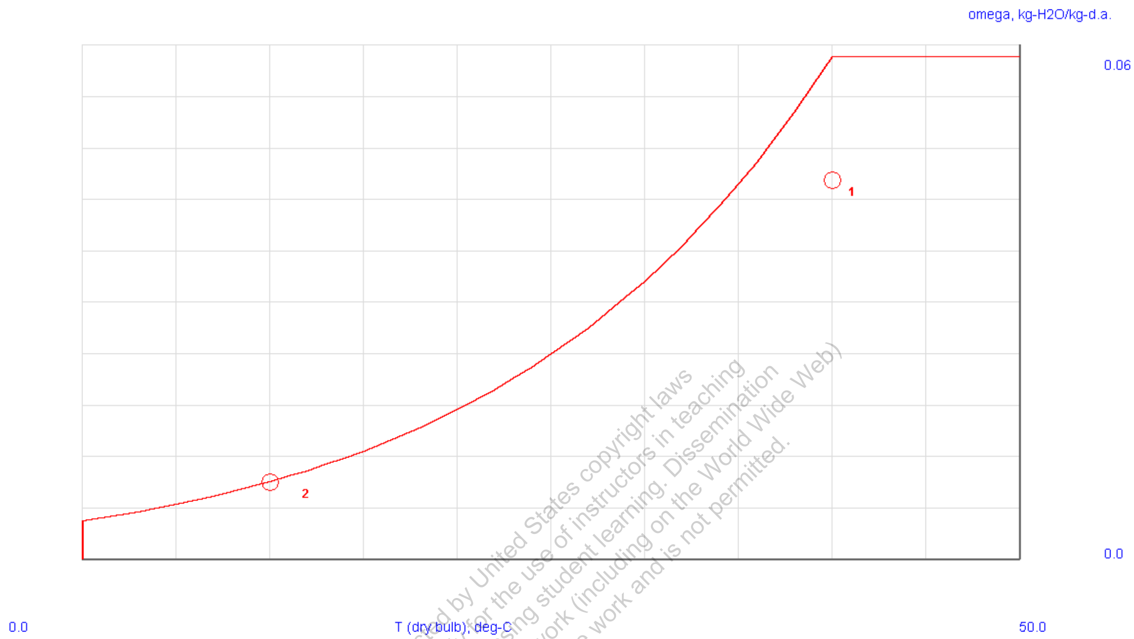
The heat transfer,

$$Q = m_a\left[\left(h_2 - h_1\right) - R_a\left(T_2 - T_1\right)\right] + m_w h_3 + \cancel{W_B}^{\,0};$$
$$Q = (108.04)\left[(20.84 - 110.34) - (0.287)(5 - 35)\right] + (2.48)(21.09) = -8687.05\ \text{kJ}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry closed process TESTcalc to verify the solution and perform the what-if study. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

12-3-3 [OMC] A tank of volume 10 m^3 contains dry air and water vapor mixture at 40^{o}C and 100 kPa at a relative humidity of 90%. The tank is cools down to 10^{o}C by transferring heat to the surroundings. Determine (a) the amount of water condensed and (b) the heat transfer (Q). (c) What-if Scenario: What would the heat transfer be if the initial pressure were 1000 kPa?

SOLUTION



Given:

$$c_{pa} = 1.005 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$R_a = 0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

State-1 (given $p_1, T_1, \cancel{V_1}, \phi_1$):

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat@}T_1} = \phi_1 p_{\text{sat@40°C}} = (0.90)(7.3799) = 6.64 \text{ kPa}$$
$$p_{a1} = p_1 - p_{v1} = 100 - 6.64 = 93.36 \text{ kPa}$$
$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{6.64}{93.36}\right) = 0.0442 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$
$$h_{g\text{@40°C}} = 2574.29 \frac{\text{kJ}}{\text{kg}}$$
$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(40) + (0.0442)(2574.29) = 153.98 \frac{\text{kJ}}{\text{kg d.a.}}$$
$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(313)}{93.36} = 0.9622 \frac{\text{m}^3}{\text{kg d.a.}}$$
$$m_{a1} = \frac{V_1}{v_1} = \frac{10}{0.9622} = 10.39 \text{ kg}$$

State-2 (given $T_2, v_2 = v_1, \phi_2$):
$$p_{a2} = \frac{R_a T_2}{v_2} = \frac{(0.287)(283)}{0.9622} = 84.41 \text{ kPa}$$
$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat@}T_2} = \phi_2 p_{\text{sat@10°C}} = (1)(1.2271) = 1.23 \text{ kPa}$$
$$p_2 = p_{a2} + p_{v2} = 84.41 + 1.23 = 85.64 \text{ kPa}$$
$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{1.23}{84.41}\right) = 0.0091 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$
$$h_{g\text{@10°C}} = 2519.75 \frac{\text{kJ}}{\text{kg}}$$
$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(10) + (0.0091)(2519.75) = 32.98 \frac{\text{kJ}}{\text{kg d.a.}}$$

State-3 (given $p_3 = p_1, T_3$):
$$p_{\text{sat@10°C}} = 1.2271 \text{ kPa}$$
$$p_3 > p_{\text{sat@10°C}} \quad \therefore \text{ subcooled liquid}$$
$$u_{f\text{@10°C}} = 42.00 \frac{\text{kJ}}{\text{kg}}; \quad v_{f\text{@10°C}} = 0.001001 \frac{\text{m}^3}{\text{kg}}$$
$$h_3 = u_{f\text{@10°C}} + p_3 v_{f\text{@10°C}} = 42.00 + (100)(0.001001) = 42.10 \frac{\text{kJ}}{\text{kg}}$$

The amount of water vapor condensed
$$m_w = m_a(\omega_1 - \omega_2) = (10.39)(0.0442 - 0.0091) = 0.36 \text{ kg}$$

The heat transfer,

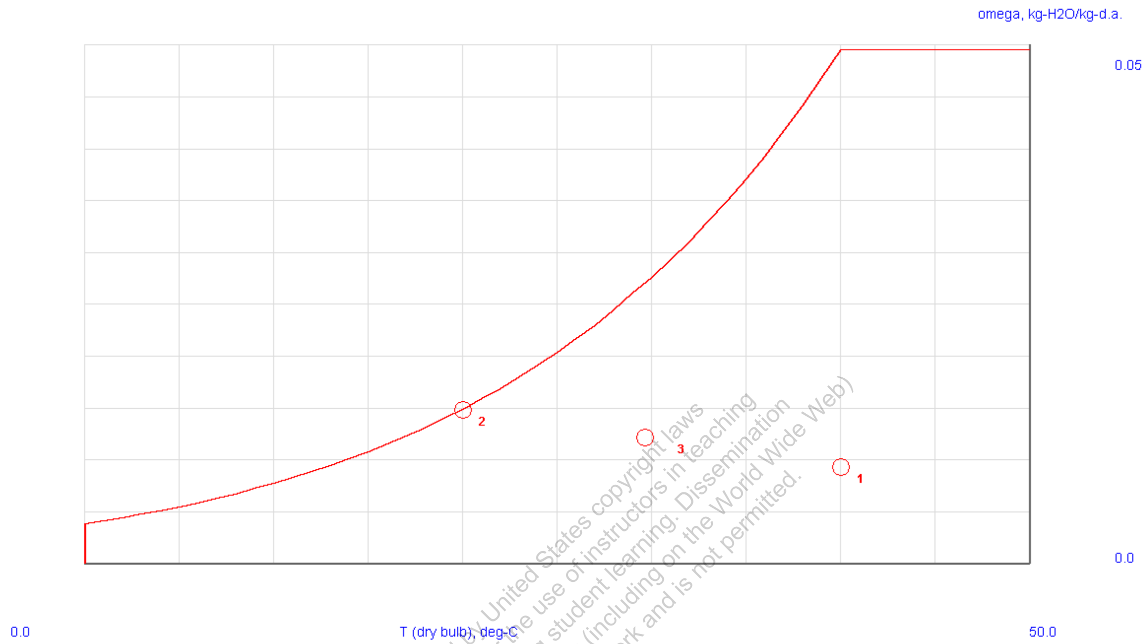
$$Q = m_a\left[\left(h_2 - h_1\right) - R_a\left(T_2 - T_1\right)\right] + m_w h_3 + \cancel{W_B}^{0};$$

$$Q = \left(10.39\right)\left[\left(32.98 - 153.98\right) - \left(0.287\right)\left(10 - 40\right)\right] + \left(0.36\right)\left(42.10\right) = -1152.58 \text{ kJ}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry closed process TESTcalc to verify the solution and perform the what-if study. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

12-3-4 [OMQ] A 50 m^3 insulated chamber containing air at 40^{o}C, 100 kPa and R.H. 20% is connected to another 50 m^3 insulated chamber containing air at 20^{o}C, 100 kPa and R.H. 100%. The valve is opened and the system is allowed to reach thermal equilibrium. Determine (a) the final pressure (p_3), (b) temperature (T_3) and (c) relative humidity.

SOLUTION



Given:

$$c_{pa} = 1.005 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$R_a = 0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

State-1 (given $p_1, T_1, \cancel{V}_1, \phi_1$):

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@40°\text{C}} = (0.20)(7.3799) = 1.48 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 100 - 1.48 = 98.52 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{1.48}{98.52}\right) = 0.0093 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@40°\text{C}} = 2574.29 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(40) + (0.0093)(2574.29) = 64.14 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(313)}{98.52} = 0.9118 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$m_{a1} = \frac{\cancel{V}_1}{v_1} = \frac{50}{0.9118} = 54.84 \text{ kg}$$

State-2 (given $p_2, T_2, \cancel{V}_2, \phi_2$):

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@20°\text{C}} = (1)(2.3390) = 2.34 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 100 - 2.34 = 97.66 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{2.34}{97.66}\right) = 0.0149 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@20°\text{C}} = 2538.10 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(20) + (0.0149)(2538.10) = 57.92 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(293)}{97.66} = 0.8611 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$m_{a2} = \frac{\cancel{V}_2}{v_2} = \frac{50}{0.8611} = 58.07 \text{ kg}$$

State-3:

$$m_{a3} = m_{a1} + m_{a2} = 54.84 + 58.07 = 112.91 \text{ kg}$$

$$\cancel{V}_3 = \cancel{V}_1 + \cancel{V}_2 = 50 + 50 = 100 \text{ m}^3$$

$$v_3 = \frac{\cancel{V}_3}{m_{a3}} = \frac{100}{112.91} = 0.8857 \frac{\text{m}^3}{\text{kg}}$$

$$\omega_3 = \frac{m_{a1}\omega_1 + m_{a2}\omega_2}{m_{a3}} = \frac{(54.84)(0.0093) + (58.07)(0.0149)}{(112.91)} = 0.0122 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

Since there is no heat transfer or work,

$$h_3 = \frac{m_{a1}h_1 + m_{a2}h_2}{m_{a3}} = \frac{(54.84)(64.14)+(58.07)(57.92)}{(112.91)} = 60.94\frac{\text{kJ}}{\text{kg d.a.}}$$

Knowing the specific humidity and specific enthalpy, the dry-bulb temperature and relative humidity can be found from the psychrometric chart (Table-F)

$T_3 = 29.7°\text{C}$

$\phi_3 = 46\%$

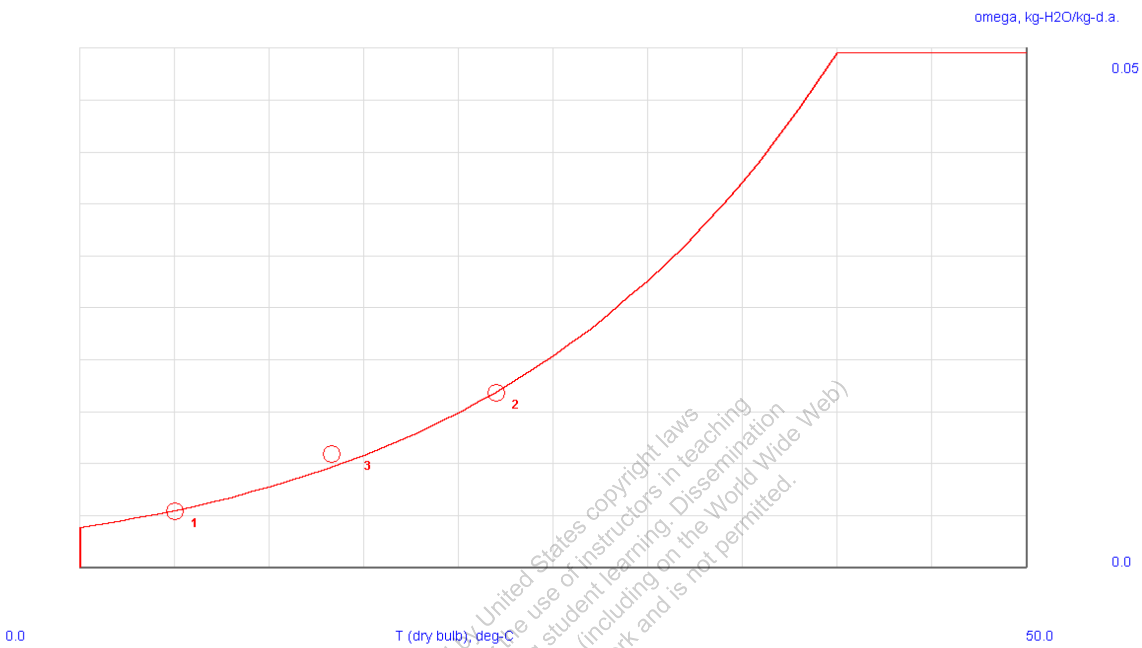
The final pressure,

$$p_3 = \frac{R_a T_3}{v_3} = \frac{(0.287)(302.7)}{0.8857} = 98.09\text{ kPa}$$

TEST Solution Use the HVAC/Psychrometry closed process TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

12-3-5 [OMV] A 50 m^3 insulated chamber containing air at 5^{o}C, 100 kPa and R.H. 100% is connected to another 50 m^3 insulated chamber containing air at 22^{o}C, 100 kPa and R.H. 100%. The valve is opened and the system is allowed to reach thermal equilibrium. Will there be condensation? (Answer 1 if Yes and 2 if No).

SOLUTION



Given:

$$c_{pa} = 1.005 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$R_a = 0.287 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

State-1 (given $p_1, T_1, \cancel{V}_1, \phi_1$):

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@5°\text{C}} = (1)(0.8697) = 0.87 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 100 - 0.87 = 99.13 \text{ kPa}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.87}{99.13}\right) = 0.0055\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@5°\text{C}} = 2510.55\frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_2} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(5) + (0.0055)(2510.55) = 18.83\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(278)}{99.13} = 0.8049\frac{\text{m}^3}{\text{kg d.a.}}$$

$$m_{a1} = \frac{\cancel{V}_1}{v_1} = \frac{50}{0.8049} = 62.12 \text{ kg}$$

State-2 (given $p_2, T_2, \cancel{V}_2, \phi_2$):

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@22°\text{C}} = (1)(2.6445) = 2.64 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 100 - 2.64 = 97.36 \text{ kPa}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{2.64}{97.36}\right) = 0.0169\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@22°\text{C}} = 2541.75\frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(22) + (0.0169)(2541.75) = 65.07\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(295)}{97.36} = 0.8696\frac{\text{m}^3}{\text{kg d.a.}}$$

$$m_{a2} = \frac{\cancel{V}_2}{v_2} = \frac{50}{0.8696} = 57.50 \text{ kg}$$

State-3:

$$m_{a3} = m_{a1} + m_{a2} = 62.12 + 57.50 = 119.62 \text{ kg}$$

$$\cancel{V}_3 = \cancel{V}_1 + \cancel{V}_2 = 50 + 50 = 100 \text{ m}^3$$

$$v_3 = \frac{\cancel{V}_3}{m_{a3}} = \frac{100}{119.62} = 0.8360\frac{\text{m}^3}{\text{kg}}$$

$$\omega_3 = \frac{m_{a1}\omega_1 + m_{a2}\omega_2}{m_{a3}} = \frac{(62.12)(0.0055) + (57.50)(0.0169)}{(119.62)} = 0.0110\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

Since there is no heat transfer or work,

$$h_3 = \frac{m_{a1}h_1 + m_{a2}h_2}{m_{a3}} = \frac{(62.12)(18.83)+(57.50)(65.07)}{(119.62)} = 41.06\,\frac{\text{kJ}}{\text{kg d.a.}}$$

Knowing the specific humidity and specific enthalpy, the dry-bulb temperature and relative humidity can be found from the psychrometric chart (Table-F)

$T_3 = 13.5°\text{C}$

$\phi_3 = 115\%$

The vapor pressure is then

$$p_{v3} = \phi_3 p_{g3} = \phi_3 p_{\text{sat}@T_3} = \phi_3 p_{\text{sat}@13.5°\text{C}} = (1.15)(1.5443) = 1.78\text{ kPa}$$

Therefore, the dew point temperature

$$T_{\text{dp},3} = T_{\text{sat}@\,p_{v3}} = T_{\text{sat}@1.78\text{ kPa}} = 15.65°\text{C}$$

Since the temperature is less than the dew point temperature, yes there will be condensation. This can also be seen reflected in the relative humidity greater than 100%.

TEST Solution Use the HVAC/Psychrometry closed process TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the professional TEST site at www.thermofluids.net.