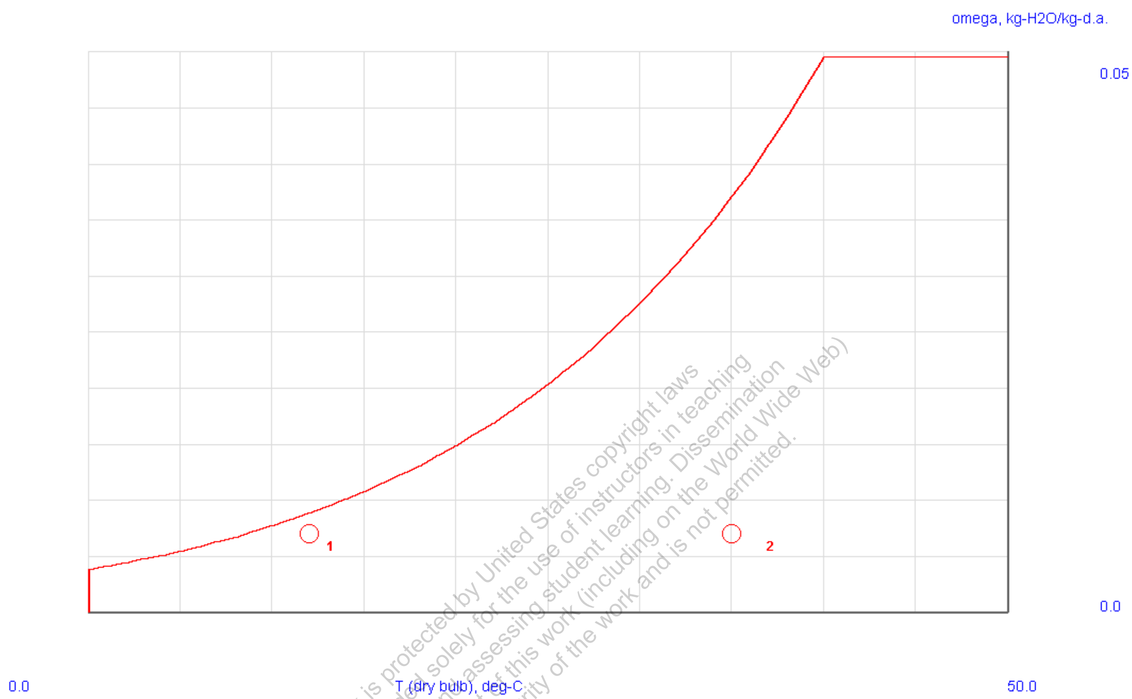
12-2-1 [ODG] Moist air at 12°C and 80% R.H. enters a duct at a rate of 150 m^3/min. The mixture is heated until it exits at 35°C. The pressure remains constant at 100 kPa. Determine (a) the rate of heat transfer and (b) the relative humidity at the exit. (c) What-if Scenario: What would the rate of heat transfer be if the mixture were heated until it exits at 50°C?

SOLUTION



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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 $p_1, T_1, \dot{V}_1, \phi_1$):

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$$p_{v1}=\phi_1 p_{g1}=\phi_1 p_{\text{sat@}T_1}=\phi_1 p_{\text{sat@12°C}}=(0.80)(1.402)=1.12\text{ kPa}$$

$$p_{a1}=p_1-p_{v1}=100-1.12=98.88\text{ kPa}$$

$$\omega_1=0.622\frac{p_{v1}}{p_{a1}}=(0.622)\left(\frac{1.12}{98.88}\right)=0.0070\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g\text{@12°C}}=2523.40\frac{\text{kJ}}{\text{kg}}$$

$$h_1=h_a+\omega_1 h_{g@T_1}=c_{pa}T_1+\omega_1 h_{g@T_1}=(1.005)(12)+(0.0070)(2523.40)=29.72\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1=\frac{R_aT_1}{p_{a1}}=\frac{(0.287)(285)}{98.88}=0.8272\frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1}=\frac{\dot{V}_1}{v_1}=\frac{150}{0.8272}=181.22\frac{\text{kg}}{\text{min}}$$

State-2 (given $p_2=p_1, T_2, \omega_2=\omega_1$):
The vapor pressure of the air remains constant, so

$$\phi_2=\frac{p_{v2}}{p_{g2}}=\frac{p_{v2}}{p_{\text{sat@35°C}}}=\frac{1.12}{5.6190}=0.1993=19.93\%$$

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

$$h_2=h_a+\omega_2 h_{g@T_2}=c_{pa}T_2+\omega_2 h_{g@T_2}=(1.005)(35)+(0.0070)(2565.30)=53.13\frac{\text{kJ}}{\text{kg d.a.}}$$

The rate of heat transfer,

$$\dot{Q}=\dot{m}(h_2-h_1)=(181.22)(53.13-29.72)=4242.36\frac{\text{kJ}}{\text{min}}$$

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TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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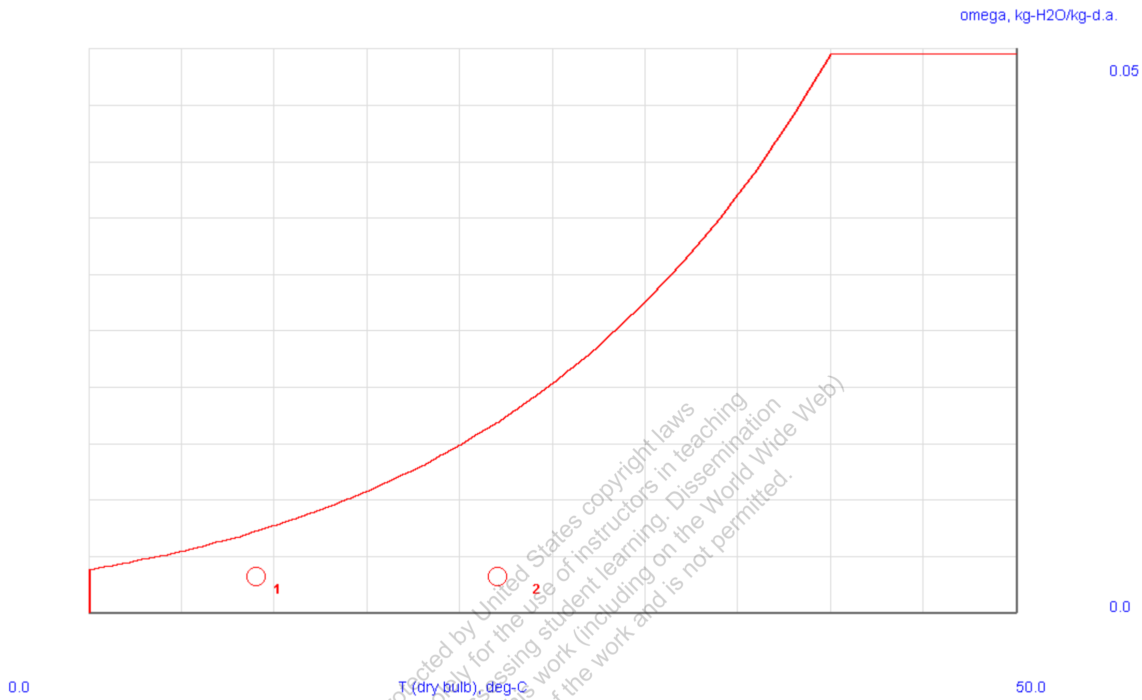
12-2-2 [ODZ] Air enters a heating section at 100 kPa, 9°C, 45% relative humidity at rate of 10m^3/min, and it leaves at 22°C. Determine (a) the rate of heat transfer in the heating section and (b) the relative humidity at the exit. (c) What-if Scenario: What would the relative humidity at the exit be if the relative humidity of the mixture changed to 75%?

SOLUTION



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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 $p_1, T_1, \dot{V}_1, \phi_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@9°\text{C}} = (0.45)(1.1446) = 0.52 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 100 - 0.52 = 99.48 \text{ kPa}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.52}{99.48}\right) = 0.0033\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@9°\text{C}} = 2517.93\frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(9) + (0.0033)(2517.93) = 17.35\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(282)}{99.48} = 0.8136\frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{10}{0.8136} = 12.29\frac{\text{kg}}{\text{min}}$$

State-2 (given $p_2 = p_1, T_2, \omega_2 = \omega_1$):
The vapor pressure of the air remains constant, so

$$\phi_2 = \frac{p_{v2}}{p_{g2}} = \frac{p_{v2}}{p_{\text{sat}@22°\text{C}}} = \frac{0.52}{2.6445} = 0.1966 = 19.66\%$$

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

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(22) + (0.0033)(2541.75) = 30.50\frac{\text{kJ}}{\text{kg d.a.}}$$

The rate of heat transfer,

$$\dot{Q} = \dot{m}(h_2 - h_1) = (12.29)(30.50 - 17.35) = 161.61\frac{\text{kJ}}{\text{min}}$$

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TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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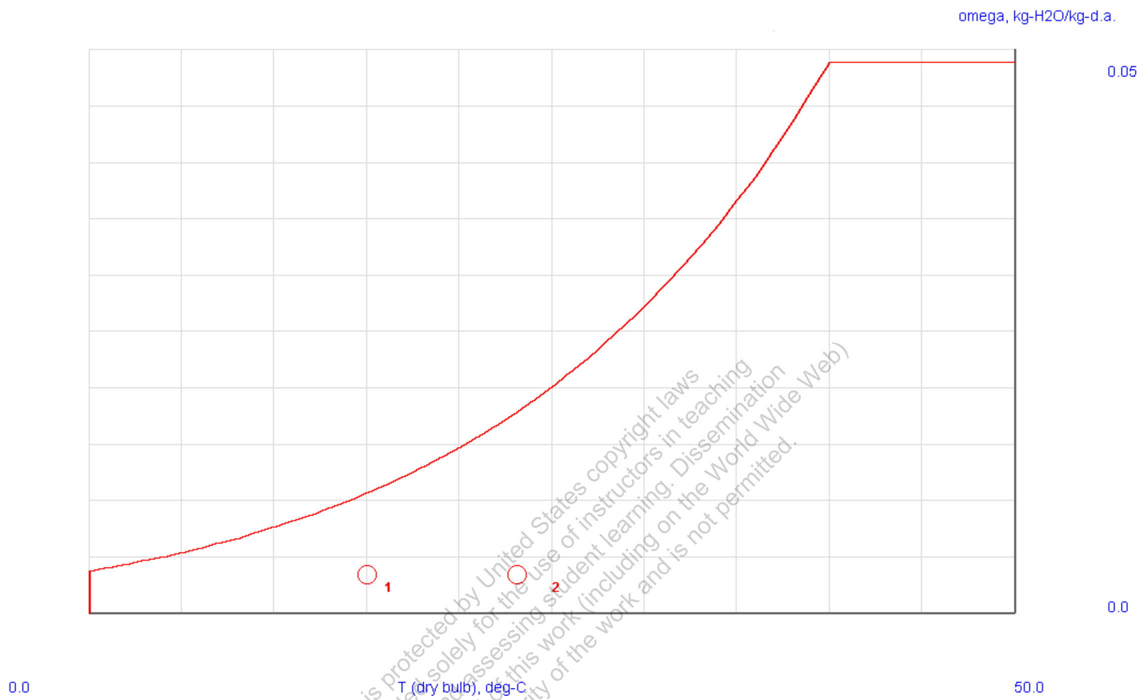
12-2-3 [ODK] A heating section consists of a 30 cm diameter duct which houses a 6 kW electric resistance heater. Air enters the heating section at 1 atm, 15^{o}C and 33% relative humidity at velocity 8.5 m/s. Determine (a) the exit temperature (T_2), (b) the exit relative humidity of the air and (c) the exit velocity (V_2). (d) What-if Scenario: What would the answers be if the inlet velocity were 5 m/s?

SOLUTION



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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 $p_1, T_1, \phi_1, V_1, D_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat@}T_1} = \phi_1 p_{\text{sat@15°C}} = (0.33)(1.7013) = 0.56 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 0.56 = 100.77 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.56}{100.77}\right) = 0.0035 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@15°\text{C}} = 2528.95 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(15) + (0.0035)(2528.95) = 23.93 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(288)}{100.77} = 0.8202 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{V}_1 = A_1 V_1 = \left(\pi \frac{D_1^2}{4}\right) V_1 = \pi \left(\frac{0.30^2}{4}\right)(8.5) = 0.60 \frac{\text{m}^3}{\text{s}} = 36.00 \frac{\text{m}^3}{\text{min}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{36.00}{0.8202} = 43.89 \frac{\text{kg}}{\text{min}}$$

State-2 (given $p_2 = p_1, \omega_2 = \omega_1, D_2 = D_1$)

Since the rate of heat transfer is known,

$$h_2 = h_1 + \frac{\dot{Q}}{\dot{m}} = 23.93 + \frac{6}{0.7315} = 32.13 \frac{\text{kJ}}{\text{kg d.a.}}$$

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Using the psychrometric chart (Table-F) and the values for h_2 and ω_2,

$$T_2 = 23°\text{C}$$

The vapor pressure of the air remains constant, so

$$\phi_2 = \frac{p_{v2}}{p_{g2}} = \frac{p_{v2}}{p_{\text{sat@23°C}}} = \frac{0.56}{2.8050} = 0.1996 = 19.96\%$$

To find the exit velocity

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(296)}{100.77} = 0.8430 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{V}_2 = \dot{m}_{a2} v_2 = (43.89)(0.8430) = 37.00 \frac{\text{m}^3}{\text{min}} = 0.6167 \frac{\text{m}^3}{\text{s}}$$

$$V_2 = \frac{\dot{V}_2}{A_2} = \frac{4\dot{V}_2}{\pi D_2^2} = \frac{4(0.6167)}{\pi(0.30^2)} = 8.72 \frac{\text{m}}{\text{s}}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state TESTcalc to verify the solution and perform the what-if study. The TEST-code for this

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problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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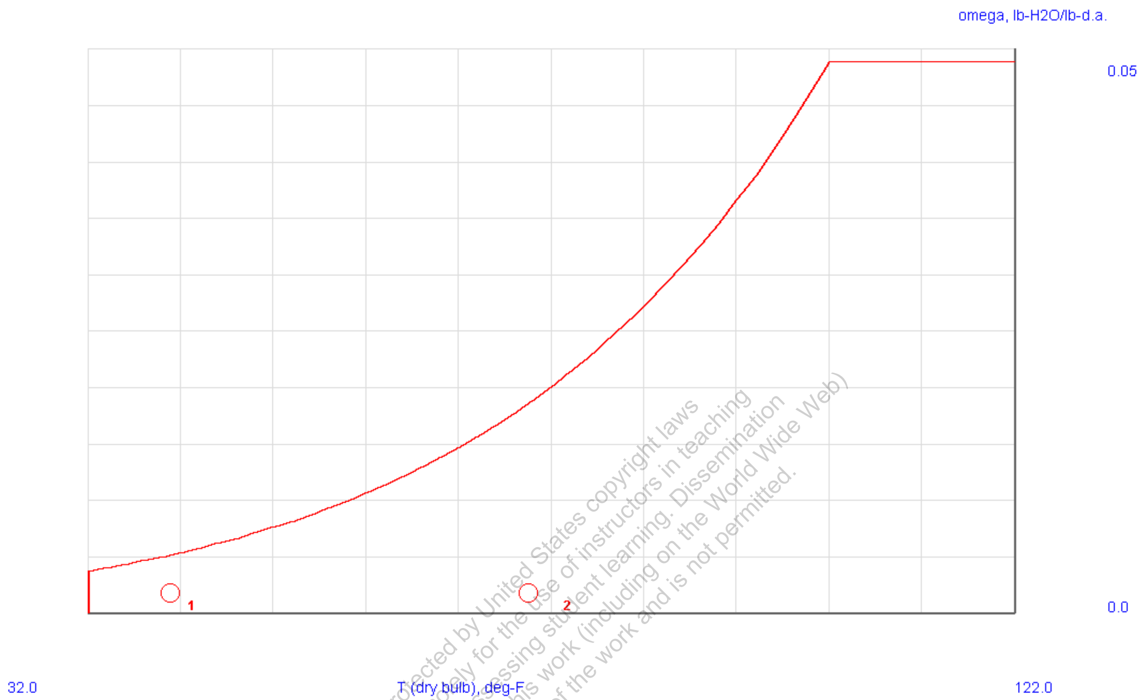
12-2-4 [ODP] A heating section consists of a 10 inch diameter duct which houses a 8 kW electric resistance heater. Air enters the heating section at 14.7 psia, 40°F and 35% relative humidity at a velocity of 21 ft/s. Determine (a) the exit temperature (T_2), (b) the exit relative humidity of the air and (c) the exit velocity (V_2).

SOLUTION



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Given:

$$c_{pa} = 0.240 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

$$R_a = 0.069 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

State-1 (given $p_1, T_1, \phi_1, V_1, D_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat@}T_1} = \phi_1 p_{\text{sat@40°F}} = (0.35)(0.1214) = 0.042 \text{ psia}$$

$$p_{a1} = p_1 - p_{v1} = 14.70 - 0.042 = 14.66 \text{ psia}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.042}{14.66}\right) = 0.0018\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$h_{g\text{@40°F}} = 1078.99\frac{\text{Btu}}{\text{lbm}}$$

$$h_1 = h_a + \omega_1 h_{g\text{@}T_1} = c_{pa}(T_1 - T_{\text{ref}}) + \omega_1 h_{g\text{@}T_1} = (0.240)(40-32) + (0.0018)(1078.99) = 3.86\frac{\text{Btu}}{\text{lbm d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.069)(499.67)}{14.66}(5.40) = 12.70\frac{\text{ft}^3}{\text{lbm d.a.}}; \quad \left[\frac{\text{Btu}}{\text{psia}} = \frac{\text{Btu}\times\text{in}^2}{\text{lbf}} = 5.40\text{ ft}^3\right]$$

$$\dot{V}_1 = A_1 V_1 = \left(\pi\frac{D_1^2}{4}\right)V_1 = \pi\left(\frac{0.833^2}{4}\right)(21) = 11.44\frac{\text{ft}^3}{\text{s}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{11.44}{12.70} = 0.90\frac{\text{lbm}}{\text{s}}$$

State-2 (given $p_2 = p_1, \omega_2 = \omega_1, D_2 = D_1$)

Since the rate of heat transfer is known,

$$h_2 = h_1 + \frac{\dot{Q}}{\dot{m}} = 3.86 + \frac{7.58}{0.90} = 12.28\frac{\text{Btu}}{\text{lbm d.a.}}$$

Using the psychrometric chart (Table-F) and the values for h_2 and ω_2,

$T_2 = 74.6°\text{F}$

The vapor pressure of the air remains constant, so

$$\phi_2 = \frac{p_{v2}}{p_{g2}} = \frac{p_{v2}}{p_{\text{sat@74.71°F}}} = \frac{0.042}{0.4238} = 0.0991 = 9.91\%$$

To find the exit velocity

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.069)(536.07)}{14.66}(5.40) = 13.62\frac{\text{ft}^3}{\text{lbm d.a.}}$$

$$\dot{V}_2 = \dot{m}_{a2} v_2 = (0.90)(13.62) = 12.26\frac{\text{ft}^3}{\text{s}}$$

$$V_2 = \frac{\dot{V}_2}{A_2} = \frac{4\dot{V}_2}{\pi D_2^2} = \frac{4(12.26)}{\pi(0.833^2)} = 22.50\frac{\text{ft}^3}{\text{s}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state TESTcalc to verify the solution. The TEST-code for this problem can be found in the problem module of the

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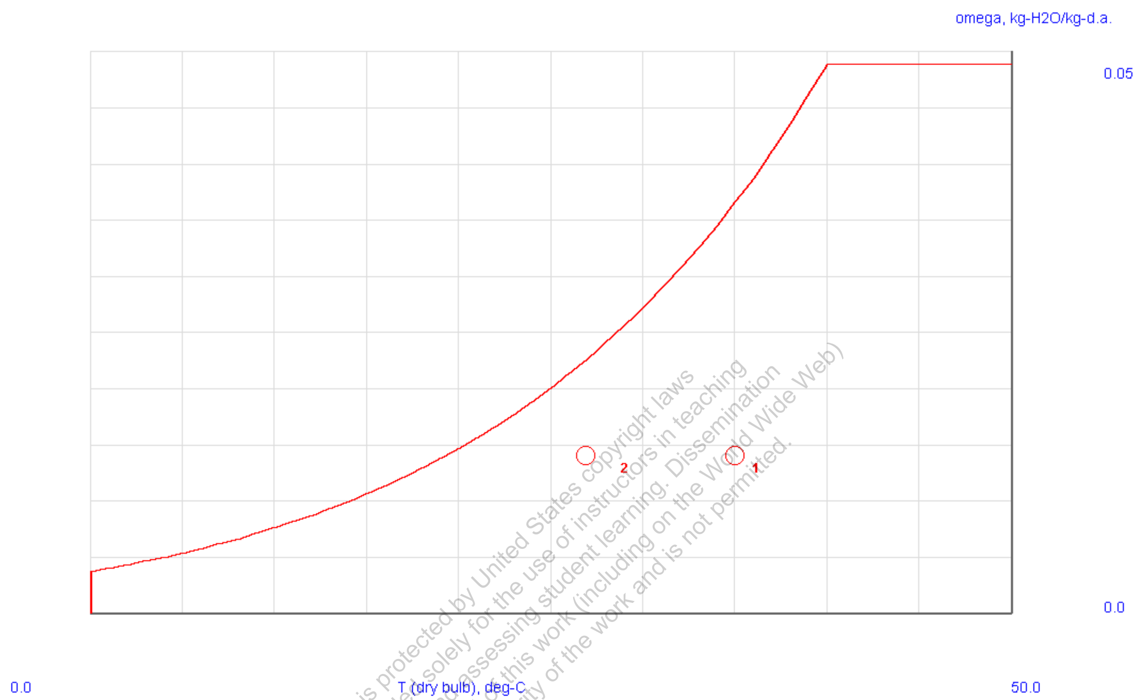
12-2-5 [ODU] Air enters a 30 cm diameter cooling section at 1 atm, 35°C and 40% relative humidity at 35 m/s. Heat is removed from the air at a rate of 1400 kJ/min. Determine (a) the exit temperature (T_2), (b) the exit relative humidity and (c) the exit velocity (V_2). (d) What-if Scenario: What would the answers be if the heat removal rate were 1000 kJ/min?

SOLUTION



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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 $p_1, T_1, \phi_1, V_1, D_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@35°\text{C}} = (0.40)(5.6190) = 2.25 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 2.25 = 99.08 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{2.25}{99.08}\right) = 0.0141 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

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

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(35) + (0.0141)(2565.30) = 71.35 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(308)}{99.08} = 0.8922 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{V}_1 = A_1 V_1 = \left(\pi \frac{D_1^2}{4}\right) V_1 = \pi \left(\frac{0.30^2}{4}\right)(35) = 2.47 \frac{\text{m}^3}{\text{s}} = 148.44 \frac{\text{m}^3}{\text{min}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{148.44}{0.8922} = 166.38 \frac{\text{kg}}{\text{min}}$$

State-2 (given $p_2 = p_1, \omega_2 = \omega_1, D_2 = D_1$)

Since the rate of heat transfer is known,

$$h_2 = h_1 + \frac{\dot{Q}}{\dot{m}} = 71.35 - \frac{1400}{166.38} = 62.94 \frac{\text{kJ}}{\text{kg d.a.}}$$

Using the psychrometric chart (Table-F) and the values for h_2 and ω_2,

$T_2 = 27°\text{C}$

The vapor pressure of the air remains constant, so

$$\phi_2 = \frac{p_{v2}}{p_{g2}} = \frac{p_{v2}}{p_{\text{sat}@26.86°\text{C}}} = \frac{2.25}{3.5664} = 0.6309 = 63.09\%$$

To find the exit velocity

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(300)}{99.08} = 0.8690 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{V}_2 = \dot{m}_{a2} v_2 = (166.38)(0.8690) = 144.58 \frac{\text{m}^3}{\text{min}} = 2.41 \frac{\text{m}^3}{\text{s}}$$

$$V_2 = \frac{\dot{V}_2}{A_2} = \frac{4\dot{V}_2}{\pi D_2^2} = \frac{4(2.41)}{\pi(0.30^2)} = 34.09 \frac{\text{m}}{\text{s}}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state TESTcalc to verify the solution and perform the what-if study. The TEST-code for this

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problem can be found in the problem module of the professional TEST site at www.thermofluids.net.

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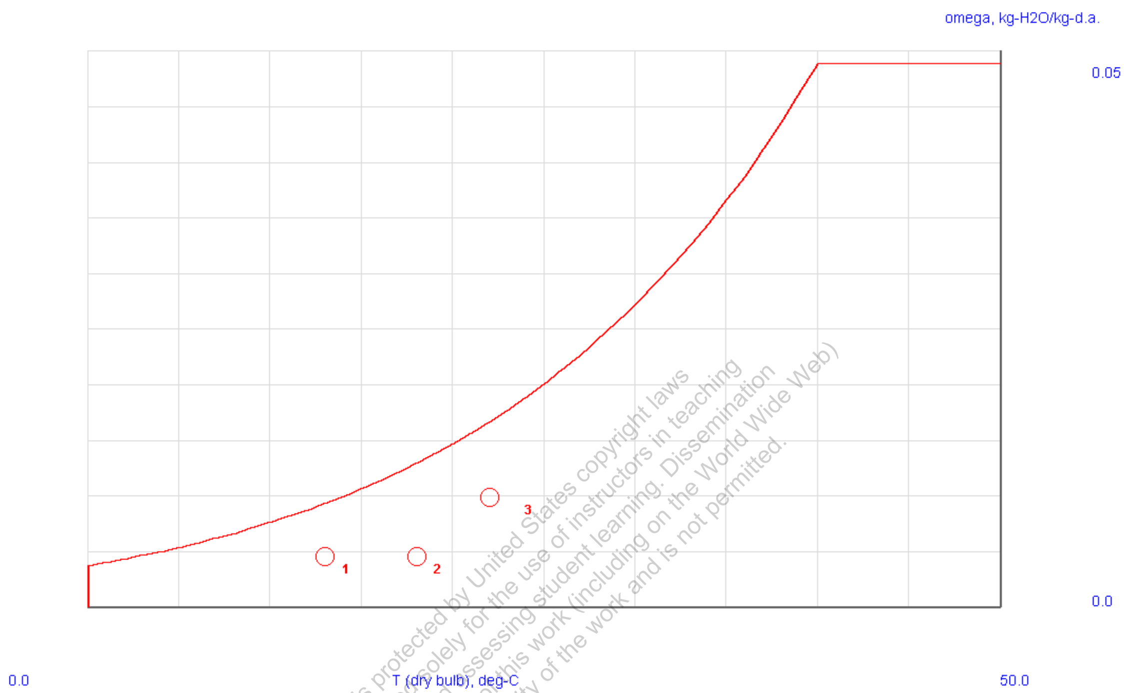
12-2-6 [ODX] Air at 1 atm, 13°C and 50% relative humidity is first heated to 18°C in a heating section and then humidified by introducing saturated water vapor at 1 atm. Air leaves the humidifying section at 22°C and 60% of relative humidity. Determine (a) the amount of steam added to the air in kg H_2O/kg dry air and (b) the amount of heat transfer (q) to the air in the heating section in kJ/kg dry air.

SOLUTION



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Given:

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

State-1 (given p_1, T_1, ϕ_1):

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@13°\text{C}} = (0.50)(1.4939) = 0.75 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 0.75 = 100.58 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.75}{100.58}\right) = 0.0046 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@13°\text{C}} = 2525.25 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(13) + (0.0046)(2525.25) = 24.68 \frac{\text{kJ}}{\text{kg d.a.}}$$

State-2 (given $p_2 = p_1, T_2, \omega_2 = \omega_1$):

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$$h_{g@18°\text{C}} = 2534.45\,\frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(18) + (0.0046)(2534.45) = 29.75\,\frac{\text{kJ}}{\text{kg d.a.}}$$

State-3 (given $p_3 = p_1, T_3, \phi_3$):

$$p_{v3} = \phi_3 p_{g3} = \phi_3 p_{\text{sat}@T_3} = \phi_3 p_{\text{sat}@22°\text{C}} = (0.60)(2.6445) = 1.59\text{ kPa}$$

$$p_{a3} = p_3 - p_{v3} = 101.325 - 1.59 = 99.74\text{ kPa}$$

$$\omega_3 = 0.622\frac{p_{v3}}{p_{a3}} = (0.622)\left(\frac{1.59}{99.74}\right) = 0.0099\,\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

The amount of steam added

$$\omega_3 - \omega_2 = 0.0099 - 0.0046 = 0.0053\,\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

The amount of heat transfer in the heating section

$$h_2 - h_1 = 29.75 - 24.68 = 5.07\,\frac{\text{kJ}}{\text{kg d.a.}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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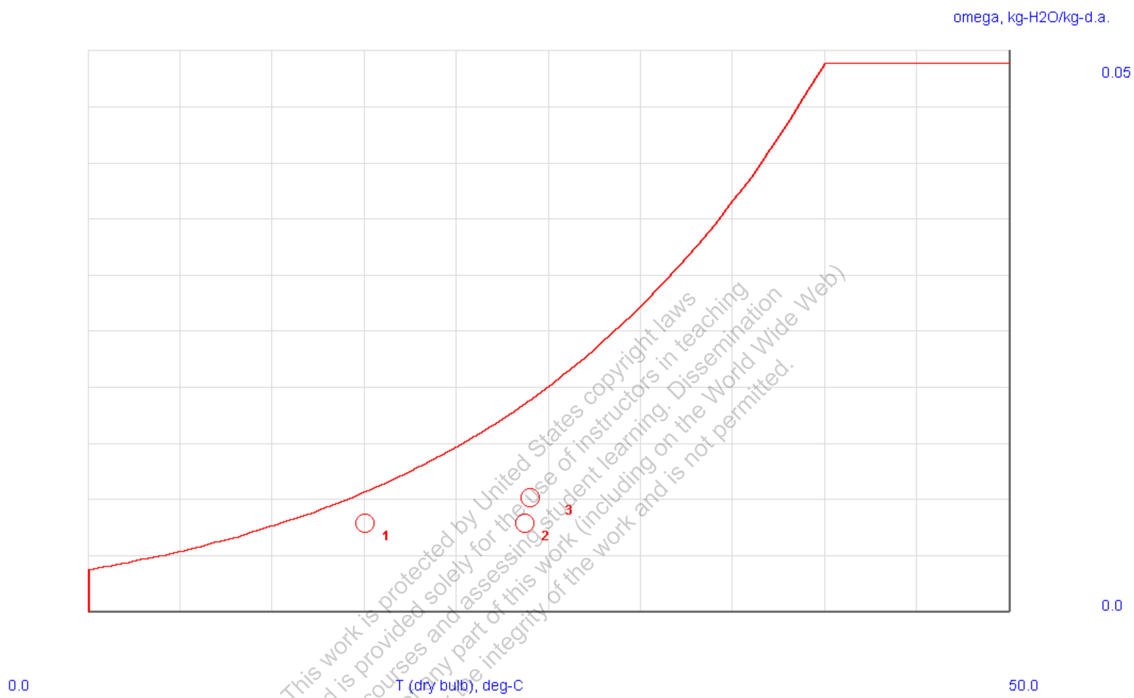
12-2-7 [ODC] An air conditioning system operates at a total pressure of 1 atm consists of a heating section and humidifier which supplies wet steam (saturated water vapor) at 1 atm. Air enters the heating section at 15°C and 75% relative humidity at 60m^3/min, and it leaves the humidifying section at 24°C and 55% relative humidity . Determine (a) the temperature and (b) relative humidity of air when it leaves the heat section, (c) rate of heat transfer in the heating section and (d) the rate at which water is added to the air in the humidifying section.

SOLUTION



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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 $p_1, T_1, \phi_1, \dot{V}_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@15°\text{C}} = (0.75)(1.7013) = 1.28 \text{ kPa}$$
$$p_{a1} = p_1 - p_{v1} = 101.325 - 1.28 = 100.05 \text{ kPa}$$
$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{1.28}{100.05}\right) = 0.0080\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$
$$h_{g@15°\text{C}} = 2528.95\frac{\text{kJ}}{\text{kg}}$$
$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(15) + (0.0080)(2528.95) = 35.31\frac{\text{kJ}}{\text{kg d.a.}}$$
$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(288)}{100.05} = 0.8261\frac{\text{m}^3}{\text{kg d.a.}}$$
$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{60}{0.8261} = 72.63\frac{\text{kg}}{\text{min}}$$

State-2 (given $p_2 = p_1, \omega_2 = \omega_1$)

State-3 (given $p_3 = p_1, T_3, \phi_3$):

$$p_{v3} = \phi_3 p_{g3} = \phi_3 p_{\text{sat}@T_3} = \phi_3 p_{\text{sat}@24°\text{C}} = (0.55)(2.9850) = 1.64 \text{ kPa}$$
$$p_{a3} = p_3 - p_{v3} = 101.325 - 1.64 = 99.69 \text{ kPa}$$
$$\omega_3 = 0.622\frac{p_{v3}}{p_{a3}} = (0.622)\left(\frac{1.64}{99.69}\right) = 0.0102\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$
$$h_{g@24°\text{C}} = 2545.40\frac{\text{kJ}}{\text{kg}}$$
$$h_3 = h_a + \omega_3 h_{g@T_3} = c_{pa}T_3 + \omega_3 h_{g@T_3} = (1.005)(24) + (0.0102)(2545.40) = 50.08\frac{\text{kJ}}{\text{kg d.a.}}$$

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State-4 (given $p_4 = p_1, x_4$):

$$h_4 = h_{g@1\text{atm}} = 2676.07\frac{\text{kJ}}{\text{kg}}$$

The rate at which steam is added

$$\dot{m}_w = \dot{m}_a(\omega_3 - \omega_2) = (72.63)(0.0102 - 0.0080) = 0.16\frac{\text{kg}}{\text{min}}$$

An energy balance on the humidifying section

$$\dot{m}_{a2}h_2 + \dot{m}_w h_4 = \dot{m}_{a3}h_3;$$
$$\Rightarrow h_2 = \frac{\dot{m}_a h_3 - \dot{m}_w h_4}{\dot{m}_a} = \frac{(72.63)(50.08) - (0.16)(2676.07)}{72.63} = 44.18\frac{\text{kJ}}{\text{kg d.a.}}$$

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Using the psychrometric chart (Table-F) and the values for h_2 and ω_2,

$T_2 = 23.7°\text{C}$

The vapor pressure of the air remains constant, so

$$\phi_2 = \frac{p_{v2}}{p_{g2}} = \frac{p_{v2}}{p_{\text{sat@}23.7°\text{C}}} = \frac{1.28}{2.9286} = 0.4371 = 43.71\%$$

The rate of heat transfer in the heating section

$$\dot{Q} = \dot{m}_a \left(h_2 - h_1\right) = (72.63)(44.18 - 35.31) = 644.23 \frac{\text{kJ}}{\text{min}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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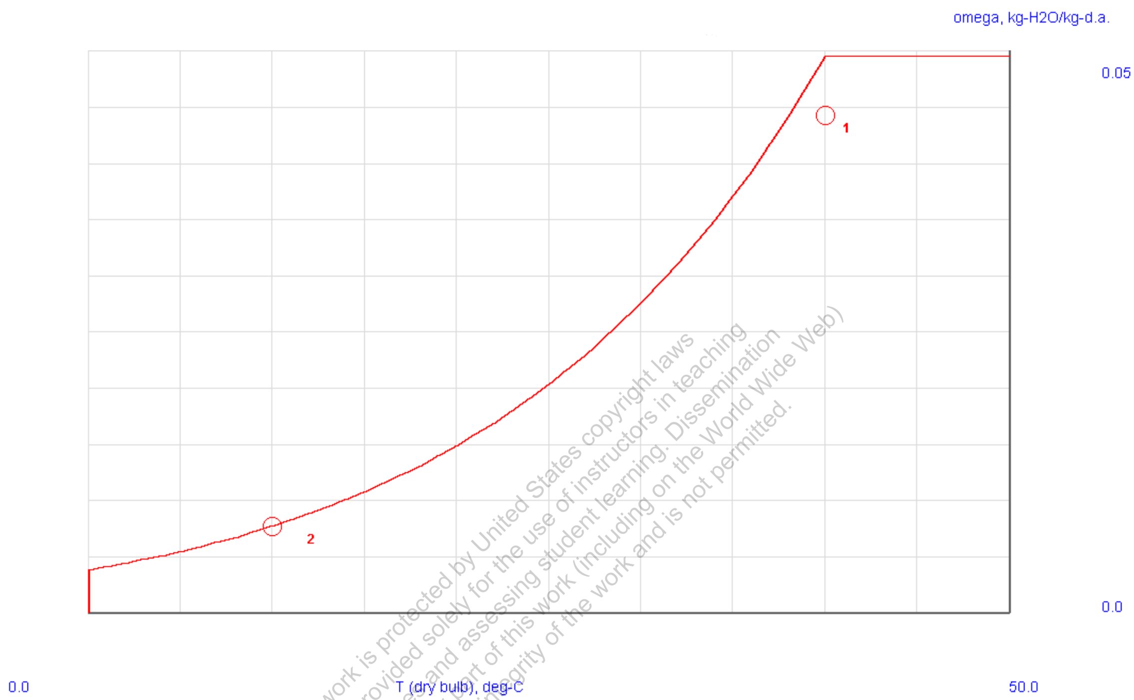
12-2-8 [ODQ] Moist air at 40°C and 90% R.H. enters a dehumidifier at a rate of 300 m^3/min. The condensate and the saturated air exit at 10°C through separate exits. The pressure remains constant at 100 kPa. Determine (a) the mass flow rate of dry air, (b) the water removal rate and (c) the required refrigeration capacity in tons. (d) What-if Scenario: What would the required refrigeration be if the moist air entered the dehumidifier at the rate of 200 m^3/min?

SOLUTION



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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 $p_1, T_1, \phi_1, \dot{V}_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@40°\text{C}} = (0.90)(7.3799) = 6.64 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 100 - 6.64 = 93.36 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{6.64}{93.36}\right) = 0.0442 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

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

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(40) + (0.0442)(2574.29) = 153.98 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(313)}{93.36} = 0.9622 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{300}{0.9622} = 311.79 \frac{\text{kg}}{\text{min}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@10°\text{C}} = (1)(1.2271) = 1.23 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 100 - 1.23 = 98.77 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{1.23}{98.77}\right) = 0.0077 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@10°\text{C}} = 2519.75 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(10) + (0.0077)(2519.75) = 29.45 \frac{\text{kJ}}{\text{kg d.a.}}$$

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

$$p_{\text{sat}@10°\text{C}} = 1.2271 \text{ kPa}$$

$$p_3 > p_{\text{sat}@10°\text{C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@10°\text{C}} = 42.00 \frac{\text{kJ}}{\text{kg}}; \quad v_{f@10°\text{C}} = 0.001001 \frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@10°\text{C}} + p_3 v_{f@10°\text{C}} = 42.00 + (100)(0.001001) = 42.10 \frac{\text{kJ}}{\text{kg}}$$

The rate at which condensate is removed

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (311.79)(0.0442 - 0.0077) = 11.38 \frac{\text{kg}}{\text{min}}$$

The required refrigeration capacity

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$$\dot{Q}_{\text{out}} = \dot{m}_a\left(h_1 - h_2\right) - \dot{m}_w h_3;$$

$$\dot{Q}_{\text{out}} = \left(311.79\right)\left(153.98 - 29.45\right) - \left(11.38\right)\left(42.10\right) = 38348.11\frac{\text{kJ}}{\text{min}} = 181.73\text{ ton}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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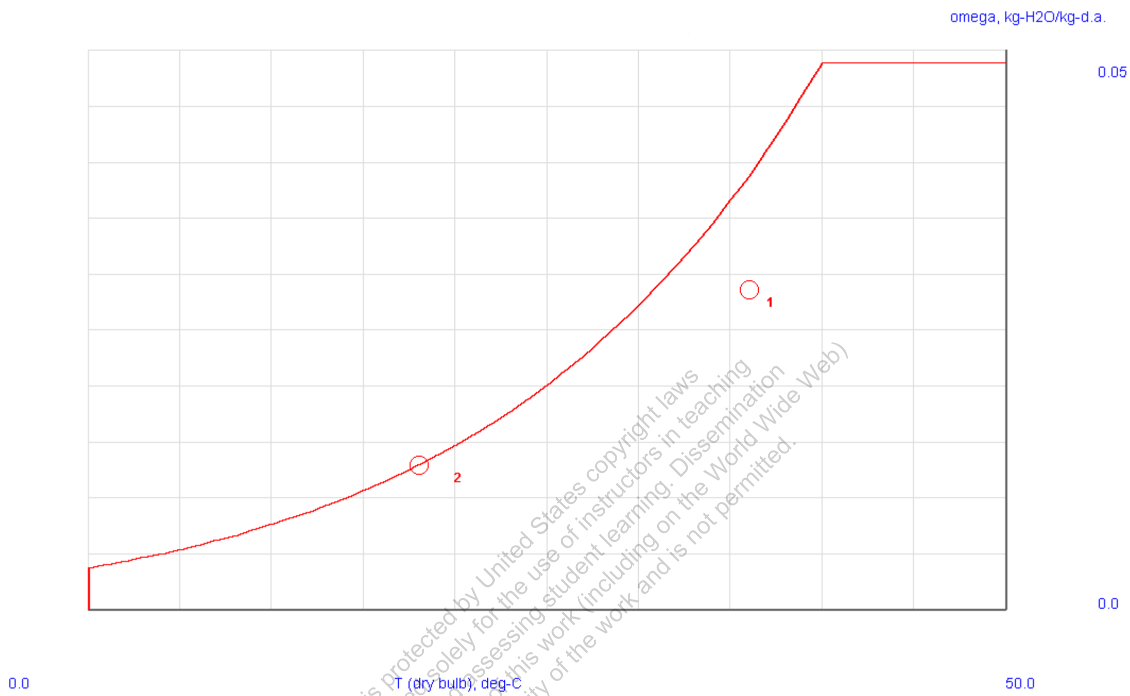
12-2-9 [ODY] Air enters a window air conditioner at 1 atm, 36°C and 75% relative humidity at a rate of 12m^3/min and it leaves as saturated air at 18°C. Part of the moisture in the air which condenses during the process is also removed at 18°C. Determine (a) the rate of heat and (b) moisture removal from the air. (c) What-if Scenario: What would the rate of heat removal be if moist air entered the dehumidifier at 95 kPa instead of 1 atm?

SOLUTION



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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 $p_1, T_1, \phi_1, \dot{V}_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@36°\text{C}} = (0.75)(5.9463) = 4.46\ \text{kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 4.46 = 96.87\ \text{kPa}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{4.46}{96.87}\right) = 0.0286\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@36°\text{C}} = 2567.10\frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(36) + (0.0286)(2567.10) = 109.60\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(309)}{96.87} = 0.9155\frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{12}{0.9155} = 13.11\frac{\text{kg}}{\text{min}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@18°\text{C}} = (1)(2.0639) = 2.06\ \text{kPa}$$

$$p_{a2} = p_2 - p_{v2} = 101.325 - 2.06 = 99.27\ \text{kPa}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{2.06}{99.27}\right) = 0.0129\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@18°\text{C}} = 2534.45\frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(18) + (0.0129)(2534.45) = 50.78\frac{\text{kJ}}{\text{kg d.a.}}$$

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

$$p_{\text{sat}@18°\text{C}} = 2.0639\ \text{kPa}$$

$$p_3 > p_{\text{sat}@18°\text{C}} \quad \therefore \ \text{subcooled liquid}$$

$$u_{f@18°\text{C}} = 75.57\frac{\text{kJ}}{\text{kg}};\ \ v_{f@18°\text{C}} = 0.001002\frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@18°\text{C}} + p_3 v_{f@18°\text{C}} = 75.57 + (101.325)(0.001002) = 75.67\frac{\text{kJ}}{\text{kg}}$$

The rate at which condensate is removed

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (13.11)(0.0286 - 0.0129) = 0.21\frac{\text{kg}}{\text{min}}$$

The rate of heat removal

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$$\dot{Q}_{\text{out}} = \dot{m}_a \left(h_1 - h_2\right) - \dot{m}_w h_3;$$

$$\dot{Q}_{\text{out}} = (13.11)(109.60 - 50.78) - (0.21)(75.67) = 755.23 \frac{\text{kJ}}{\text{min}} = 12.59 \text{ kW}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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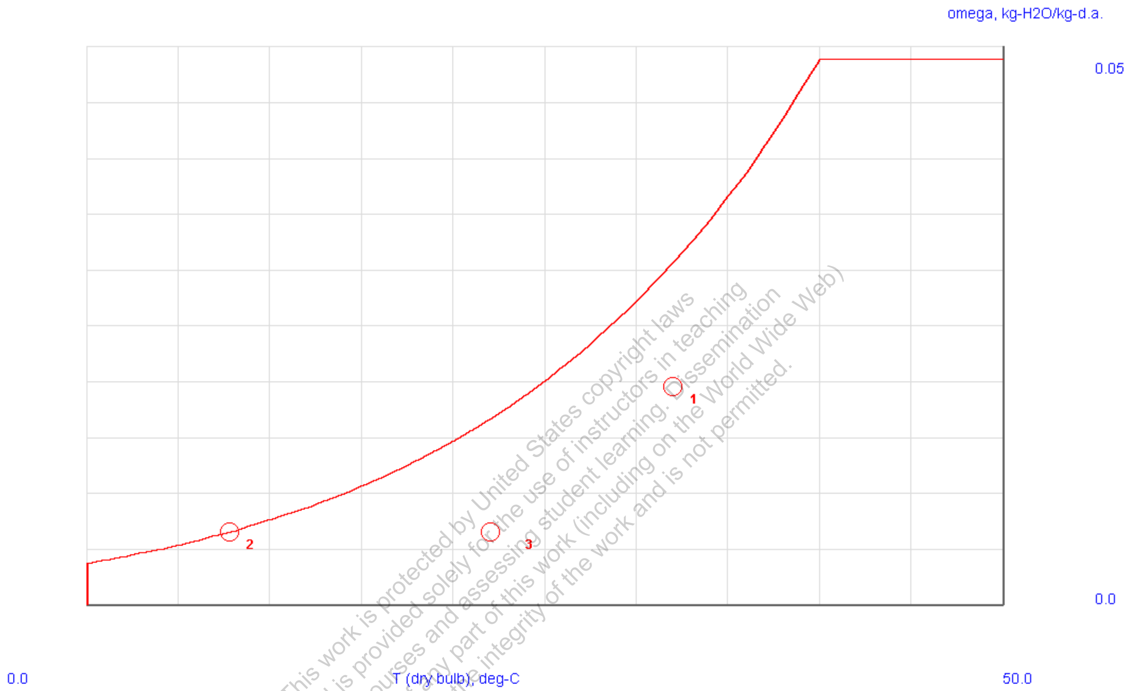
12-2-10 [ODV] An air conditioning system is to take in air at 1 atm, 32^{o}C, 65% relative humidity and deliver it at 22^{o}C, 40% relative humidity. Air flows first over the cooling coils, where it is cooled and dehumidified, and then over the resistance heating wires, where it is heated to the desired temperature. Assuming that the condensate is removed from the cooling section at 7^{o}C, determine (a) the temperature (T) of air before it enters the heating section, (b) the amount of heat removed in the cooling section and (c) the amount of heat transferred (q) in the heating section, both in kJ/kg dry air.

SOLUTION



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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, ϕ_1):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@32°\text{C}} = (0.65)(4.7581) = 3.09 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 3.09 = 98.24 \text{ kPa}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{3.09}{98.24}\right) = 0.0196\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@32°\text{C}} = 2559.90\frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(32) + (0.0196)(2559.90) = 82.33\frac{\text{kJ}}{\text{kg d.a.}}$$

State-2 (given $p_2 = p_1, \phi_2, \omega_2 = \omega_3$):

Using the psychrometric chart (Table-F) and the values for ϕ_2 and ω_2,

$T_2 = 7.8°\text{C}$

$$h_{g@7.8°\text{C}} = 2515.73\frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(7.8) + (0.0066)(2515.73) = 24.44\frac{\text{kJ}}{\text{kg d.a.}}$$

State-3 (given $p_3 = p_1, T_2$):

$$p_{v3} = \phi_3 p_{g3} = \phi_3 p_{\text{sat}@T_3} = \phi_3 p_{\text{sat}@22°\text{C}} = (0.40)(2.6445) = 1.06 \text{ kPa}$$

$$p_{a3} = p_3 - p_{v3} = 101.325 - 1.06 = 100.27 \text{ kPa}$$

$$\omega_3 = 0.622\frac{p_{v3}}{p_{a3}} = (0.622)\left(\frac{1.06}{100.27}\right) = 0.0066\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

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

$$h_3 = h_a + \omega_3 h_{g@T_3} = c_{pa}T_3 + \omega_3 h_{g@T_3} = (1.005)(22) + (0.0066)(2541.75) = 38.89\frac{\text{kJ}}{\text{kg d.a.}}$$

State-4 (given $p_4 = p_1, T_4$):

$$p_{\text{sat}@7°\text{C}} = 0.9988 \text{ kPa}$$

$$p_4 > p_{\text{sat}@7°\text{C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@7°\text{C}} = 29.39\frac{\text{kJ}}{\text{kg}}; \quad v_{f@7°\text{C}} = 0.001000\frac{\text{m}^3}{\text{kg}}$$

$$h_4 = u_{f@7°\text{C}} + p_4 v_{f@7°\text{C}} = 29.39 + (101.325)(0.001000) = 29.49\frac{\text{kJ}}{\text{kg}}$$

The amount of condensate removed per unit of dry air

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$$\frac{\dot{m}_w}{\dot{m}_a} = \omega_1 - \omega_2 = 0.0196 - 0.0066 = 0.0130 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

The amount of heat removed in the cooling section per mass of dry air

$$q_{\text{out}} = (h_1 - h_2) - \frac{\dot{m}_w}{\dot{m}_a} h_4 = (82.33 - 24.44) - (0.0130)(29.49) = 57.51 \frac{\text{kJ}}{\text{kg d.a.}}$$

The amount of heat added in the heating section per mass of dry air

$$q_{\text{in}} = h_3 - h_2 = 38.89 - 24.44 = 14.45 \frac{\text{kJ}}{\text{kg d.a.}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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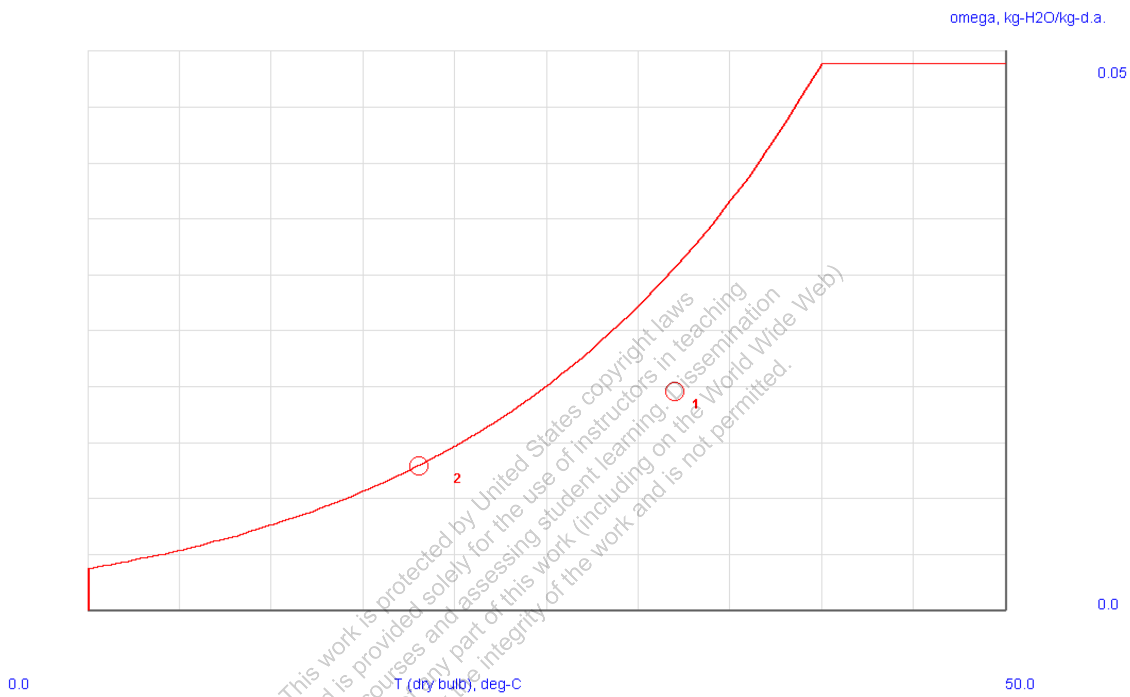
12-2-11 [ODT] Air enters a 20 cm diameter cooling section at 1 atm, 32°C and 65% relative humidity at 60 m/min. Air is cooled by passing it over a cooling coil through which cold water flows. The water experiences a temperature rise of 10°C. Air leaves the cooling section saturated at 18°C. Determine (a) the rate of heat transfer, (b) the mass flow rate of the water and (c) the exit velocity (V_2) of the airstreams. (d) What-if Scenario: What would the rate of heat transfer be if moist air entered the dehumidifier at 95 kPa instead of 1 atm?

SOLUTION



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Given:

$$c_{pw} = 4.184 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

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

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

State-1 (given $p_1, T_1, \phi_1, V_1, D_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@32°\text{C}} = (0.65)(4.7581) = 3.09 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 3.09 = 98.24 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{3.09}{98.24}\right) = 0.0196 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@32°\text{C}} = 2559.90 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(32) + (0.0196)(2559.90) = 82.33 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(305)}{98.24} = 0.8910 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{\mathcal{V}}_1 = A_1 V_1 = \left(\pi \frac{D_1^2}{4}\right) V_1 = \pi\left(\frac{0.20^2}{4}\right)(1) = 0.0314 \frac{\text{m}^3}{\text{s}} = 1.88 \frac{\text{m}^3}{\text{min}}$$

$$\dot{m}_{a1} = \frac{\dot{\mathcal{V}}_1}{v_1} = \frac{1.88}{0.8910} = 2.11 \frac{\text{kg}}{\text{min}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@18°\text{C}} = (1)(2.0639) = 2.06 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 101.325 - 2.06 = 99.27 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{2.06}{99.27}\right) = 0.0129 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@18°\text{C}} = 2534.45 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(18) + (0.0129)(2534.45) = 50.78 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(291)}{99.27} = 0.8413 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{\mathcal{V}}_2 = \dot{m}_{a2} v_2 = (2.11)(0.8413) = 1.78 \frac{\text{m}^3}{\text{min}}$$

$$V_2 = \frac{\dot{\mathcal{V}}_2}{A_2} = \frac{4\dot{\mathcal{V}}_2}{\pi D_2^2} = \frac{4(1.78)}{\pi(0.20^2)} = 56.66 \frac{\text{m}}{\text{min}}$$

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

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$p_{\text{sat@18°C}} = 2.0639 \text{ kPa}$

$p_3 > p_{\text{sat@18°C}} \;\; \therefore$ subcooled liquid

$$u_{f\text{@18°C}} = 75.57 \frac{\text{kJ}}{\text{kg}}; \;\; v_{f\text{@18°C}} = 0.001002 \frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f\text{@18°C}} + p_3 v_{f\text{@18°C}} = 75.57 + (101.325)(0.001002) = 75.67 \frac{\text{kJ}}{\text{kg}}$$

The rate at which condensate is removed

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (2.11)(0.0196 - 0.0129) = 0.014 \frac{\text{kg}}{\text{min}}$$

The rate of heat transfer (neglecting the minimal contribution from kinetic energy)

$$\dot{Q} = \dot{m}_a(h_2 - h_1) + \dot{m}_w h_3;$$

$$\dot{Q} = (2.11)(50.78 - 82.33) + (0.014)(75.67) = -65.51 \frac{\text{kJ}}{\text{min}}$$

The cooling water receives the heat rejected by the air. Using the SL Model for the cooling water

$$\dot{Q} = \dot{m}_w c_{pw} \Delta T;$$

$$\Rightarrow \dot{m}_w = \frac{\dot{Q}}{c_{pw}\Delta T} = \frac{65.51}{(4.184)(10)} = 1.56 \frac{\text{kg}}{\text{min}}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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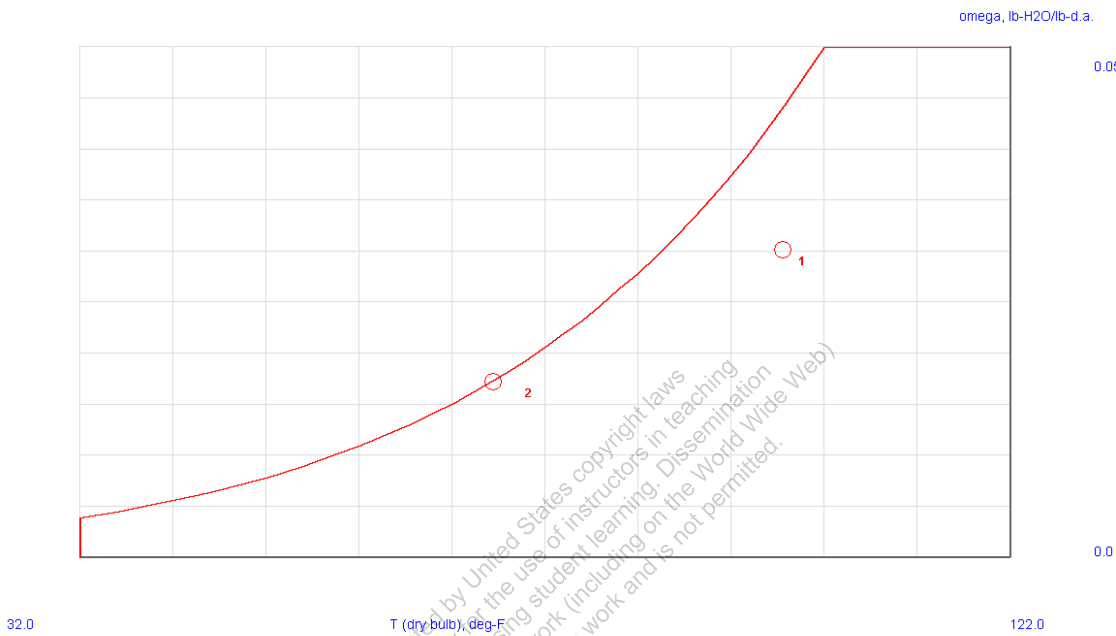
12-2-12 [ODF] Air enters a 1.5 ft diameter cooling section at 14.4 psia, 100°F and 70% relative humidity at 500 ft/min. Air is cooled by passing it over a cooling coil through which cold water flows. The water experiences a temperature rise of 15°F. Air leaves the cooling section saturated at 72°F. Determine (a) the rate of heat transfer, (b) the mass flow rate of the water and (c) the exit velocity (V_2) of the airstreams.

SOLUTION



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Given:

$$c_{pw} = 0.999 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

$$c_{pa} = 0.240 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

$$R_a = 0.069 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

State-1 (given $p_1, T_1, \phi_1, V_1, D_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@100°\text{F}} = (0.70)(0.9508) = 0.67 \text{ psia}$$

$$p_{a1} = p_1 - p_{v1} = 14.40 - 0.67 = 13.73 \text{ psia}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.67}{13.73}\right) = 0.0304\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$h_{g@100°\text{F}} = 1105.13\frac{\text{Btu}}{\text{lbm}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}(T_1 - T_{\text{ref}}) + \omega_1 h_{g@T_1} = (0.240)(100-32) + (0.0304)(1105.13) = 49.92\frac{\text{Btu}}{\text{lbm d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.069)(559.67)}{13.73}(5.40) = 15.19\frac{\text{ft}^3}{\text{lbm d.a.}}; \left[\frac{\text{Btu}}{\text{psia}} = \frac{\text{Btu}\times\text{in}^2}{\text{lbf}} = 5.40 \text{ ft}^3\right]$$

$$\dot{\mathcal{V}}_1 = A_1 V_1 = \left(\pi\frac{D_1^2}{4}\right)V_1 = \pi\left(\frac{1.5^2}{4}\right)(8.33) = 14.72\frac{\text{ft}^3}{\text{s}}$$

$$\dot{m}_{a1} = \frac{\dot{\mathcal{V}}_1}{v_1} = \frac{14.72}{15.19} = 0.97\frac{\text{lbm}}{\text{s}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@72°\text{F}} = (1)(0.3890) = 0.39 \text{ psia}$$

$$p_{a2} = p_2 - p_{v2} = 14.40 - 0.39 = 14.01 \text{ psia}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{0.39}{14.01}\right) = 0.0173\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$h_{g@72°\text{F}} = 1093.02\frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}(T_2 - T_{\text{ref}}) + \omega_2 h_{g@T_2} = (0.240)(72-32) + (0.0173)(1093.02) = 28.51\frac{\text{Btu}}{\text{lbm d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.069)(531.67)}{14.01}(5.40) = 14.14\frac{\text{ft}^3}{\text{lbm d.a.}}$$

$$\dot{\mathcal{V}}_2 = \dot{m}_{a2} v_2 = (0.97)(14.14) = 13.73\frac{\text{ft}^3}{\text{s}}$$

$$V_2 = \frac{\dot{\mathcal{V}}_2}{A_2} = \frac{4\dot{\mathcal{V}}_2}{\pi D_2^2} = \frac{4(13.73)}{\pi(1.5^2)} = 7.77\frac{\text{ft}}{\text{s}} = 466.20\frac{\text{ft}}{\text{min}}$$

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

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$p_{\text{sat@72°F}} = 0.3885\ \text{psia}$

$p_3 > p_{\text{sat@72°C}}\ \therefore$ subcooled liquid

$$u_{f@72°\text{F}} = 40.10\frac{\text{Btu}}{\text{lbm}};\ v_{f@72°\text{F}} = 0.01606\frac{\text{ft}^3}{\text{lbm}}$$

$$h_3 = u_{f@72°\text{F}} + p_3 v_{f@72°\text{F}} = 40.10 + (14.40)\left(\frac{0.01606}{5.40}\right) = 40.14\frac{\text{Btu}}{\text{lbm}}$$

The rate at which condensate is removed

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = (0.97)(0.0304 - 0.0173) = 0.013\frac{\text{lbm}}{\text{s}}$$

The rate of heat transfer (neglecting the minimal contribution from kinetic energy)

$$\dot{Q} = \dot{m}_a(h_2 - h_1) + \dot{m}_w h_3;$$

$$\dot{Q} = (0.97)(28.51 - 49.92) + (0.013)(40.14) = -20.24\frac{\text{Btu}}{\text{s}} = -1214.75\frac{\text{Btu}}{\text{min}}$$

The cooling water receives the heat rejected by the air. Using the SL Model for the cooling water

$$\dot{Q} = \dot{m}_w c_{pw}\Delta T;$$

$$\Rightarrow \dot{m}_w = \frac{\dot{Q}}{c_{pw}\Delta T} = \frac{1214.75}{(0.999)(15)} = 81.06\frac{\text{lbm}}{\text{min}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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12-2-13 [ODD] A saturated stream of carbon dioxide enters a dehumidifier with a flow rate of 100 m^3/min at 39^{o}C, 100 kPa. The mixture is cooled to 10^{o}C by circulating cold water before being electrically heated back to 30^{o}C. Determine (a) the rate of water removal in kg/min, (b) the cooling load, (c) the heating load and (d) the relative humidity at the exit.

SOLUTION

Given:

$$c_{pw} = 4.184 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$c_{p,\text{CO}_2} = 0.846 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

$$R_{\text{CO}_2} = 0.189 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$$

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

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@39°\text{C}} = (1)(7.0057) = 7.01 \text{ kPa}$$

$$p_{\text{CO}_2,1} = p_1 - p_{v1} = 100 - 7.01 = 92.99 \text{ kPa}$$

$$\omega_1 = 0.409 \frac{p_{v1}}{p_{\text{CO}_2,1}} = (0.409)\left(\frac{7.01}{92.99}\right) = 0.0308 \frac{\text{kg H}_2\text{O}}{\text{kg CO}_2}$$

$$h_{g@39°\text{C}} = 2572.50 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_{\text{CO}_2} + \omega_1 h_{g@T_1} = c_{p,\text{CO}_2} T_1 + \omega_1 h_{g@T_1} = (0.846)(39) + (0.0308)(2572.50) = 112.23 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_{\text{CO}_2} T_1}{p_{\text{CO}_2,1}} = \frac{(0.189)(312)}{92.99} = 0.6341 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{\text{CO}_2,1} = \frac{\dot{V}_1}{v_1} = \frac{100}{0.6341} = 157.70 \frac{\text{kg}}{\text{min}}$$

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

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$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{sat@T_2} = \phi_2 p_{sat@10°C} = (1)(1.2271) = 1.23\ \text{kPa}$$
$$p_{CO_2,2} = p_2 - p_{v2} = 100 - 1.23 = 98.77\ \text{kPa}$$
$$\omega_2 = 0.409\frac{p_{v2}}{p_{CO_2,2}} = (0.409)\left(\frac{1.23}{98.77}\right) = 0.0051\frac{\text{kg H}_2\text{O}}{\text{kg CO}_2}$$
$$h_{g@10°C} = 2519.75\frac{\text{kJ}}{\text{kg}}$$
$$h_2 = h_{CO_2} + \omega_2 h_{g@T_2} = c_{p,CO_2}T_2 + \omega_2 h_{g@T_2} = (0.846)(10) + (0.0051)(2519.75) = 21.31\frac{\text{kJ}}{\text{kg d.a.}}$$

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

State-4 (given $p_4 = p_1, T_4, \omega_4 = \omega_2$):
The vapor pressure remains constant, so
$$\phi_4 = \frac{p_{v4}}{p_{g2}} = \frac{p_{v4}}{p_{sat@30°C}} = \frac{1.23}{4.2460} = 0.2897 = 28.97\%$$
$$h_{g@30°C} = 2556.30\frac{\text{kJ}}{\text{kg}}$$
$$h_4 = h_{CO_2} + \omega_2 h_{g@T_4} = c_{p,CO_2}T_4 + \omega_4 h_{g@T_4} = (0.846)(30) + (0.0051)(2556.30) = 38.42\frac{\text{kJ}}{\text{kg d.a.}}$$

The rate at which condensate is removed
$$\dot{m}_w = \dot{m}_{CO_2}(\omega_1 - \omega_2) = (157.70)(0.0308 - 0.0051) = 4.05\frac{\text{kg}}{\text{min}}$$

The cooling load
$$\dot{Q}_{out} = \dot{m}_{CO_2}(h_1 - h_2) - \dot{m}_w h_3;$$
$$\dot{Q}_{out} = (157.70)(112.23 - 21.31) - (4.05)(42.10) = 14167.58\frac{\text{kJ}}{\text{min}} = 67.14\ \text{ton}$$

The heating load

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$$\dot{W}_{\text{in,el}} = \dot{m}_{\text{CO}_2}\left(h_4 - h_2\right);$$

$$\dot{W}_{\text{in,el}} = (157.70)(38.42 - 21.31) = 2698.25\frac{\text{kJ}}{\text{min}} = 44.97\ \text{kW}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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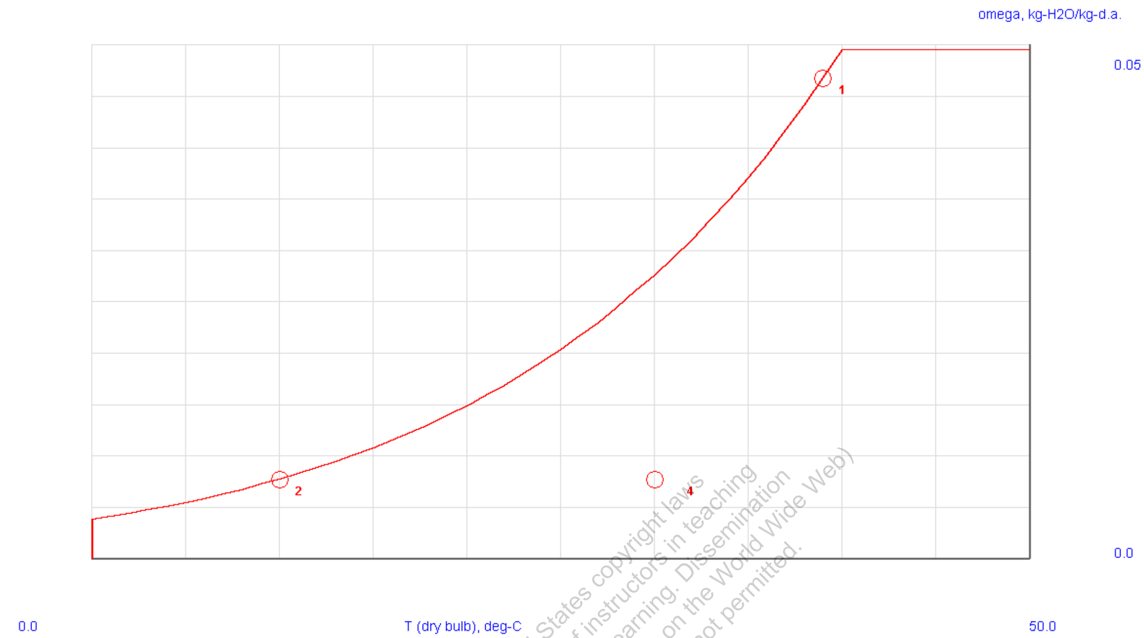
12-2-14 [ODM] Repeat problem 12-2-13 [ODD] above assuming the gas mixture to be composed of dry air and water vapor.

SOLUTION



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Given:

$$c_{pw} = 4.184 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

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

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

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

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@39°\text{C}} = (1)(7.0057) = 7.02 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 100 - 7.01 = 92.99 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{7.02}{92.99}\right) = 0.0470 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@39°\text{C}} = 2572.50 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(39) + (0.0470)(2572.50) = 160.10 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(312)}{92.99} = 0.9629 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{100}{0.9629} = 103.85 \frac{\text{kg}}{\text{min}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@10°\text{C}} = (1)(1.2271) = 1.23 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 100 - 1.23 = 98.77 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{1.23}{98.77}\right) = 0.0077 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@10°\text{C}} = 2519.75 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(10) + (0.0077)(2519.75) = 29.45 \frac{\text{kJ}}{\text{kg d.a.}}$$

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

$$p_{\text{sat}@10°\text{C}} = 1.2271 \text{ kPa}$$

$p_3 > p_{\text{sat}@10°\text{C}}$ $\therefore$ subcooled liquid

$$u_{f@10°\text{C}} = 42.00 \frac{\text{kJ}}{\text{kg}}; \; v_{f@10°\text{C}} = 0.001001 \frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@10°\text{C}} + p_3 v_{f@10°\text{C}} = 42.00 + (100)(0.001001) = 42.10 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, T_4, \omega_4 = \omega_2$):

The vapor pressure of the air remains constant, so

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$$\phi_4 = \frac{p_{v4}}{p_{g2}} = \frac{p_{v4}}{p_{\text{sat@30°C}}} = \frac{1.23}{4.2460} = 0.2897 = 28.97\%$$

$$h_{g@30°\text{C}} = 2556.30 \frac{\text{kJ}}{\text{kg}}$$

$$h_4 = h_a + \omega_2 h_{g@T_4} = c_{pa} T_4 + \omega_4 h_{g@T_4} = (1.005)(30) + (0.0077)(2556.30) = 49.83 \frac{\text{kJ}}{\text{kg d.a.}}$$

The rate at which condensate is removed

$$\dot{m}_w = \dot{m}_a (\omega_1 - \omega_2) = (103.85)(0.0470 - 0.0077) = 4.08 \frac{\text{kg}}{\text{min}}$$

The cooling load

$$\dot{Q}_{\text{out}} = \dot{m}_a (h_1 - h_2) - \dot{m}_w h_3;$$

$$\dot{Q}_{\text{out}} = (103.85)(160.10 - 29.45) - (4.08)(42.10) = 13396.23 \frac{\text{kJ}}{\text{min}} = 63.49 \text{ ton}$$

The heating load

$$\dot{W}_{\text{in,el}} = \dot{m}_a (h_4 - h_2);$$

$$\dot{W}_{\text{in,el}} = (103.85)(49.83 - 29.45) = 2116.46 \frac{\text{kJ}}{\text{min}} = 35.27 \text{ kW}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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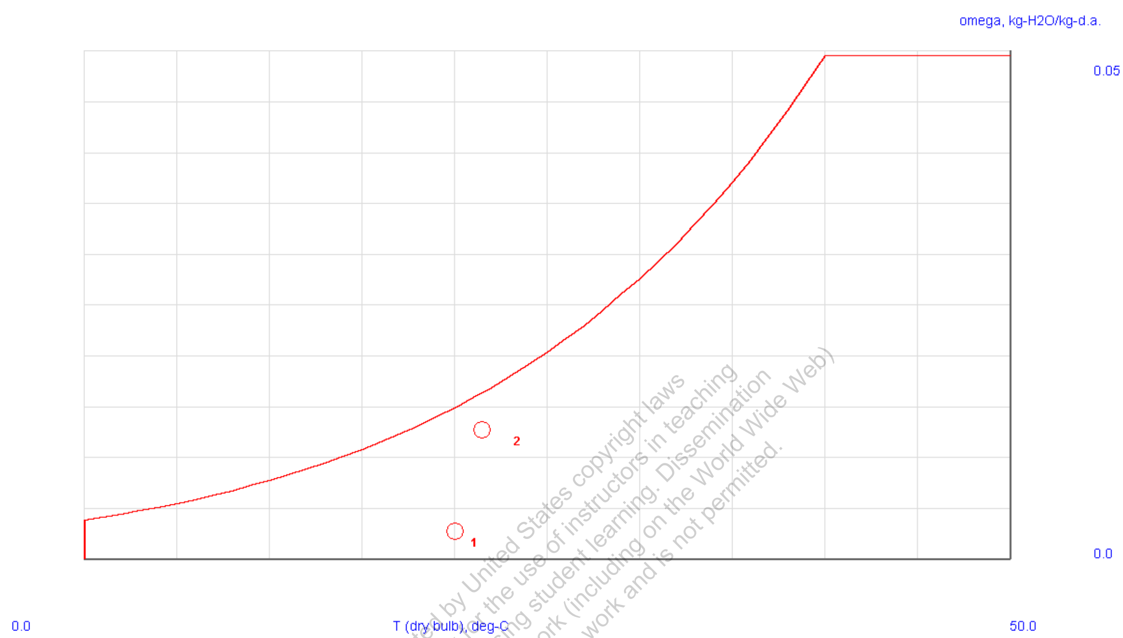
12-2-15 [ODJ] Moist air with dry and wet bulb temperatures of 20^{o}C and 9^{o}C, respectively, enters a steam-spray humidifier at rate of 100 kg of dry air/min. Saturated water vapor at 110^{o}C is injected at 1 kg/min. The pressure remains constant at 100 kPa. Determine (a) the inlet R.H. and (b) exit R.H. (c) What-if Scenario: What would the exit R.H. be if saturated water vapor were injected at 0.5 kg/min?

SOLUTION



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State-1 (given $p_1, T_1, T_{\text{wb},1}, \dot{m}_{a1}$):

Given the dry- and wet-bulb temperatures, the relative humidity, absolute humidity, and specific enthalpy can be easily found from the psychrometric chart (Table-F)

$\phi_1 = 19.5\%$

$$\omega_1 = 0.0028 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_1 = 27.25 \frac{\text{kJ}}{\text{kg d.a.}}$$

State-2 (given $p_2 = p_1$)

State-3 (given $p_3 = p_1, T_3, \dot{m}_3$):

$$h_3 = h_{g@110^\circ\text{C}} = 2691.50 \frac{\text{kJ}}{\text{kg}}$$

The specific humidity as state-2 can be calculated knowing the rate of steam injection

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$$\omega_2 = \omega_1 + \frac{\dot{m}_3}{\dot{m}_{a2}} = 0.0028 + \frac{1}{100} = 0.0126 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

The specific enthalpy at state-2 can also be found as

$$h_2 = h_1 + \frac{\dot{m}_3}{\dot{m}_{a2}} h_3 = 27.25 + \left(\frac{1}{100}\right)(2691.50) = 54.17 \frac{\text{kJ}}{\text{kg d.a.}}$$

Using the psychrometric chart (Table-F) and the values for h_2 and ω_2,

$\phi_2 = 78.7\%$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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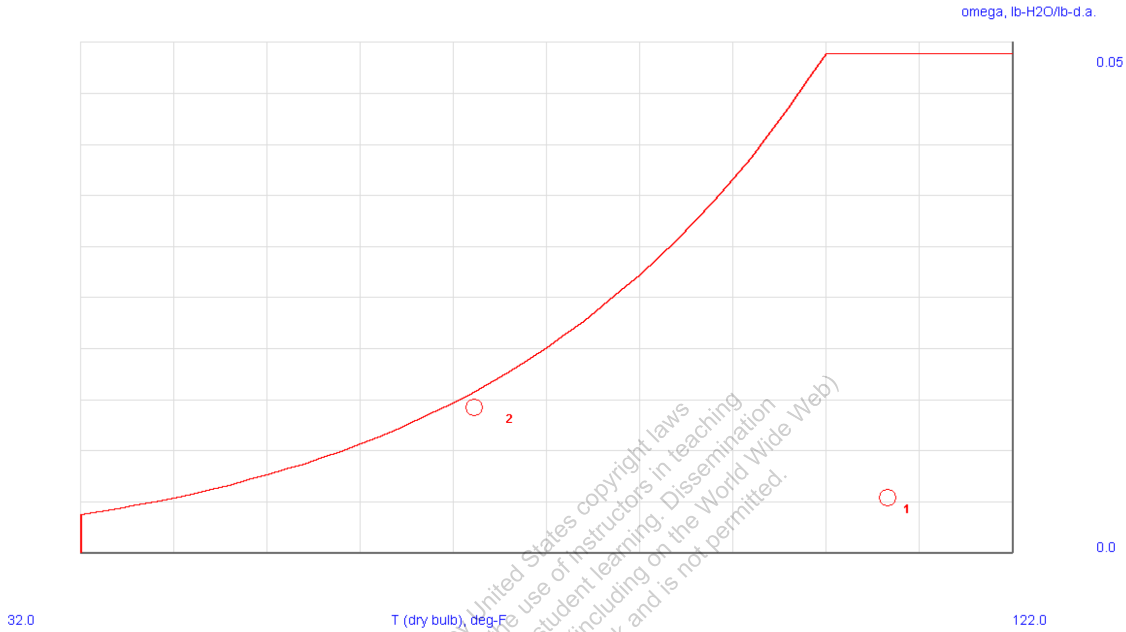
12-2-16 [ODW] Air at 110°F and 10% R.H. enters an evaporative cooler at a flow rate of 5500 ft^3/min. Air leaves at 70°F. Determine (a) the mass flow rate of water and (b) the exit R.H. Assume the pressure (1 atm) and wet-bulb temperature to remain constant along the flow.

SOLUTION



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Given:

$$R_a = 0.069\frac{\text{Btu}}{\text{lbm}\cdot\text{R}}$$

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

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat@}T_1} = \phi_1 p_{\text{sat@110°F}} = (0.10)(1.2772) = 0.13 \text{ psia}$$

$$p_{a1} = p_1 - p_{v1} = 14.70 - 0.13 = 14.57 \text{ psia}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.13}{14.57}\right) = 0.0055\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.069)(569.67)}{14.57}(5.40) = 14.57\frac{\text{ft}^3}{\text{lbm d.a.}}; \left[\frac{\text{Btu}}{\text{psia}} = \frac{\text{Btu}\times\text{in}^2}{\text{lbf}} = 5.40 \text{ ft}^3\right]$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{5500}{14.57} = 377.49\frac{\text{lbm}}{\text{min}} = 6.29\frac{\text{lbm}}{\text{s}}$$

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

$$T_{\text{wb},1} = 20°\text{C} = 68°\text{F}$$

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State-2 (given $p_2 = p_1, T_2, T_{\text{wb},2} = T_{\text{wb},1}$):

Knowing the dry- and wet-bulb temperatures, the specific humidity and the relative humidity at state-2 can be found from the psychrometric chart,

$$\omega_2 = 0.0143 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$\phi_2 = 90\%$$

The mass flow rate of water

$$\dot{m}_w = \dot{m}_{a1}\left(\omega_2 - \omega_1\right) = \left(6.29\right)\left(0.0143 - 0.0055\right) = 0.055 \frac{\text{lbm}}{\text{s}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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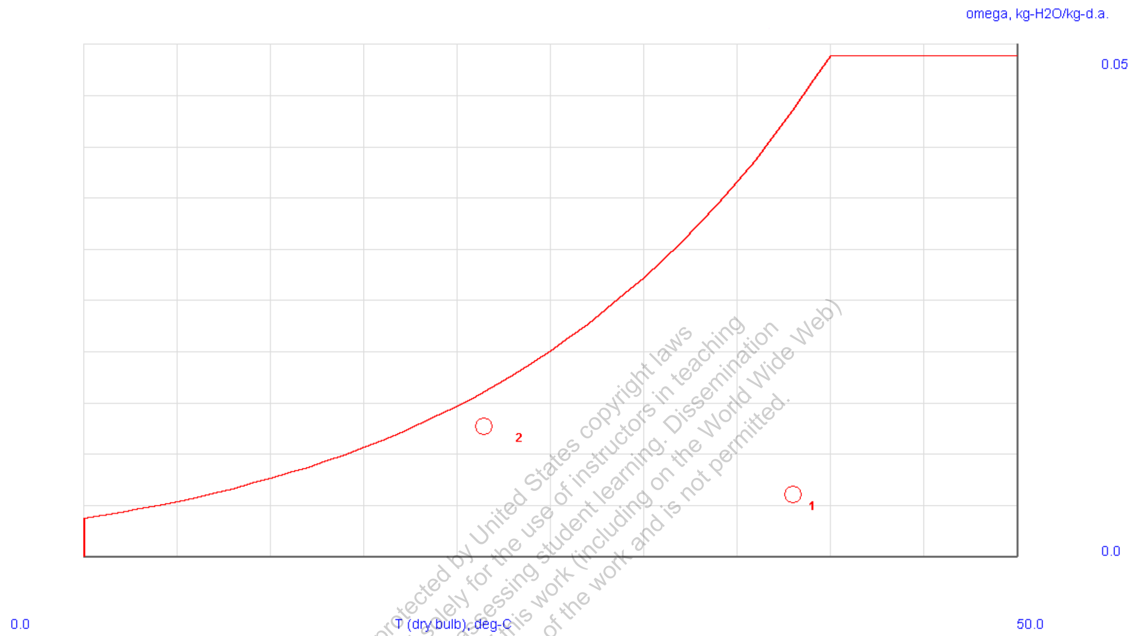
12-2-17 [OMR] Air enters an evaporative cooler at 1 atm, 38°C and 15% relative humidity at a rate of 5 m^3/min, and it leaves with a relative humidity of 80%. Determine (a) the exit temperature (T_2) of the air, (b) the required rate of water supply to the evaporative cooler. (c) What-if Scenario: What would the required rate of water supply be if the moist air entered the evaporative cooler at a rate of 10 m^3/min instead of 5 m^3/min?

SOLUTION



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Given:

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

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

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@38°\text{C}} = (0.15)(6.6320) = 0.99 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 0.99 = 101.34 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.99}{101.34}\right) = 0.0061 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(311)}{101.34} = 0.8808 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{5}{0.8808} = 5.68 \frac{\text{kg}}{\text{min}}$$

From the psychrometric chart (Table-F)

$$T_{\text{wb},1} = 19°\text{C}$$

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State-2 (given $p_2 = p_1, T_{\text{wb},2} = T_{\text{wb},1}, \phi_2$):

Knowing the wet-bulb temperature and the relative humidity, from the psychrometric chart (Table-F)

$T_2 = 21.5°\text{C}$

$$\omega_2 = 0.0128 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

The required rate of water supply to the cooler

$$\dot{m}_w = \dot{m}_{a1}\left(\omega_2 - \omega_1\right) = (5.68)(0.0128 - 0.0061) = 0.038 \frac{\text{kg}}{\text{min}}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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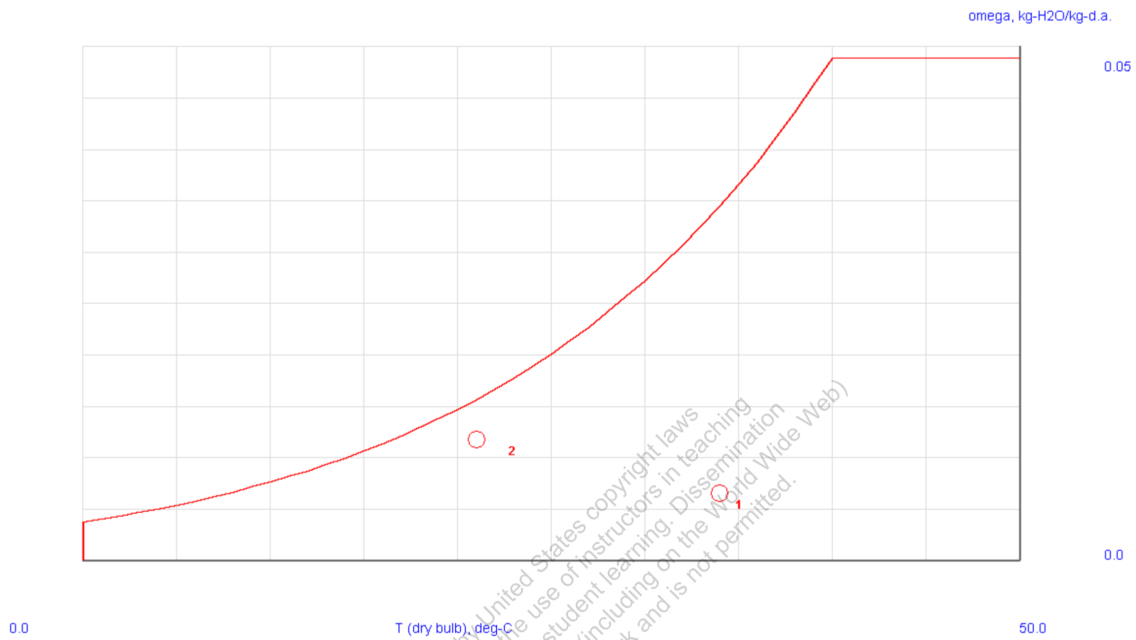
12-2-18 [OMO] Air enters an evaporative cooler at 1 atm, 34°C and 20% relative humidity at a rate of 8 m^3/min, and it leaves at 21°C. Determine (a) the the final relative humidity and (b) the amount of water added to the air. (c) What-if Scenario: What would the answers be if air entered the evaporative cooler at 93 kPa?

SOLUTION



Given:

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

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

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat@}T_1} = \phi_1 p_{\text{sat@34°C}} = (0.20)(5.3240) = 1.06 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 1.06 = 100.27 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{1.06}{100.27}\right) = 0.0066 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(307)}{100.27} = 0.8787 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{8}{0.8787} = 9.10 \frac{\text{kg}}{\text{min}}$$

From the psychrometric chart (Table-F)

$$T_{\text{wb},1} = 18°\text{C}$$

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State-2 (given $p_2 = p_1, T_2, T_{\mathrm{wb},2} = T_{\mathrm{wb},1}$):

Knowing the dry- and wet-bulb temperatures, from the psychrometric chart (Table-F)

$\phi_2 = 75\%$

$$\omega_2 = 0.0118 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

The rate at which water is added to the air

$$\dot{m}_w = \dot{m}_{a1}\left(\omega_2 - \omega_1\right) = (9.10)(0.0118 - 0.0066) = 0.047 \frac{\text{kg}}{\text{min}}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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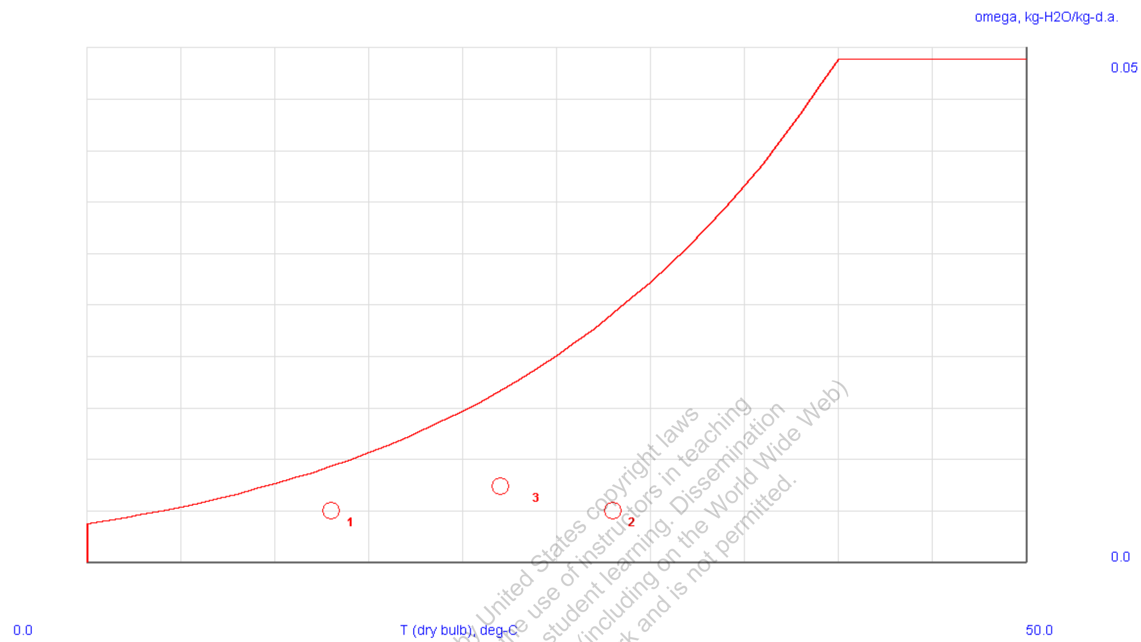
12-2-19 [OMS] Air at 1 atm, 13^{o}C and 55 percent relative humidity is first heated to 28^{o}C in a heating section and then is passed through an evaporative cooler where its temperature drops to 22^{o}C. Determine (a) the exit relative humidity and (b) the amount of water added to the air in kg H_2O/kg dry air.

SOLUTION



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State-1 (given p_1, T_1, ϕ_1):

$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@13°\text{C}} = (0.55)(1.5000) = 0.83 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 0.83 = 100.50 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.83}{100.50}\right) = 0.0051 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

State-2 (given $p_2 = p_1, T_2, \omega_2 = \omega_1$):

The vapor pressure of the air remains constant, so

$$\phi_2 = \frac{p_{v2}}{p_{g2}} = \frac{p_{v2}}{p_{\text{sat}@28°\text{C}}} = \frac{0.83}{3.7929} = 0.2188 = 21.88\%$$

From the psychrometric chart (Table-F)

$$T_{\text{wb},2} = 14.5°\text{C}$$

State-3 (given $p_3 = p_1, T_3, T_{\text{wb},3} = T_{\text{wb},2}$):

Knowing the dry- and wet-bulb temperatures, from the psychrometric chart (Table-F)

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$\phi_3 = 45\%$

$$\omega_2 = 0.0075 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

The amount of water added per unit mass of dry air

$$\frac{\dot{m}_w}{\dot{m}_{a1}} = \omega_3 - \omega_2 = 0.0075 - 0.0051 = 0.0024 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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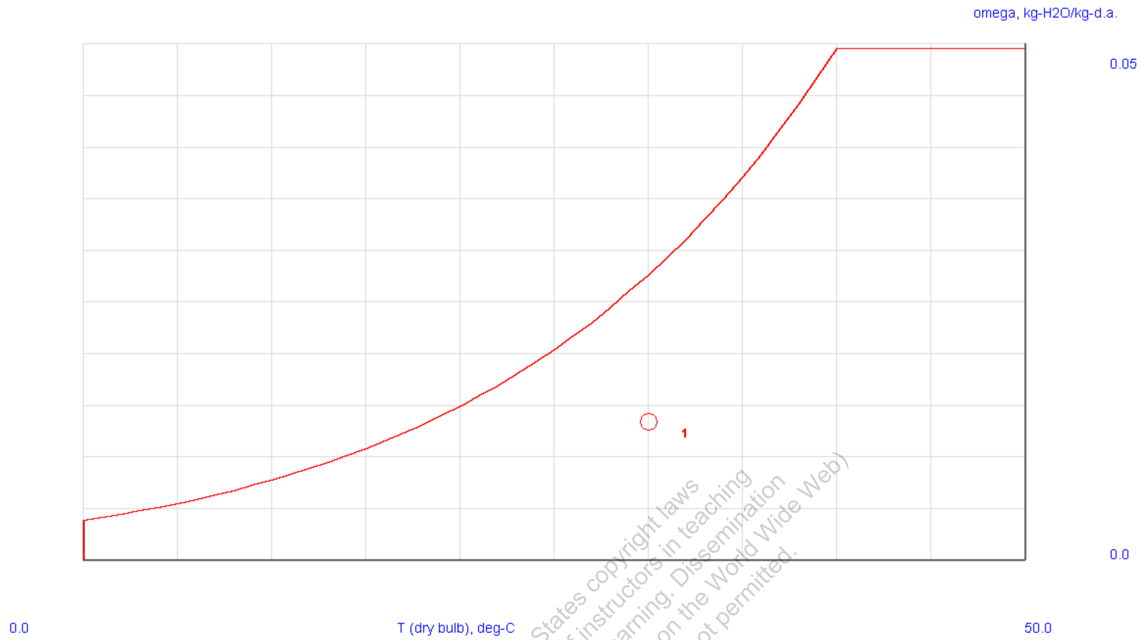
12-2-20 [OMH] Determine the adiabatic saturation temperature of air at 100 kPa, 30°C and 50% relative humidity.

SOLUTION



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State-1 (given p_1, T_1, ϕ_1):
The adiabatic saturation temperature can be approximated by the wet-bub temperature (refer to Section 12.3). Therefore, knowing dry-bulb temperature and relative humidity, the adiabatic saturation temperature can be found from the psychrometric chart (Table-F)
$T_{\text{wb},1} = 22°\text{C}$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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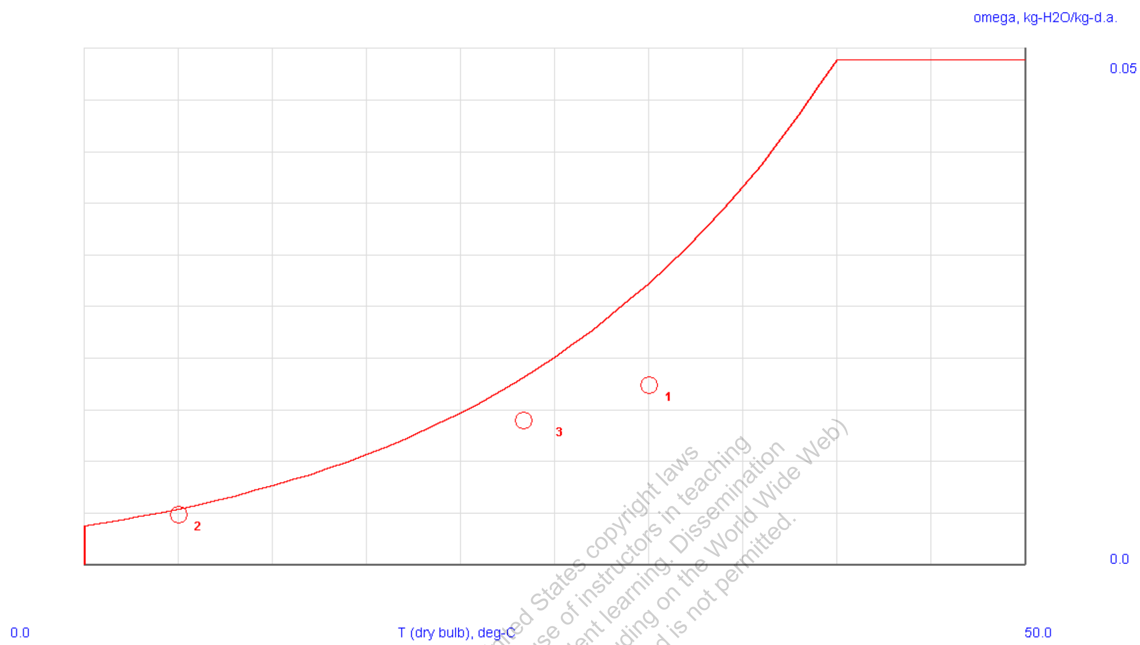
12-2-21 [OMB] A 150 m^3/min stream of air at 30^{o}C and 65% R.H. is mixed with a 50 m^3/min stream of air at 5^{o}C and 90% R.H. in an adiabatic mixing chamber. Determine (a) the R.H. at the exit. Assume pressure to be 1 atm.

SOLUTION



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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 $p_1, T_1, \phi_1, \dot{V}_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@30°\text{C}} = (0.65)(4.2460) = 2.76 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 2.76 = 98.57 \text{ kPa}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{2.76}{98.57}\right) = 0.0174\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@30°\text{C}} = 2556.30\frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(30) + (0.0174)(2556.30) = 74.63\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(303)}{98.57} = 0.8822\frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{150}{0.8822} = 170.03\frac{\text{kg}}{\text{min}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@5°\text{C}} = (0.90)(0.8737) = 0.79 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 101.325 - 0.79 = 100.54 \text{ kPa}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{0.79}{100.54}\right) = 0.0049\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

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

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(5) + (0.0049)(2510.55) = 17.33\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(278)}{100.54} = 0.7936\frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{50}{0.7936} = 63.00\frac{\text{kg}}{\text{min}}$$

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

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

$$\omega_3 = \frac{\dot{m}_{a1}\omega_1 + \dot{m}_{a2}\omega_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(170.03)(0.0174) + (63.00)(0.0049)}{170.03 + 63.00} = 0.0140\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_3 = \frac{\dot{m}_{a1}h_1 + \dot{m}_{a2}h_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(170.03)(74.63) + (63.00)(17.33)}{170.03 + 63.00} = 59.14\frac{\text{kJ}}{\text{kg d.a.}}$$

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

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$\phi_3 = 77.5\%$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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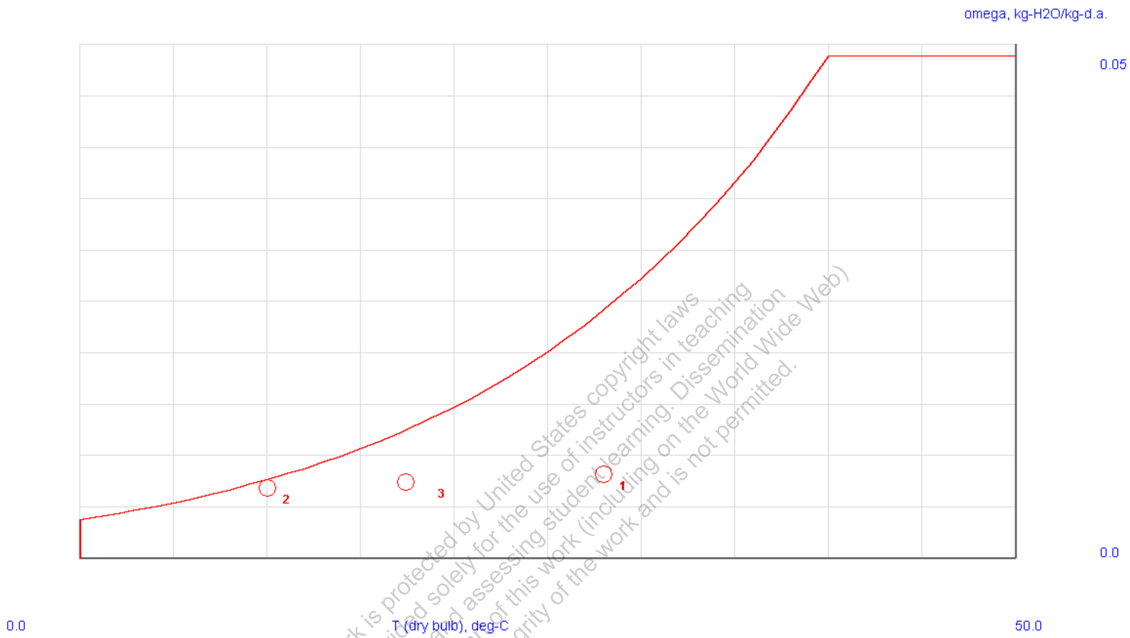
12-2-22 [OMA] Two airstreams are mixed steadily and adiabatically. The first stream enters at 28°C and 35% relative humidity at rate of 15 m^3/min, while the second stream enters at 10°C and 90% of relative humidity at rate of 20 m^3/min. Assuming that the mixing process occurs at a pressure of 1 atm, determine (a) the specific humidity (ω), (b) relative humidity, (c) the dry-bulb temperature and (d) the volume flow rate of the mixture. (e) What-if Scenario: What would the answers be if the total mixing-chamber pressure were 92 kPa?

SOLUTION



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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 $p_1, T_1, \phi_1, \dot{V}_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@28°\text{C}} = (0.35)(3.7929) = 1.33 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 1.33 = 100.00 \text{ kPa}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{1.33}{100.00}\right) = 0.0083\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@28°\text{C}} = 2552.67\frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(28) + (0.0083)(2552.67) = 49.33\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(301)}{100.00} = 0.8639\frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{15}{0.8639} = 17.36\frac{\text{kg}}{\text{min}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@10°\text{C}} = (0.90)(1.2271) = 1.10 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 101.325 - 1.10 = 100.23 \text{ kPa}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{1.10}{100.23}\right) = 0.0068\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@10°\text{C}} = 2519.75\frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(10) + (0.0068)(2519.75) = 27.18\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(283)}{100.23} = 0.8103\frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{20}{0.8103} = 24.68\frac{\text{kg}}{\text{min}}$$

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

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

$$\omega_3 = \frac{\dot{m}_{a1}\omega_1 + \dot{m}_{a2}\omega_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(17.36)(0.0083) + (24.68)(0.0068)}{17.36 + 24.68} = 0.0074\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_3 = \frac{\dot{m}_{a1}h_1 + \dot{m}_{a2}h_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(17.36)(49.33) + (24.68)(27.18)}{17.36 + 24.68} = 36.33\frac{\text{kJ}}{\text{kg d.a.}}$$

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

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$T_3 = 17.5°\text{C}$

$$v_3 = 0.8330 \frac{\text{m}^3}{\text{kg d.a.}}$$

$\phi_3 = 60\%$

The volume flow rate of the mixture

$$\dot{V}_3 = \dot{m}_{a3} v_3 = (17.36 + 24.68)(0.8330) = 35.02 \frac{\text{m}^3}{\text{min}}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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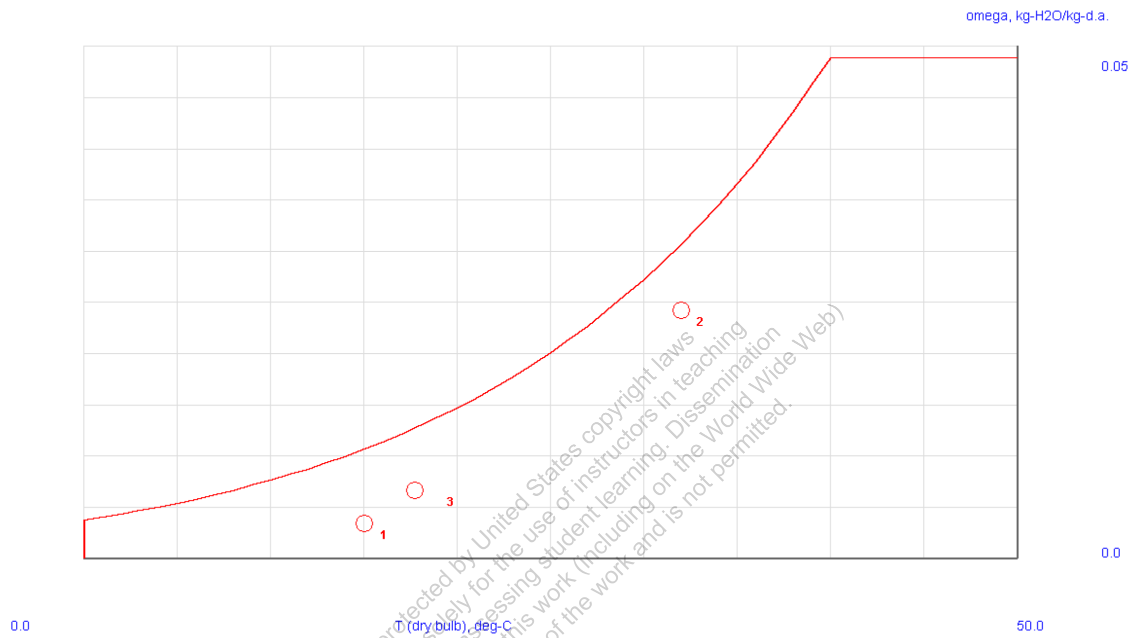
12-2-23 [OMN] During an air conditioning process 50 m^3/min of conditioned air at 15^{o}C and 33% relative humidity is mixed adiabatically with 10 m^3/min of outside air at 32^{o}C and 80% relative humidity at pressure of 1 atm. Determine (a) the temperature (T), (b) the specific humidity (ω) and (c) the relative humidity of the mixture. (d) What-if Scenario: What would the temperature of the mixture be if the volumes were 40 m^3/min and 25 m^3/min respectively?

SOLUTION



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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 $p_1, T_1, \phi_1, \dot{V}_1$):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@15°\text{C}} = (0.33)(1.7080) = 0.56 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 0.56 = 100.77 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.56}{100.77}\right) = 0.0035 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@15°\text{C}} = 2528.95 \frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(15) + (0.0035)(2528.95) = 23.93 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(288)}{100.77} = 0.8202 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{50}{0.8202} = 60.96 \frac{\text{kg}}{\text{min}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@32°\text{C}} = (0.80)(4.7581) = 3.81 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 101.325 - 3.81 = 97.52 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{3.81}{97.52}\right) = 0.0243 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@32°\text{C}} = 2559.90 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(32) + (0.0243)(2559.90) = 94.37 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.287)(305)}{97.52} = 0.8976 \frac{\text{m}^3}{\text{kg d.a.}}$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{10}{0.8976} = 11.14 \frac{\text{kg}}{\text{min}}$$

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

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

$$\omega_3 = \frac{\dot{m}_{a1}\omega_1 + \dot{m}_{a2}\omega_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(60.96)(0.0035) + (11.14)(0.0243)}{60.96 + 11.14} = 0.0067 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_3 = \frac{\dot{m}_{a1}h_1 + \dot{m}_{a2}h_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(60.96)(23.93) + (11.14)(94.37)}{60.96 + 11.14} = 34.81 \frac{\text{kJ}}{\text{kg d.a.}}$$

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

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$$T_3 = 17.5°\text{C}$$
$$\phi_3 = 53\%$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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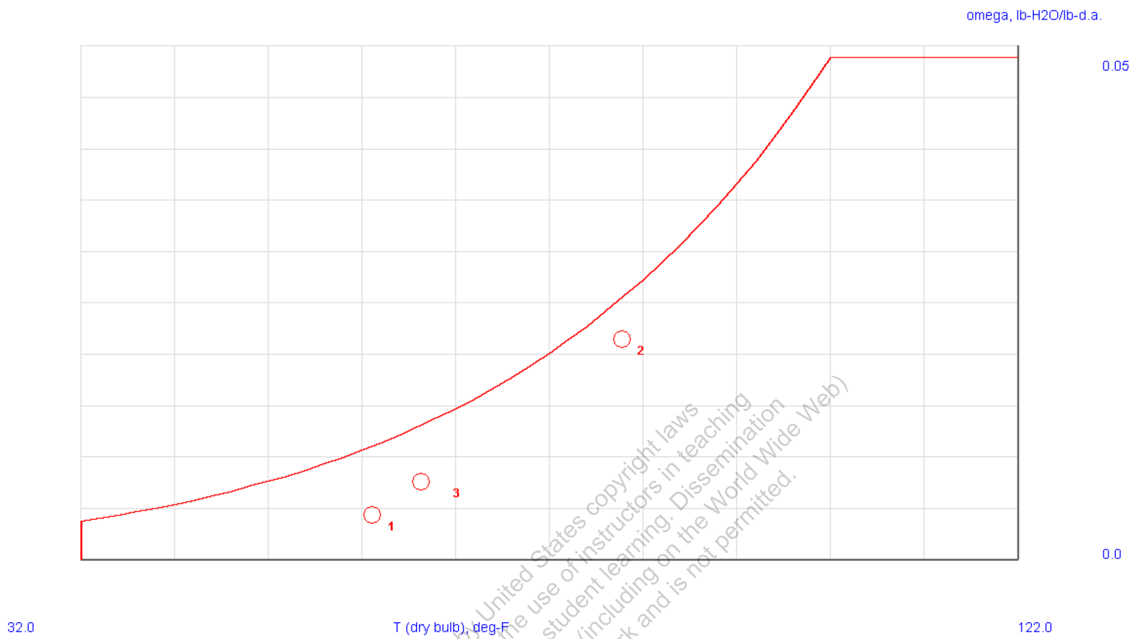
12-2-24 [OMI] During an air conditioning process 800 ft^3/min of conditioned air at 60^oF and 40% relative humidity is mixed adiabatically with 200 ft^3/min of outside air at 84^oF and 85% relative humidity at pressure of 14.7 psia. Determine (a) the temperature (T), (b) the specific humidity (ω) and (c) the relative humidity of the mixture.

SOLUTION



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Given:

$$c_{pa} = 0.240 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

$$R_a = 0.069 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

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

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@60°\text{F}} = (0.40)(0.2566) = 0.10 \text{ psia}$$

$$p_{a1} = p_1 - p_{v1} = 14.70 - 0.10 = 14.60 \text{ psia}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.10}{14.60}\right) = 0.0043\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$h_{g@60°\text{F}} = 1087.79\frac{\text{Btu}}{\text{lbm}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}(T_1 - T_{\text{ref}}) + \omega_1 h_{g@T_1} = (0.240)(60-32) + (0.0043)(1087.79) = 11.39\frac{\text{Btu}}{\text{lbm d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.069)(519.67)}{14.60}(5.40) = 13.26\frac{\text{ft}^3}{\text{lbm d.a.}}; \left[\frac{\text{Btu}}{\text{psia}} = \frac{\text{Btu}\times\text{in}^2}{\text{lbf}} = 5.40 \text{ ft}^3\right]$$

$$\dot{m}_{a1} = \frac{\dot{V}_1}{v_1} = \frac{800}{13.26} = 60.33\frac{\text{lbm}}{\text{min}}$$

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

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@84°\text{F}} = (0.85)(0.5793) = 0.49 \text{ psia}$$

$$p_{a2} = p_2 - p_{v2} = 14.70 - 0.49 = 14.21 \text{ psia}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{0.49}{14.21}\right) = 0.0214\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$h_{g@84°\text{F}} = 1098.24\frac{\text{Btu}}{\text{lbm}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}(T_2 - T_{\text{ref}}) + \omega_2 h_{g@T_2} = (0.240)(84-32) + (0.0214)(1098.24) = 35.98\frac{\text{Btu}}{\text{lbm d.a.}}$$

$$v_2 = \frac{R_a T_2}{p_{a2}} = \frac{(0.069)(543.67)}{14.21}(5.40) = 14.26\frac{\text{ft}^3}{\text{lbm d.a.}}; \left[\frac{\text{Btu}}{\text{psia}} = \frac{\text{Btu}\times\text{in}^2}{\text{lbf}} = 5.40 \text{ ft}^3\right]$$

$$\dot{m}_{a2} = \frac{\dot{V}_2}{v_2} = \frac{200}{14.26} = 14.03\frac{\text{lbm}}{\text{min}}$$

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

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

$$\omega_3 = \frac{\dot{m}_{a1}\omega_1 + \dot{m}_{a2}\omega_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(60.33)(0.0043) + (14.03)(0.0214)}{60.33 + 14.03} = 0.0075\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$h_3 = \frac{\dot{m}_{a1}h_1 + \dot{m}_{a2}h_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(60.33)(11.39) + (14.03)(35.98)}{60.33 + 14.03} = 16.03\frac{\text{Btu}}{\text{lbm d.a.}}$$

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

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$T_3 = 64.5°\text{C}$

$\phi_3 = 59\%$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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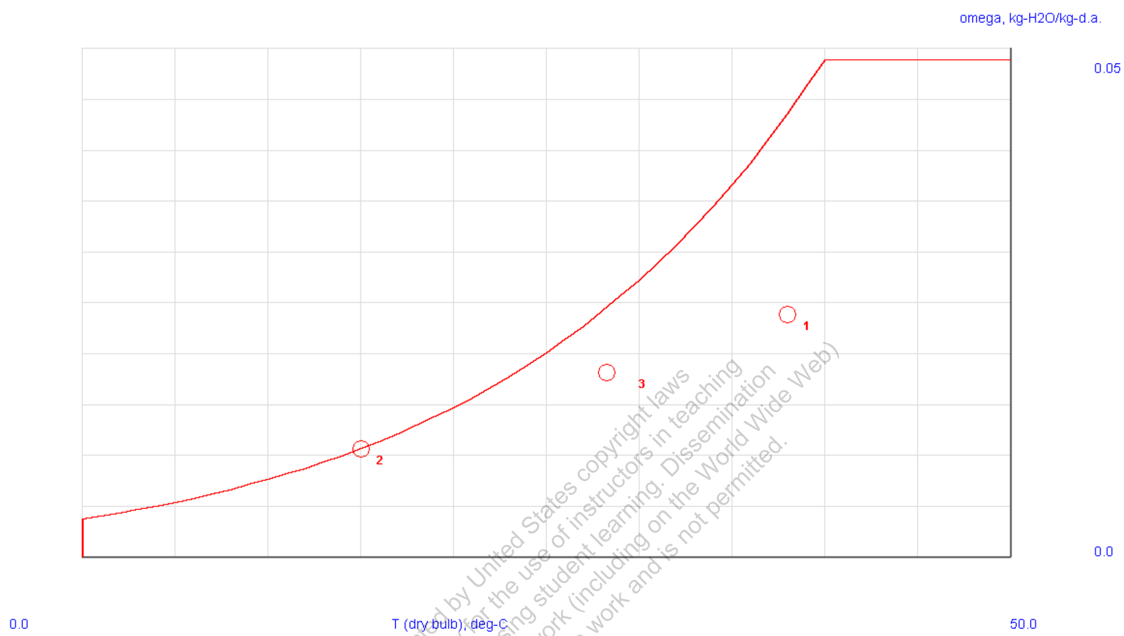
12-2-25 [OMP] A stream of warm air with a dry-bulb temperature of 38°C and wet-bulb of 30°C is mixed adiabatically with a stream of saturated cool air at 15°C. The dry mass flow rates of the warm and cool air streams are 8 kg/s and 6 kg/s, respectively. Assuming a total pressure of 1 atm, determine (a) the temperature (T), (b) the specific humidity (ω) and (c) relative humidity of the mixture.

SOLUTION



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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 $p_1, T_1, T_{\text{wb},1}, \dot{m}_{a1}$):

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

$$h_1 = 100.00 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$\omega_1 = 0.0240 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

State-2 (given $p_2, T_2, \phi_2, \dot{m}_{a2}$):

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$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@15°\text{C}} = (1)(1.7080) = 1.71 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 101.325 - 1.71 = 99.62 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{1.71}{99.62}\right) = 0.0107 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@15°\text{C}} = 2528.95 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(15) + (0.0107)(2528.95) = 42.13 \frac{\text{kJ}}{\text{kg d.a.}}$$

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

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1}$$

$$\omega_3 = \frac{\dot{m}_{a1}\omega_1 + \dot{m}_{a2}\omega_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(8)(0.0240) + (6)(0.0107)}{8+6} = 0.0183 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_3 = \frac{\dot{m}_{a1}h_1 + \dot{m}_{a2}h_2}{\dot{m}_{a1} + \dot{m}_{a2}} = \frac{(8)(100.00) + (6)(42.13)}{8+6} = 75.20 \frac{\text{kJ}}{\text{kg d.a.}}$$

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

$T_3 = 28°\text{C}$

$\phi_3 = 75\%$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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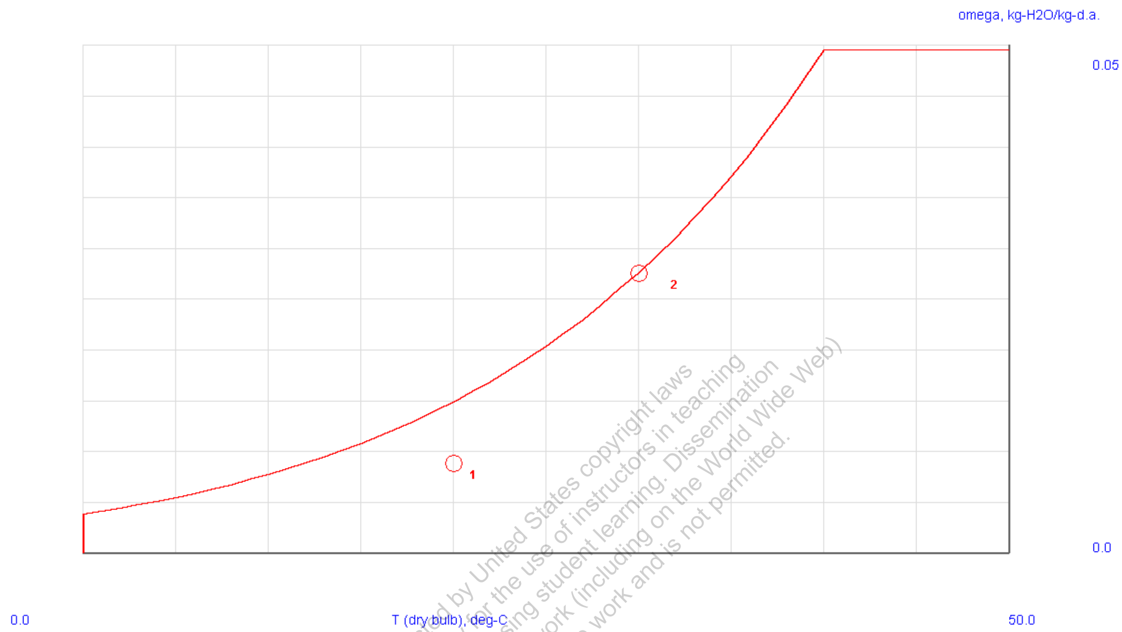
12-2-26 [OME] Cooling water leaves the condenser of a power plant and enters a wet cooling tower at 35°C at a rate of 100 kg/s. The water is cooled to 22°C in the cooling tower by air which enters the tower at 100 kPa, 20°C, 60% R.H. and leaves saturated at 30°C. Neglecting the power input to the fan, determine (a) the volume flow rate of air into the cooling tower and (b) the mass flow rate of the required makeup water.

SOLUTION



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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, ϕ_1):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat@}T_1} = \phi_1 p_{\text{sat@20°C}} = (0.60)(2.3390) = 1.40 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 100 - 1.40 = 98.60 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{1.40}{98.60}\right) = 0.0088 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

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

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(20) + (0.0088)(2538.10) = 42.44 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(293)}{98.60} = 0.8528 \frac{\text{m}^3}{\text{kg d.a.}}$$

State-2 (given p_2, T_2, ϕ_2):

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat@}T_2} = \phi_2 p_{\text{sat@30°C}} = (1)(4.2460) = 4.25 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 100 - 4.25 = 95.75 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{4.25}{95.75}\right) = 0.0276 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@30°\text{C}} = 2556.30 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(30) + (0.0276)(2556.30) = 100.70 \frac{\text{kJ}}{\text{kg d.a.}}$$

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

$$p_{\text{sat@35°C}} = 5.6190 \text{ kPa}$$

$$p_3 > p_{\text{sat@35°C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@35°\text{C}} = 146.68 \frac{\text{kJ}}{\text{kg}}; \; v_{f@35°\text{C}} = 0.001006 \frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@35°\text{C}} + p_3 v_{f@35°\text{C}} = 146.68 + (100)(0.001006) = 146.78 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, T_4$):

$$p_{\text{sat@22°C}} = 2.6445 \text{ kPa}$$

$$p_4 > p_{\text{sat@22°C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@22°\text{C}} = 92.33 \frac{\text{kJ}}{\text{kg}}; \; v_{f@22°\text{C}} = 0.001003 \frac{\text{m}^3}{\text{kg}}$$

$$h_4 = u_{f@22°\text{C}} + p_4 v_{f@22°\text{C}} = 92.33 + (100)(0.001003) = 92.43 \frac{\text{kJ}}{\text{kg}}$$

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The mass flow rate of air and the volume flow of air into the cooling tower

$$\dot{m}_a = \frac{\dot{m}_w\left(h_3 - h_4\right)}{\left(h_2 - h_1\right) - h_4\left(\omega_2 - \omega_1\right)} = \frac{(100)(146.78 - 92.43)}{(100.70 - 42.44) - (92.43)(0.0276 - 0.0088)} = 96.16\,\frac{\text{kg}}{\text{s}}$$

$$\dot{V}_1 = \dot{m}_a v_1 = (96.16)(0.8528) = 82.01\,\frac{\text{m}^3}{\text{s}}$$

The mass flow rate of makeup water

$$\dot{m}_{\text{makeup}} = \dot{m}_a\left(\omega_2 - \omega_1\right) = (96.16)(0.0276 - 0.0088) = 1.81\,\frac{\text{kg}}{\text{s}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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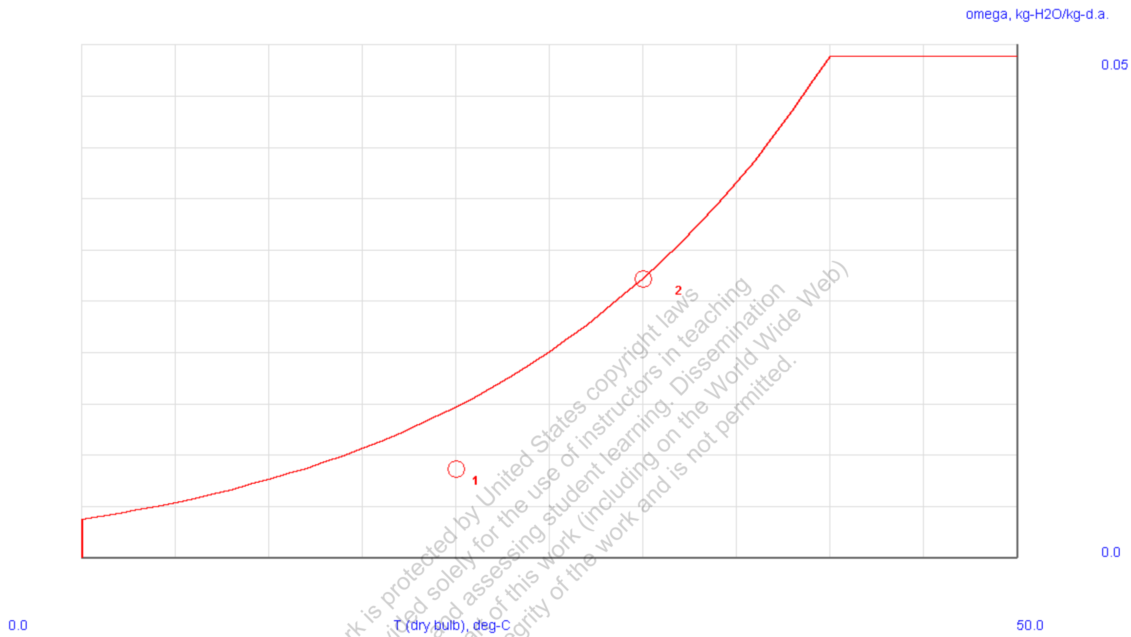
12-2-27 [OML] The cooling water from the condenser of a power plant enters a wet cooling tower at 45°C at a rate of 40 kg/s. The water is cooled to 22°C in the cooling tower by air which enters the tower at 1 atm, 20°C, 60% relative humidity and leaves saturated at 30°C. Neglecting the power input to the fan, determine (a) the volume flow rate of the air into the cooling tower and (b) the mass flow rate of the required makeup water. (c) What-if Scenario: What would the mass flow rate in (b) be if mass flow rate of water were 60 kg/s instead of 40 kg/s?

SOLUTION



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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, ϕ_1):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat@}T_1} = \phi_1 p_{\text{sat@20°C}} = (0.60)(2.3390) = 1.40 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 101.325 - 1.40 = 99.93 \text{ kPa}$$

$$\omega_1 = 0.622 \frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{1.40}{99.93}\right) = 0.0087 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

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

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa} T_1 + \omega_1 h_{g@T_1} = (1.005)(20) + (0.0087)(2538.10) = 42.18 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(293)}{99.93} = 0.8415 \frac{\text{m}^3}{\text{kg d.a.}}$$

State-2 (given p_2, T_2, ϕ_2):

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat@}T_2} = \phi_2 p_{\text{sat@30°C}} = (1)(4.2460) = 4.25 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 101.325 - 4.25 = 97.52 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{4.25}{97.52}\right) = 0.0271 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@30°\text{C}} = 2556.30 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(30) + (0.0271)(2556.30) = 99.43 \frac{\text{kJ}}{\text{kg d.a.}}$$

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

$$p_{\text{sat@45°C}} = 9.5788 \text{ kPa}$$

$$p_3 > p_{\text{sat@45°C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@45°\text{C}} = 188.45 \frac{\text{kJ}}{\text{kg}}; \; v_{f@45°\text{C}} = 0.001010 \frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@45°\text{C}} + p_3 v_{f@45°\text{C}} = 188.45 + (101.325)(0.001010) = 188.55 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, T_4$):

$$p_{\text{sat@22°C}} = 2.6445 \text{ kPa}$$

$$p_4 > p_{\text{sat@22°C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@22°\text{C}} = 92.33 \frac{\text{kJ}}{\text{kg}}; \; v_{f@22°\text{C}} = 0.001003 \frac{\text{m}^3}{\text{kg}}$$

$$h_4 = u_{f@22°\text{C}} + p_4 v_{f@22°\text{C}} = 92.33 + (101.325)(0.001003) = 92.43 \frac{\text{kJ}}{\text{kg}}$$

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The mass flow rate of air and the volume flow of air into the cooling tower

$$\dot{m}_a = \frac{\dot{m}_w \left(h_3 - h_4\right)}{\left(h_2 - h_1\right) - h_4 \left(\omega_2 - \omega_1\right)} = \frac{(40)(188.55 - 92.43)}{(99.43 - 42.18) - (92.43)(0.0271 - 0.0087)} = 69.21 \frac{\text{kg}}{\text{s}}$$

$$\dot{V}_1 = \dot{m}_a v_1 = (69.21)(0.8415) = 58.22 \frac{\text{m}^3}{\text{s}}$$

The mass flow rate of makeup water

$$\dot{m}_{\text{makeup}} = \dot{m}_a \left(\omega_2 - \omega_1\right) = (69.21)(0.0271 - 0.0087) = 1.27 \frac{\text{kg}}{\text{s}}$$

TEST Solution and What-if Scenario Use the HVAC/Psychrometry open steady-state 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.

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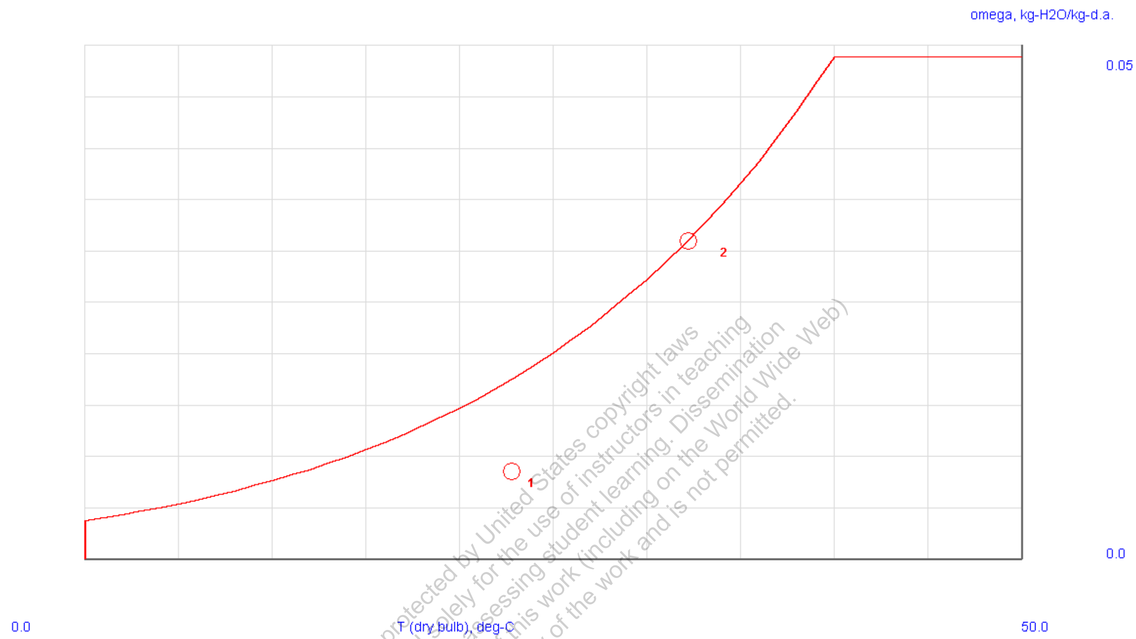
12-2-28 [OMG] The cooling water from the condenser of a power plant enters a wet cooling tower at 105°F at a rate of 90 lbm/s. The water is cooled to 85°F in the cooling tower by air which enters the tower at 1 atm, 73°F, 50% relative humidity and leaves saturated at 90°F. Neglecting the power input to the fan, determine (a) the volume flow rate of the air into the cooling tower and (b) the mass flow rate of the required makeup water.

SOLUTION



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Given:

$$c_{pa} = 0.240 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

$$R_a = 0.069 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}}$$

State-1 (given p_1, T_1, ϕ_1):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat@}T_1} = \phi_1 p_{\text{sat@73°F}} = (0.50)(0.4014) = 0.20 \text{ psia}$$

$$p_{a1} = p_1 - p_{v1} = 14.70 - 0.20 = 14.50 \text{ psia}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{0.20}{14.50}\right) = 0.0086\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$h_{g\text{@73°F}} = 1093.46\frac{\text{Btu}}{\text{lbm}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}(T_1 - T_{\text{ref}}) + \omega_1 h_{g@T_1} = (0.240)(73-32) + (0.0086)(1093.46) = 19.24\frac{\text{Btu}}{\text{lbm d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.069)(532.67)}{14.50}(5.40) = 13.69\frac{\text{ft}^3}{\text{lbm d.a.}}; \left[\frac{\text{Btu}}{\text{psia}} = \frac{\text{Btu}\times\text{in}^2}{\text{lbf}} = 5.40 \text{ ft}^3\right]$$

State-2 (given p_2, T_2, ϕ_2):

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat@}T_2} = \phi_2 p_{\text{sat@90°F}} = (1)(0.6992) = 0.70 \text{ psia}$$

$$p_{a2} = p_2 - p_{v2} = 14.70 - 0.70 = 14.00 \text{ psia}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{0.70}{14.00}\right) = 0.0311\frac{\text{lbm H}_2\text{O}}{\text{lbm d.a.}}$$

$$h_{g\text{@90°F}} = 1100.83\frac{\text{Btu}}{\text{lbm}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}(T_2 - T_{\text{ref}}) + \omega_2 h_{g@T_2} = (0.240)(90-32) + (0.0311)(1100.83) = 48.16\frac{\text{Btu}}{\text{lbm d.a.}}$$

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

$$p_{\text{sat@105°F}} = 1.1019 \text{ psia}$$

$$p_3 > p_{\text{sat@105°F}} \;\therefore\; \text{subcooled liquid}$$

$$u_{f\text{@105°F}} = 73.05\frac{\text{Btu}}{\text{lbm}};\; v_{f\text{@105°F}} = 0.01614\frac{\text{ft}^3}{\text{lbm}}$$

$$h_3 = u_{f\text{@105°F}} + p_3 v_{f\text{@105°F}} = 73.05 + (14.70)\left(\frac{0.01614}{5.40}\right) = 73.09\frac{\text{Btu}}{\text{lbm}}$$

State-4 (given $p_4 = p_1, T_4$):

$$p_{\text{sat@85°F}} = 0.5950 \text{ psia}$$

$$p_4 > p_{\text{sat@85°F}} \;\therefore\; \text{subcooled liquid}$$

$$u_{f\text{@85°F}} = 53.09\frac{\text{Btu}}{\text{lbm}};\; v_{f\text{@85°F}} = 0.01608\frac{\text{ft}^3}{\text{lbm}}$$

$$h_4 = u_{f\text{@85°F}} + p_4 v_{f\text{@85°F}} = 53.09 + (14.70)\left(\frac{0.01608}{5.40}\right) = 53.13\frac{\text{Btu}}{\text{lbm}}$$

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The mass flow rate of air and the volume flow of air into the cooling tower

$$\dot{m}_a = \frac{\dot{m}_w\left(h_3 - h_4\right)}{\left(h_2 - h_1\right) - h_4\left(\omega_2 - \omega_1\right)} = \frac{(90)(73.09 - 53.13)}{(48.16 - 19.24) - (53.13)(0.0311 - 0.0086)} = 64.79\,\frac{\text{lbm}}{\text{s}}$$

$$\dot{V}_1 = \dot{m}_a v_1 = (64.79)(13.69) = 886.98\,\frac{\text{ft}^3}{\text{s}}$$

The mass flow rate of makeup water

$$\dot{m}_{\text{makeup}} = \dot{m}_a\left(\omega_2 - \omega_1\right) = (64.79)(0.0311 - 0.0086) = 1.46\,\frac{\text{lbm}}{\text{s}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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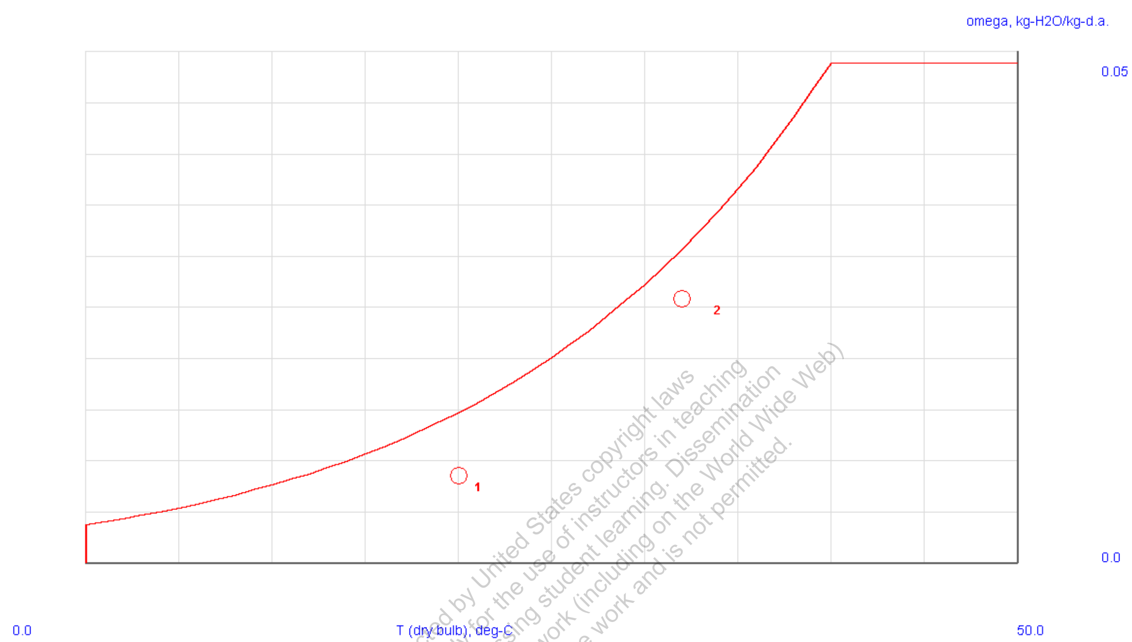
12-2-29 [OMZ] A wet cooling tower is to cool 50 kg/s of water from 38°C to 24°C. Atmospheric air enters the tower at 1 atm with dry and wet-bulb temperatures of 20°C and 15°C, respectively, and leaves at 32°C with a relative humidity of 85%. Determine (a) the volume flow rate of air into the cooling tower and (b) the mass flow rate of the required makeup water.

SOLUTION



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Given:

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

State-1 (given $p_1, T_1, T_{\text{wb},1}$):

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

$$h_1 = 42.00 \frac{\text{kJ}}{\text{kg d.a.}}$$

$$\omega_1 = 0.0087 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$v_1 = 0.8420 \frac{\text{m}^3}{\text{kg d.a.}}$$

State-2 (given p_2, T_2, ϕ_2):

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$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@32°\text{C}} = (0.85)(4.7581) = 4.04 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 101.325 - 4.04 = 97.29 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{4.04}{97.29}\right) = 0.0258 \frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@32°\text{C}} = 2559.90 \frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa} T_2 + \omega_2 h_{g@T_2} = (1.005)(32) + (0.0258)(2559.90) = 98.21 \frac{\text{kJ}}{\text{kg d.a.}}$$

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

$$p_{\text{sat}@38°\text{C}} = 6.6320 \text{ kPa}$$

$$p_3 > p_{\text{sat}@38°\text{C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@38°\text{C}} = 159.21 \frac{\text{kJ}}{\text{kg}}; \quad v_{f@38°\text{C}} = 0.001007 \frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@38°\text{C}} + p_3 v_{f@38°\text{C}} = 159.21 + (101.325)(0.001007) = 159.31 \frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, T_4$):

$$p_{\text{sat}@24°\text{C}} = 2.9850 \text{ kPa}$$

$$p_4 > p_{\text{sat}@24°\text{C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@24°\text{C}} = 100.70 \frac{\text{kJ}}{\text{kg}}; \quad v_{f@24°\text{C}} = 0.001003 \frac{\text{m}^3}{\text{kg}}$$

$$h_4 = u_{f@24°\text{C}} + p_4 v_{f@24°\text{C}} = 100.70 + (101.325)(0.001003) = 100.80 \frac{\text{kJ}}{\text{kg}}$$

The mass flow rate of air and the volume flow of air into the cooling tower

$$\dot{m}_a = \frac{\dot{m}_w (h_3 - h_4)}{(h_2 - h_1) - h_4(\omega_2 - \omega_1)} = \frac{(50)(159.31 - 100.80)}{(98.21 - 42.00) - (100.80)(0.0258 - 0.0087)} = 53.69 \frac{\text{kg}}{\text{s}}$$

$$\dot{V}_1 = \dot{m}_a v_1 = (53.69)(0.8420) = 45.21 \frac{\text{m}^3}{\text{s}}$$

The mass flow rate of makeup water

$$\dot{m}_{\text{makeup}} = \dot{m}_a (\omega_2 - \omega_1) = (53.69)(0.0258 - 0.0087) = 0.92 \frac{\text{kg}}{\text{s}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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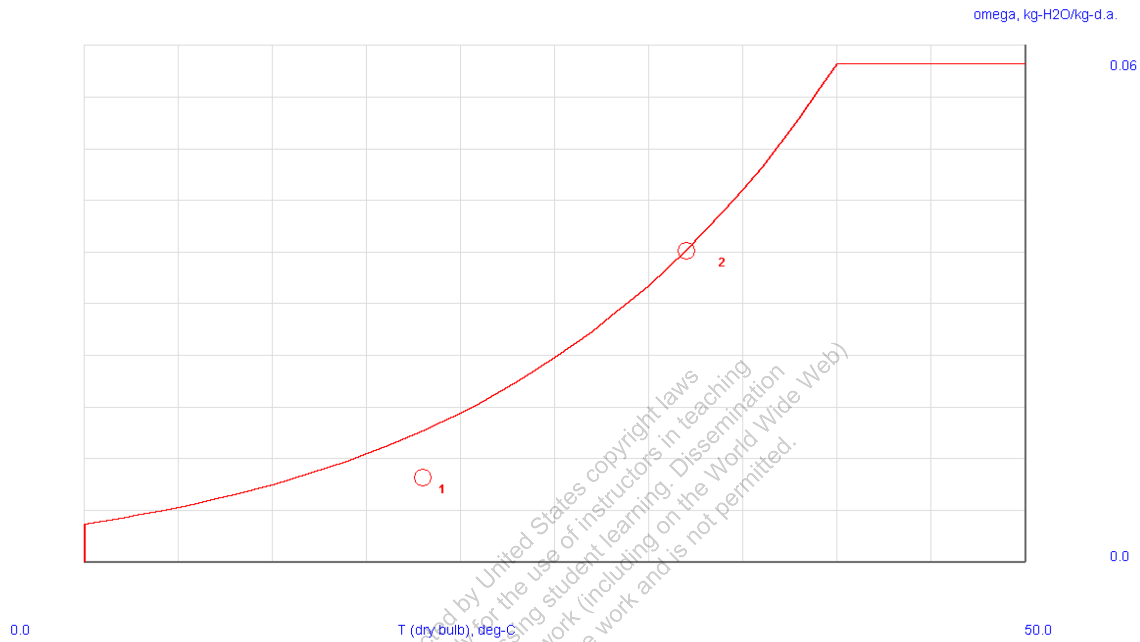
12-2-30 [OMK] A wet cooling tower is to cool 100 kg/s of cooling water from 45°C to 24°C at a location where the atmospheric pressure is 94 kPa. Atmospheric air enters the tower at 18°C and 65% relative humidity and leaves saturated at 32°C. Neglecting the power input to the fan, determine (a) the volume flow rate of air into the cooling tower and (b) the mass flow rate of the required makeup water.

SOLUTION



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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, ϕ_1):

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$$p_{v1} = \phi_1 p_{g1} = \phi_1 p_{\text{sat}@T_1} = \phi_1 p_{\text{sat}@18°\text{C}} = (0.65)(2.0639) = 1.34 \text{ kPa}$$

$$p_{a1} = p_1 - p_{v1} = 94 - 1.34 = 92.66 \text{ kPa}$$

$$\omega_1 = 0.622\frac{p_{v1}}{p_{a1}} = (0.622)\left(\frac{1.34}{92.66}\right) = 0.0090\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@18°\text{C}} = 2534.45\frac{\text{kJ}}{\text{kg}}$$

$$h_1 = h_a + \omega_1 h_{g@T_1} = c_{pa}T_1 + \omega_1 h_{g@T_1} = (1.005)(18) + (0.0090)(2534.45) = 40.90\frac{\text{kJ}}{\text{kg d.a.}}$$

$$v_1 = \frac{R_a T_1}{p_{a1}} = \frac{(0.287)(291)}{92.66} = 0.9013\frac{\text{m}^3}{\text{kg d.a.}}$$

State-2 (given p_2, T_2, ϕ_2):

$$p_{v2} = \phi_2 p_{g2} = \phi_2 p_{\text{sat}@T_2} = \phi_2 p_{\text{sat}@32°\text{C}} = (1)(4.7581) = 4.76 \text{ kPa}$$

$$p_{a2} = p_2 - p_{v2} = 94 - 4.76 = 89.24 \text{ kPa}$$

$$\omega_2 = 0.622\frac{p_{v2}}{p_{a2}} = (0.622)\left(\frac{4.76}{89.24}\right) = 0.0332\frac{\text{kg H}_2\text{O}}{\text{kg d.a.}}$$

$$h_{g@30°\text{C}} = 2559.90\frac{\text{kJ}}{\text{kg}}$$

$$h_2 = h_a + \omega_2 h_{g@T_2} = c_{pa}T_2 + \omega_2 h_{g@T_2} = (1.005)(32) + (0.0332)(2559.90) = 117.15\frac{\text{kJ}}{\text{kg d.a.}}$$

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

$$p_{\text{sat}@45°\text{C}} = 9.5788 \text{ kPa}$$

$$p_3 > p_{\text{sat}@45°\text{C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@45°\text{C}} = 188.45\frac{\text{kJ}}{\text{kg}};\ v_{f@45°\text{C}} = 0.001010\frac{\text{m}^3}{\text{kg}}$$

$$h_3 = u_{f@45°\text{C}} + p_3 v_{f@45°\text{C}} = 188.45 + (94)(0.001010) = 188.54\frac{\text{kJ}}{\text{kg}}$$

State-4 (given $p_4 = p_1, T_4$):

$$p_{\text{sat}@24°\text{C}} = 2.9850 \text{ kPa}$$

$$p_4 > p_{\text{sat}@24°\text{C}} \quad \therefore \text{ subcooled liquid}$$

$$u_{f@24°\text{C}} = 100.70\frac{\text{kJ}}{\text{kg}};\ v_{f@24°\text{C}} = 0.001003\frac{\text{m}^3}{\text{kg}}$$

$$h_4 = u_{f@24°\text{C}} + p_4 v_{f@24°\text{C}} = 100.70 + (94)(0.001003) = 100.79\frac{\text{kJ}}{\text{kg}}$$

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The mass flow rate of air and the volume flow of air into the cooling tower

$$\dot{m}_a = \frac{\dot{m}_w\left(h_3 - h_4\right)}{\left(h_2 - h_1\right) - h_4\left(\omega_2 - \omega_1\right)} = \frac{(100)(188.54 - 100.79)}{(117.15 - 40.90) - (100.79)(0.0332 - 0.0090)} = 118.88\,\frac{\text{kg}}{\text{s}}$$

$$\dot{V}_1 = \dot{m}_a v_1 = (118.88)(0.9013) = 107.15\,\frac{\text{m}^3}{\text{s}}$$

The mass flow rate of makeup water

$$\dot{m}_{\text{makeup}} = \dot{m}_a\left(\omega_2 - \omega_1\right) = (118.88)(0.0332 - 0.0090) = 2.88\,\frac{\text{kg}}{\text{s}}$$

TEST Solution Use the HVAC/Psychrometry open steady-state 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.

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