SECTION 13

Humidification and Water Cooling

PROBLEM 13.1

In a process in which benzene is used as a solvent, it is evaporated into dry nitrogen. The resulting mixture at a temperature of 297 K and a pressure of 101.3 kN/m^2 has a relative humidity of 60%. It is required to recover 80% of the benzene present by cooling to 283 K and compressing to a suitable pressure. What must this pressure be? Vapour pressures of benzene: at 297 K = 12.2 kN/m^2: at 283 K = 6.0 kN/m^2.

Solution

See Volume 1, Example 13.1

PROBLEM 13.2

0.6 m^3/s of gas is to be dried from a dew point of 294 K to a dew point of 277.5 K. How much water must be removed and what will be the volume of the gas after drying? Vapour pressure of water at 294 K = 2.5 kN/m^2. Vapour pressure of water at 277.5 K = 0.85 kN/m^2.

Solution

When the gas is cooled to 294 K, it will be saturated and $P_{w0} = 2.5$ kN/m^2.

From Section 13.2:

$$\text{mass of vapour} = P_{w0}M_w/\mathbf{R}T = (2.5 \times 18)/(8.314 \times 294) = 0.0184 \text{ kg/m}^3 \text{ gas.}$$

When water has been removed, the gas will be saturated at 277.5 K, and $P_w = 0.85$ kN/m^2.

At this stage, mass of vapour = $(0.85 \times 18)/(8.314 \times 277.5) = 0.0066$ kg/m^3 gas

Hence, water to be removed = $(0.0184 - 0.0066) = 0.0118$ kg/m^3 gas

or: $$(0.0118 \times 0.6) = \underline{\underline{0.00708 \text{ kg/s}}}$$

Assuming the gas flow, 0.6 m^3/s, is referred to 273 K and 101.3 kN/m^2, 0.00708 kg/s of water is equivalent to $(0.00708/18) = 3.933 \times 10^{-4}$ kmol/s.

1 kmol of vapour occupies 22.4 m^3 at STP,

and: volume of water removed $= (3.933 \times 10^{-4} \times 22.4) = 0.00881\ m^3/s$

Assuming no volume change on mixing, the gas flow after drying

$$= (0.60 - 0.00881) = \underline{\underline{0.591\ m^3/s \text{ at STP}}}.$$

PROBLEM 13.3

Wet material, containing 70% moisture on a wet basis, is to be dried at the rate of 0.15 kg/s in a counter-current dryer to give a product containing 5% moisture (both on a wet basis). The drying medium consists of air heated to 373 K and containing water vapour with a partial pressure of 1.0 kN/m^2. The air leaves the dryer at 313 K and 70% saturated. Calculate how much air will be required to remove the moisture. The vapour pressure of water at 313 K may be taken as 7.4 kN/m^2.

Solution

The feed is 0.15 kg/s wet material containing 0.70 kg water/kg feed.

Thus water in feed $= (0.15 \times 0.70) = 0.105$ kg/s and dry solids $= (0.15 - 0.105) = 0.045$ kg/s.

The product contains 0.05 kg water/kg product. Thus, if w kg/s is the amount of water in the product, then:

$$w/(w + 0.045) = 0.05 \text{ or } w = 0.00237 \text{ kg/s}$$

and: water to be removed $= (0.105 - 0.00237) = 0.1026$ kg/s.

The inlet air is at 373 K and the partial pressure of the water vapour is 1 kN/m^2.

Assuming a total pressure of 101.3 kN/m^2, the humidity is:

$$\mathscr{H}_1 = [P_w/(P - P_w)](M_w/M_A) \qquad \text{(equation 13.1)}$$

$$= [1.0/(101.3 - 1.0)](18/29) = 0.0062 \text{ kg/kg dry air}$$

The outlet air is at 313 K and is 70% saturated. Thus, as in Example 13.1, Volume 1:

$$P_w = P_{w0} \times RH/100 = (7.4 \times 70/100) = 5.18 \text{ kN/m}^2$$

and: $\mathscr{H}_2 = [5.18/(101.3 - 5.18)](18/29) = 0.0335$ kg/kg dry air

The increase in humidity is $(0.0335 - 0.0062) = 0.0273$ kg/kg dry air and this must correspond to the water removed, 0.1026 kg/s. Thus if G kg/s is the mass flowrate of dry air, then:

$$0.0273G = 0.1026 \quad \text{and} \quad G = 3.76 \text{ kg/s dry air}$$

In the inlet air, this is associated with 0.0062 kg water vapour, or:

$$(0.0062 \times 3.76) = 0.0233 \text{ kg/s}$$

Hence, the mass of moist air required at the inlet conditions

$$= (3.76 + 0.0233) = \underline{\underline{3.783 \text{ kg/s}}}$$

PROBLEM 13.4

30,000 m^3 of cool gas (measured at 289 K and 101.3 kN/m^2 saturated with water vapour) is compressed to 340 kN/m^2 pressure, cooled to 289 K and the condensed water is drained off. Subsequently the pressure is reduced to 170 kN/m^3 and the gas is distributed at this pressure and 289 K. What is the percentage humidity after this treatment? The vapour pressure of water at 289 K is 1.8 kN/m^2.

Solution

At 289 K and 101.3 kN/m^2, the gas is saturated and $P_{w0} = 1.8$ kN/m^2.

Thus from equation 13.2, $\mathscr{H}_0 = [1.8/(101.3 - 1.8)](18/M_A) = (0.3256/M_A)$ kg/kg dry gas, where M_A is the molecular mass of the gas.

At 289 K and 340 kN/m^2, the gas is in contact with condensed water and therefore still saturated. Thus $P_{w0} = 1.8$ kN/m^2 and:

$$\mathscr{H}_0 = [1.8/(340 - 1.8)](18/M_A) = (0.0958/M_A) \text{ kg/kg dry gas}$$

At 289 K and 170 kN/m^2, the humidity is the same, and in equation 13.2:

$$(0.0958/M_A) = [P_w/(170 - P_w)](18/M_A)$$

or:

$$P_w = 0.90 \text{ kN/m}^2$$

The percentage humidity is then:

$$= [(P - P_{w0})/(P - P_w)](100P_w/P_{w0}) \quad \text{(equation 13.3)}$$

$$= [(170 - 1.8)/(170 - 0.90)](100 \times 0.90/1.8) = \underline{\underline{49.73\%}}$$

PROBLEM 13.5

A rotary countercurrent dryer is fed with ammonium nitrate containing 5% moisture at the rate of 1.5 kg/s, and discharges the nitrate with 0.2% moisture. The air enters at 405 K and leaves at 355 K; the humidity of the entering air being 0.007 kg moisture/kg dry air. The nitrate enters at 294 K and leaves at 339 K.

Neglecting radiation losses, calculate the mass of dry air passing through the dryer and the humidity of the air leaving the dryer. Latent heat of water at 294 K = 2450 kJ/kg. Specific heat capacity of ammonium nitrate = 1.88 kJ/kg K. Specific heat capacity of dry air = 0.99 kJ/kg K. Specific heat capacity of water vapour = 2.01 kJ/kg K.

Solution

The feed rate of wet nitrate is 1.5 kg/s containing 5.0% moisture or $(1.5 \times 5/100) = 0.075$ kg/s water.

$$\therefore \qquad \text{flow of dry solids} = (1.5 - 0.075) = 1.425 \text{ kg/s}$$

If the product contains w kg/s water, then:

$$w/(w + 1.425) = (0.2/100) \quad \text{or} \quad w = 0.00286 \text{ kg/s}$$

and: $$\text{the water evaporated} = (0.075 - 0.00286) = 0.07215 \text{ kg/s}$$

The problem now consists of an enthalpy balance around the unit, and for this purpose a datum temperature of 294 K will be chosen. It will be assumed that the flow of dry air into the unit is m kg/s.

Considering the inlet streams:

(i) Nitrate: this enters at the datum of 294 K and hence the enthalpy = 0.
(ii) Air: G kg/s of dry air is associated with 0.007 kg moisture/kg dry air.

$$\therefore \qquad \text{enthalpy} = [(G \times 0.99) + (0.007G \times 2.01)](405 - 294) = 111.5G \text{ kW}$$

and the total heat into the system = $111.5G$ kW.

Considering the outlet streams:

(i) Nitrate: 1.425 kg/s dry nitrate contains 0.00286 kg/s water and leaves the unit at 339 K.

$$\therefore \qquad \text{enthalpy} = [(1.425 \times 1.88) + (0.00286 \times 4.18)](339 - 294) = 120.7 \text{ kW}$$

(ii) Air: the air leaving contains 0.007 G kg/s water from the inlet air plus the water evaporated. It will be assumed that evaporation takes place at 294 K.

Thus:

enthalpy of dry air = $G \times 0.99(355 - 294) = 60.4G$ kW
enthalpy of water from inlet air = $0.007G \times 2.01(355 - 294) = 0.86G$ kW
enthalpy in the evaporated water = $0.07215[2450 + 2.01(355 - 294)] = 185.6$ kW

and the total heat out of the system, neglecting losses = $(306.3 + 61.3G)$ kW.

Making a balance:

$$111.5G = (306.3 + 61.3G) \quad \text{or} \quad G = 6.10 \text{ kg/s dry air}$$

Thus, including the moisture in the inlet air, moist air fed to the dryer is:

$$6.10(1 + 0.007) = \underline{\underline{6.15 \text{ kg/s}}}$$

Water entering with the air = $(6.10 \times 0.007) = 0.0427$ kg/s.
Water evaporated = 0.07215 kg/s.
Water leaving with the air = $(0.0427 + 0.07215) = 0.1149$ kg/s
Humidity of outlet air = $(0.1149/6.10) = \underline{\underline{0.0188 \text{ kg/kg dry air}}}$.

PROBLEM 13.6

Material is fed to a dryer at the rate of 0.3 kg/s and the moisture removed is 35% of the wet charge. The stock enters and leaves the dryer at 324 K. The air temperature falls from 341 K to 310 K, its humidity rising from 0.01 to 0.02 kg/kg. Calculate the heat loss to the surroundings. Latent heat of water at 324 K = 2430 kJ/kg. Specific heat capacity of dry air = 0.99 kJ/kg K. Specific heat capacity of water vapour = 2.01 kJ/kg K.

Solution

The wet feed is 0.3 kg/s and the water removed is 35%, or: $(0.3 \times 35/100) = 0.105$ kg/s

If the flowrate of dry air is G kg/s, the increase in humidity = $(0.02 - 0.01) =$ 0.01 kg/kg

or: $$0.01G = 0.105 \quad \text{and} \quad G = 10.5 \text{ kg/s}$$

This completes the mass balance, and the next step is to make an enthalpy balance along the lines of Problem 13.5. As the stock enters and leaves at 324 K, no heat is transferred from the air and the heat lost by the air must represent the heat used for evaporation plus the heat losses, say L kW.

Thus heat lost by the inlet air and associated moisture is:

$$[(10.5 \times 0.99) + (0.01 \times 10.5 \times 2.01)](341 - 310) = 328.8 \text{ kW}$$

Heat leaving in the evaporated water = $0.105[2430 + 2.01(310 - 324)] = 252.2$ kW.

Making a balance:

$$328.8 = (252.2 + L) \quad \text{or} \quad \underline{\underline{L = 76.6 \text{ kW}}}$$

PROBLEM 13.7

A rotary dryer is fed with sand at the rate of 1 kg/s. The feed is 50% wet and the sand is discharged with 3% moisture. The entering air is at 380 K and has an absolute humidity of 0.007 kg/kg. The wet sand enters at 294 K and leaves at 309 K and the air leaves at 310 K. Calculate the mass flowrate of air passing through the dryer and the humidity of the air leaving the dryer. Allow for a radiation loss of 25 kJ/kg dry air. Latent heat of water at 294 K = 2450 kJ/kg. Specific heat capacity of sand = 0.88 kJ/kg K. Specific heat capacity of dry air = 0.99 kJ/kg k. Specific heat capacity of vapour = 2.01 kg K.

Solution

The feed rate of wet sand is 1 kg/s and it contains 50% moisture or $(1.0 \times 50/100) =$ 0.50 kg/s water.

$$\therefore \quad \text{flow of dry sand} = (1.0 - 0.5) = 0.50 \text{ kg/s}$$

If the dried sand contains w kg/s water, then:

$$w/(w + 0.50) = (3.0/100) \text{ or } w = 0.0155 \text{ kg/s}$$

and: the water evaporated $= (0.50 - 0.0155) = 0.4845$ kg/s.

Assuming a flowrate of G kg/s dry air, then a heat balance may be made based on a datum temperature of 294 K.

Inlet streams:

(i) Sand: this enters at 294 K and hence the enthalpy = 0.
(ii) Air: G kg/s of dry air is associated with 0.007 kg/kg moisture.

$$\therefore \quad \text{enthalpy} = [(G \times 0.99) + (0.007G \times 2.01)](380 - 294) = 86.4G \text{ kW}$$

and: the total heat into the system $= 86.4G$ kW.

Outlet streams:

(i) Sand: 0.50 kg/s dry sand contains 0.0155 kg/s water and leaves the unit at 309 K.

$$\therefore \quad \text{enthalpy} = [(0.5 \times 0.88) + (0.0155 \times 4.18)](309 - 294) = 7.6 \text{ kW}$$

(ii) Air: the air leaving contains 0.07 G kg/s water from the inlet air plus the water evaporated. It will be assumed that evaporation takes place at 294 K. Thus:
enthalpy of dry air $= G \times 0.99(310 - 294) = 15.8m$ kW
enthalpy of water from inlet air $= 0.007G \times 2.01(310 - 294) = 0.23G$ kW
enthalpy in the evaporated water $= 0.4845[2430 + 2.01(310 - 294)] = 1192.9$ kW, a total of $(16.03G + 1192.9)$ kW

(iii) Radiation losses = 25 kJ/kg dry air or $25G$ kW and the total heat out $= (41.03G +$ 1200.5) kW.

Mass balance:

$$86.4G = (41.03G + 1200.5) \text{ or } G = 26.5 \text{ kg/s}$$

Thus the flow of dry air through the dryer = <u>26.5 kg/s</u>

and the flow of inlet air $= (26.5 \times 1.007) =$ <u>26.7 kg/s</u>

As in Problem 13.5, water leaving with the air is: $(26.5 \times 0.007) + 0.4845 = 0.67$ kg/s and humidity of the outlet air $= (0.67/26.5) =$ <u>0.025 kg/kg</u>.

PROBLEM 13.8

Water is to be cooled in a packed tower from 330 to 295 K by means of air flowing countercurrently. The liquid flows at the rate of 275 cm^3/m^2 s and the air at 0.7 m^3/m^2 s. The entering air has a temperature of 295 K and a humidity of 20%. Calculate the required height of tower and the condition of the air leaving at the top.

The whole of the resistance to heat and mass transfer can be considered as being within the gas phase and the product of the mass transfer coefficient and the transfer surface per unit volume of column ($h_D a$) may be taken as 0.2 s^{-1}.

Solution

Assuming, the latent heat of water at 273 K	= 2495 kJ/kg
specific heat capacity of dry air	= 1.003 kJ/kg K
specific heat capacity of water vapour	= 2.006 kJ/kg K

then the enthalpy of the inlet air stream is:

$$H_{G1} = 1.003(295 - 273) + \mathscr{H}(2495 + 2.006(295 - 273))$$

From Fig. 13.4, when $\theta = 295$ K, at 20% humidity, $\mathscr{H} = 0.003$ kg/kg, and:

$$H_{G1} = (1.003 \times 22) + 0.003(2495 + (2.006 \times 22)) = 29.68 \text{ kJ/kg}$$

In the inlet air, the humidity is 0.003 kg/kg dry air or $(0.003/18)/(1/29) =$ 0.005 kmol/kmol dry air.

Hence the flow of dry air $= (1 - 0.005)0.70 = 0.697$ m^3/m^2 s.

Density of air at 295 K $= (29/22.4)(273/295) = 1.198$ kg/m^3.

and hence the mass flow of dry air $= (0.697 \times 1.198) = 0.835$ kg/m^2 s

and the mass flow of water $= 275 \times 10^{-6}$ m^3/m^2 s or $(275 \times 10^{-6} \times 1000) =$ 0.275 kg/m^2 s.

The slope of the operating line, given by equation 13.37 is:

$$LC_L/G = (0.275 \times 4.18/0.835) = 1.38$$

The coordinates of the bottom of the operating line are:

$$\theta_{L1} = 295 \text{ K and } H_{G1} = 29.7 \text{ kJ/kg}$$

Hence, on an enthalpy–temperature diagram (Fig. 13a), the operating line of slope 1.38 is drawn through the point (29.7, 295).

The top point of the operating line is given by $\theta_{L2} = 330$ K, and from Fig. 13a, $H_{G2} =$ 78.5 kJ/kg.

From Figs 13.4 and 13.5 the curve representing the enthalpy of saturated air as a function of temperature is obtained and drawn in. This plot may also be obtained by calculation using equation 13.60.

The integral:

$$\int \mathrm{d}H_G/(H_f - H_G)$$

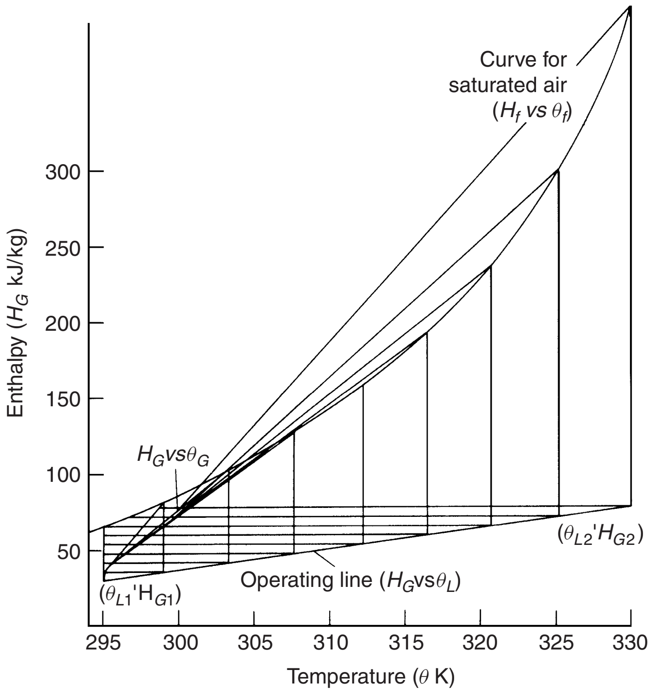

Figure 13a.

is now evaluated between the limits $H_{G1} = 29.68$ kJ/kg and $H_{G2} = 78.5$ kJ/kg, as follows:

H_G	θ	H_f	$(H_f - H_G)$	$1/(H_f - H_G)$
29.7	295	65	35.3	0.0283
40	302	98	58	0.0173
50	309	137	87	0.0115
60	316	190	130	0.0077
70	323	265	195	0.0051
78.5	330	408	329.5	0.0030

From a plot of $1/(H_f - H_G)$ and H_G the area under the curve is 0.573.
Thus:

$$\text{height of packing, } z = \int_{H_{G1}}^{H_{G2}} [\mathrm{d}H_G/(H_f - H_G)]G/h_D a\rho \quad \text{(equation 13.53)}$$

$$= (0.573 \times 0.835)/(0.2 \times 1.198)$$

$$= 1.997, \text{ say } \underline{\underline{2.0 \text{ m}}}$$

In Fig. 13a, a plot of H_G and θ_G is obtained using the construction given in Section 13.6.3. and shown in Fig. 13.16. From this plot, the value of θ_{G2} corresponding to $H_{G2} = 78.5$ kJ/kg is 300 K. From Fig. 13.5 the exit air therefore has a humidity of 0.02 kg/kg which from Fig. 13.4 corresponds to a percentage humidity of $\underline{\underline{90\%}}$.

PROBLEM 13.9

Water is to be cooled in a small packed column from 330 to 285 K by means of air flowing countercurrently. The rate of flow of liquid is 1400 cm^3/m^2s and the flowrate of the air, which enters at 295 K with a humidity of 60% is 3.0 m^3/m^2s. Calculate the required height of tower if the whole of the resistance to heat and mass transfer can be considered as being in the gas phase and the product of the mass transfer coefficient and the transfer surface per unit volume of column is 2 s^{-1}. What is the condition of the air which leaves at the top?

Solution

As in Problem 13.8, assuming the relevant latent and specific heat capacities:

$$H_{G1} = 1.003(295 - 273) + \mathscr{H}(2495 + 2.006(295 - 273))$$

From Fig. 13.4, at $\theta = 295$ and 60% humidity, $\mathscr{H} = 0.010$ kg/kg and hence:

$$H_{G1} = (1.003 \times 22) + 0.010(2495 + 44.13) = 47.46 \text{ kJ/kg}$$

In the inlet air, water vapour $= 0.010$ kg/kg dry air or $(0.010/18)/(1/29) = 0.016$ kmol/kmol dry air.

Thus the flow of dry air $= (1 - 0.016)3.0 = 2.952$ m^3/m^2s.

Density of air at 295 K $= (29/22.4)(273/293) = 1.198$ kg/m^3.

and mass flow of dry air $= (1.198 \times 2.952) = 3.537$ kg/m^2s.

Liquid flow $= 1.4 \times 10^{-3}$ m^3/m^2s

and mass flow of liquid $= (1.4 \times 10^{-3} \times 1000) = 1.4$ kg/m^2s.

The slope of the operating line is thus: $LC_L/G = (1.40 \times 4.18)/3.537 = 1.66$ and the coordinates of the bottom of the line are:

$$\theta_{L1} = 285 \text{ K}, \quad H_{G1} = 47.46 \text{ kJ/kg}$$

From these data, the operating line may be drawn in as shown in Fig. 13b and the top point of the operating line is:

$$\theta_{L2} = 330 \text{ K}, \quad H_{G2} = 122 \text{ kJ/kg}$$

Again as in Problem 13.8, the relation between enthalpy and temperature at the interface H_f vs. θ_f is drawn in Fig. 13b. It is seen that the operating line cuts the saturation curve, which is clearly an impossible situation and, indeed, it is not possible to cool the water to 285 K under these conditions. As discussed in Section 13.6.1, with mechanical draught towers, it is possible, at the best, to cool the water to within, say, 1 deg K of the wet

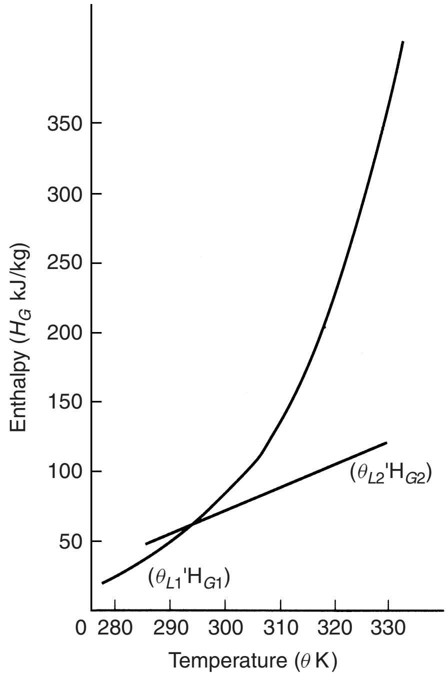

Figure 13b.

bulb temperature. From Fig. 13.4, at 295 K and 60% humidity, the wet-bulb temperature of the inlet air is 290 K and at the best water might be cooled to 291 K. In the present case, therefore, 291 K will be chosen as the water outlet temperature.

Thus an operating line of slope: $LC_L/G = 1.66$ and bottom coordinates: $\theta_{L1} = 291$ K and $H_{G1} = 47.5$ kJ/kg is drawn as shown in Fig. 13c. At the top of the operating line:

$$\theta_{L2} = 330 \text{ K and } H_{G2} = 112.5 \text{ kJ/kg}$$

As an alternative to the method used in Problem 13.8, the approximate method of Carey and Williamson (equation 13.54) is adopted.

At the bottom of the column:

$$H_{G1} = 47.5 \text{ kJ/kg}, \quad H_{f1} = 52.0 \text{ kJ/kg} \quad \therefore \Delta H_1 = 4.5 \text{ kJ/kg}$$

At the top of the column:

$$H_{G2} = 112.5 \text{ kJ/kg}, \quad H_{f2} = 382 \text{ kJ/kg} \quad \therefore \Delta H_2 = 269.5 \text{ kJ/kg}$$

At the mean water temperature of $0.5(330 + 291) = 310.5$ K:

$$H_{Gm} = 82.0 \text{ kJ/kg}, \quad H_{fm} = 152.5 \text{ kJ/kg} \quad \therefore \Delta H_m = 70.5 \text{ kJ/kg}$$

$$\therefore \quad \Delta H_m/\Delta H_1 = 15.70 \text{ and } \Delta H_m/\Delta H_2 = 0.262$$

and from Fig. 13.17: $f = 0.35$ (extending the scales)

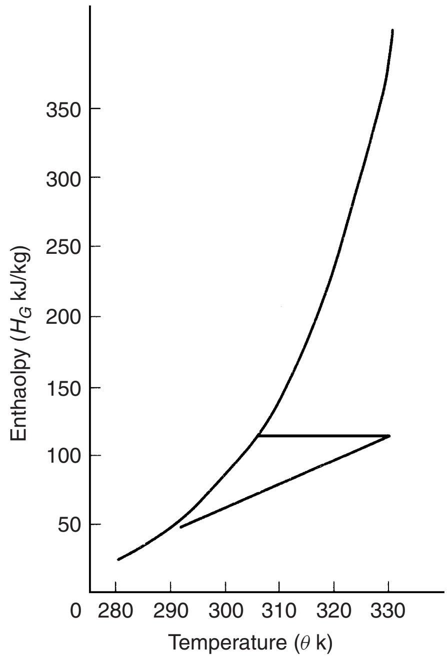

Figure 13c.

Thus:

$$\text{height of packing, } z = \int_{H_{G1}}^{H_{G2}} [\mathrm{d}H_G/(H_f - H_G)]G/h_D a\rho \quad \text{(equation 13.53)}$$

$$= (0.35 \times 3.537)/(2.0 \times 1.198) = \underline{\underline{0.52 \text{ m}}}$$

Due to the close proximity of the operating line to the line of saturation, the gas will be saturated on leaving the column and will therefore be at 100% humidity. From Fig. 13*c* the exit gas will be at $\underline{\underline{306 \text{ K}}}$.

PROBLEM 13.10

Air containing 0.005 kg water vapour/kg dry air is heated to 325 K in a dryer and passed to the lower shelves. It leaves these shelves at 60% humidity and is reheated to 325 K and passed over another set of shelves, again leaving with 60% humidity. This is again reheated for the third and fourth sets of shelves after which the air leaves the dryer. On the assumption that the material in each shelf has reached the wet bulb temperature and that heat losses from the dryer can be neglected, determine:

(a) the temperature of the material on each tray,
(b) the rate of water removal if 5 m^3/s of moist air leaves the dryer,

(c) the temperature to which the inlet air would have to be raised to carry out the drying in a single stage.

Solution

See Volume 1, Example 13.4

PROBLEM 13.11

0.08 m^3/s of air at 305 K and 60% humidity is to be cooled to 275 K. Calculate, using a psychrometric chart, the amount of heat to be removed for each 10 deg K interval of the cooling process. What total mass of moisture will be deposited? What is the humid heat of the air at the beginning and end of the process?

Solution

At 305 K and 60% humidity, from Fig. 13.4, the wet-bulb temperature is 299 K and $\mathscr{H} = 0.018$ kg/kg. Thus, as the air is cooled, the per cent humidity will increase until saturation occurs at 299 K and the problem is then one of cooling saturated vapour from 299 K to 275 K.

Considering the cooling in 10 deg K increments, the following data are obtained from Fig. 13.4:

θ (K)	θ_w (K)	% Humidity	$\mathscr{H}$	Humid heat (kJ/kg K)	Latent heat (kJ/kg)
305	299	60	0.018	1.032	2422
299	299	100	0.018	1.032	2435
295	295	100	0.017	1.026	2445
285	285	100	0.009	1.014	2468
275	275	100	0.0045	1.001	2491

At 305 K: the specific volume of dry air $= 0.861\ m^3/kg$

the saturated volume $= 0.908\ m^3/kg$

and hence the specific volume at 60% humidity $= [0.861 + (0.908 - 0.861)60/100]$

$= 0.889\ m^3/kg$

Thus: mass flow of moist air $= (0.08/0.889) = 0.090$ kg/s

Thus the flowrate of dry air $= 0.090/(1 + 0.018) = 0.0884$ kg/s.

From Fig. 13.4, specific heat of dry air (at $\mathscr{H} = 0$) $= 0.995$ kJ/kg K.

$$\therefore \quad \text{enthalpy of moist air} = (0.0884 \times 0.995)(299 - 273) + (0.018 \times 0.0884)$$

$$\times[4.18(299 - 273) + 2435] + 0.090 \times 1.032(305 - 299) = \underline{\underline{6.89\ \text{kW}}}$$

At 295 K: Enthalpy of moist air $= (0.0884 \times 0.995)(295 - 273) + (0.017 \times 0.0884) \times [4.18(295 - 273) + 2445] = \underline{\underline{5.75 \text{ kW}}}$

At 285 K: Enthalpy of moist air $= (0.0884 \times 0.995)(285 - 273) + (0.009 \times 0.0884) \times [4.18(285 - 273) + 2468] = \underline{\underline{3.06 \text{ kW}}}$

At 275 K: Enthalpy of moist air $= (0.0884 \times 0.995)(275 - 273) + (0.0045 \times 0.0884) \times [4.18(275 - 273) + 2491] = \underline{\underline{1.17 \text{ kW}}}$

and hence in cooling from 305 to 295 K, heat to be removed $= (6.89 - 5.75) = 1.14$ kW

in cooling from 295 to 285 K, heat to be removed $= (5.75 - 3.06) = 2.69$ kW

in cooling from 285 to 275 K, heat to be removed $= (3.06 - 1.17) = 1.89$ kW

The mass of water condensed $= 0.0884(0.018 - 0.0045) = \underline{\underline{0.0012 \text{ kg/s}}}$.

The humid heats at the beginning and end of the process are:

$\underline{\underline{1.082 \text{ and } 1.001 \text{ kJ/kg K}}}$ respectively.

PROBLEM 13.12

A hydrogen stream at 300 K and atmospheric pressure has a dew point of 275 K. It is to be further humidified by adding to it (through a nozzle) saturated steam at 240 kN/m^2 at the rate of 1 kg steam: 30 kg of hydrogen feed. What will be the temperature and humidity of the resultant stream?

Solution

At 275 K, the vapour pressure of water = 0.72 kN/m^2 (from Tables) and the hydrogen is saturated.

The mass of water vapour: $P_{w0}M_w/\mathbf{R}T = (0.72 \times 18)/(8.314 \times 275) = 0.00567$kg/m^3 and the mass of hydrogen: $(P - P_{w0})M_A/\mathbf{R}T = (101.3 - 0.72)2/(8.314 \times 275) = 0.0880$ kg/m^3

Therefore the humidity at saturation, $\mathscr{H}_0 = (0.00567/0.0880) = 0.0644$ kg/kg dry hydrogen and at 300 K, the humidity will be the same, $\mathscr{H}_1 = 0.0644$ kg/kg.

At 240 kN/m^2 pressure, steam is saturated at 400 K at which temperature the latent heat is 2185 kJ/kg.

The enthalpy of the steam is therefore:

$$H_2 = 4.18(400 - 273) + 2185 = 2715.9 \text{ kJ/kg}$$

Taking the mean specific heat capacity of hydrogen as 14.6 kJ/kg K, the enthalpy in 30 kg moist hydrogen or $30/(1 + 0.0644) = 28.18$ kg dry hydrogen is:

$$(28.18 \times 14.6)(300 - 273) = 11{,}110 \text{ kJ}$$

The latent heat of water at 275 K is 2490 kJ/kg and, taking the specific heat of water vapour as 2.01 kJ/kg K, the enthalpy of the water vapour is:

$$(28.18 \times 0.0644)(4.18(275 - 273) + 2490 + 2.01(300 - 275)) = 4625 \text{ kJ}$$

Hence the total enthalpy: $H_1 = 15{,}730$ kJ

In mixing the two streams, 28.18 kg dry hydrogen plus $(30 - 28.18) = 1.82$ kg water is mixed with 1 kg steam and hence the final humidity:

$$\mathscr{H} = (1 + 1.82)/28.18 = \underline{\underline{0.100 \text{ kg/kg}}}$$

In the final mixture, 0.1 kg water vapour is associated with 1 kg dry hydrogen or $(0.1/18) = 0.0056$ kmol water is associated with $(1/2) = 0.5$ kmol hydrogen, a total of 0.5056 kmol.

$\therefore$ partial pressure of water vapour $= (0.0056/0.5056)101.3 = 1.11$ kN/m^2

Water has a vapour pressure of 1.11 kN/m^2 at 281 K at which the latent heat is 2477 kJ/kg. Thus if T K is the temperature of the mixture, then:

$$(2716 + 15730) = (28.18 \times 14.6)(T - 273) + 2.82[4.18(281 - 273) + 2447 + 2.01(T - 281)]$$

$$\text{and } \underline{\underline{T = 300.5 \text{ K}}}$$

It may be noted that this relatively low increase in temperature occurs because the latent heat in the steam is not recovered, as would be the case in, say, a shell and tube unit.

PROBLEM 13.13

In a countercurrent packed column, n-butanol flows down at the rate of 0.25 kg/m^2 s and is cooled from 330 to 295 K. Air at 290 K, initially free of n-butanol vapour, is passed up the column at the rate of 0.7 m^3/m^2 s. Calculate the required height of tower and the condition of the exit air. Data: Mass transfer coefficient per unit volume, $h_D a = 0.1$ s^{-1}. Psychrometric ratio, $(h/h_D \rho_A s) = 2.34$. Heat transfer coefficients, $h_L = 3h_G$. Latent heat of vaporisation of n-butanol, $\lambda = 590$ kJ/kg. Specific heat capacity of liquid n-butanol, $C_L = 2.5$ kJ/kg K. Humid heat of gas: $s = 1.05$ kJ/kg K.

Temperature (K)	Vapour pressure of n-butanol (kN/m^2)
295	0.59
300	0.86
305	1.27
310	1.75
315	2.48
320	3.32
325	4.49

Temperature (K)	Vapour pressure of n-butanol (kN/m^2)
330	5.99
335	7.89
340	10.36
345	14.97
350	17.50

Solution

See Volume 1, Example 13.10

PROBLEM 13.14

Estimate the height and base diameter of a natural draught hyperbolic cooling tower which will handle 5000 kg/s water entering at 300 K and leaving at 294 K. The dry-bulb air temperature is 287 K and the ambient wet-bulb temperature is 284 K.

Solution

See Volume 1, Example 13.8