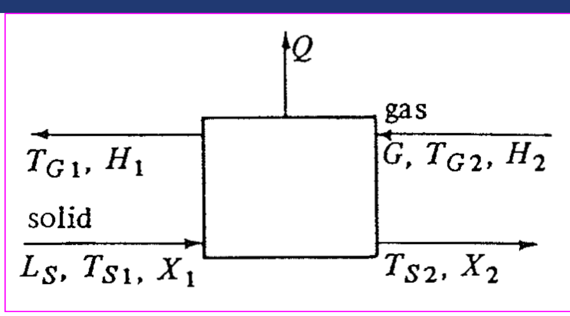
Continuous Drying

Balances for countercurrent continuous dryers:



G: Mass flow rate of **dry air**
L_S: Mass flow rate of dry solid
X: Free moisture content.
H: Humidity
T_S: Wet solid temperature
T_G: dry gas temperature

- **Steady-state material balance on the moisture:**

$$L_S(X_1 - X_2) = G(H_1 - H_2)$$

- **Steady-state heat balance on dryer:**

$$L_S(H'_{S1} - H'_{S2}) = G(H_{y1} - H_{y2}) + Q$$

H'_{S1} and H'_{S2} : Enthalpies of wet solid in kJ/kg dry solid at T_{S1} and T_{S2}, respectively

H_{y1} and H_{y2} : Enthalpies of humid air in kJ/kg dry air at T_{G1} and T_{G2}, respectively.

Balances for countercurrent continuous dryers

- Heat capacity of dry solid (C_{pS}) and heat capacity of liquid water ($C_L \cong 4.187$ kJ/kg.K) can be used to calculate the enthalpy of wet solid at inlet and outlet :

$$H'_{S1} = C_{pS}(T_{S1} - T_0) + X_{T,1} C_L (T_{S1} - T_0)$$

$$H'_{S2} = C_{pS}(T_{S2} - T_0) + X_{T,2} C_L (T_{S2} - T_0)$$

where T_0 is base temperature has a convenient value of 0 °C

- The enthalpy of humid gas at inlet and outlet can be calculated from (**See humidification handout**):

$$H_{y1} = c_{S1}(T_{G1} - T_0) + \lambda_0 H_1 \qquad c_{S1} = 1.005 + 1.88 H_1$$

$$H_{y2} = c_{S2}(T_{G2} - T_0) + \lambda_0 H_2 \qquad c_{S2} = 1.005 + 1.88 H_2$$

λ_0=2501 kJ/kg

- **Adiabatic drying**: Q = 0
- **Remark.** the difference in the free moisture content equals the difference in the total moisture content. **Why?**

Example

Continuous countercurrent dryer is being used to dry 453.6 kg dry solid/h containing 0.04 kg total moisture/kg dry solid to a value of 0.002 kg total moisture/kg dry solid. The granular solid enters at 26.7 °C and is to be discharged at 62.8 °C . The dry solid heat capacity is assumed to be constant at 1.465 kJ/(kg.K). Heating air enters the dryer at 93.3 °C with a humidity of 0.01 kg H_2O/kg dry air and leaves at 37.8 °C. Calculate the air flow rate and the outlet humidity. Neglect heat losses in the dryer.

Solution:

L_S=453.6 kg dry solid/h; Q=0

G=?
H_1=?

$X_{T,1}$= 0.04 kg H_2O/kg dry

$X_{T,2}$ =0.002 kg H_2O/kg dry

T_{S1}= 26.7 °C ; T_{S2}= 62.8 °C

T_{G1}= 37.8 °C ; T_{G2}= 93.3 °C ; H_2 = 0.01 kg H_2O/kg dry air

C_{pS}=1.465 kJ/(kg.K).

Solution Cont.d

- Steady-state moisture material balance:

$$L_S(X_1 - X_2) = G(H_1 - H_2) \rightarrow 453.6(0.04 - 0.002) = G(H_1 - 0.01)$$

$$GH_1 - 0.01G = 17.237$$ **Eq. (1)**

- Steady-state heat balance: $L_S(H'_{S1} - H'_{S2}) = G(H_{y1} - H_{y2})$

$$H'_{S1} = C_{pS}(T_{S1} - T_0) + X_{T,1}C_L(T_{S1} - T_0) \rightarrow H'_{S1} = C_{pS}T_{S1} + X_{T,1}C_L T_{S1}$$

T_0 = 0 °C

$$H'_{S2} = C_{pS}(T_{S2} - T_0) + X_{T,2}C_L(T_{S2} - T_0) \rightarrow H'_{S2} = C_{pS}T_{S2} + X_{T,2}C_L T_{S2}$$

$$H'_{S1} - H'_{S2} = C_{pS}(T_{S1} - T_{S2}) + C_L\left[X_{T,1}T_{S1} - X_{T,2}T_{S2}\right]$$

$$H'_{S1} - H'_{S2} = 1.465(26.7 - 62.8) + 4.187\left[(0.04)(26.7) - (0.002)(62.8)\right] = -48.94 \text{ kJ/kg dry air}$$

Solution Cont.d

$$c_{S2} = 1.005 + 1.88H_2 = 1.005 + 1.88(0.01) = 1.0238 \text{ kJ/kg dry air.K}$$

$$H_{y2} = c_{S2}(T_{G2} - T_0) + \lambda_0 H_2 = 1.0238(93.3 - 0) + 2501 \times 0.01 = 120.5 \frac{\text{J}}{\text{kg}}$$

$$c_{S1} = 1.005 + 1.88H_1$$

$$H_{y1} = c_{S1}(T_{G1} - T_0) + \lambda_0 H_1 = (1.005 + 1.88H_1)(37.8) + 2501H_1 = 37.99 + 2572H_1$$

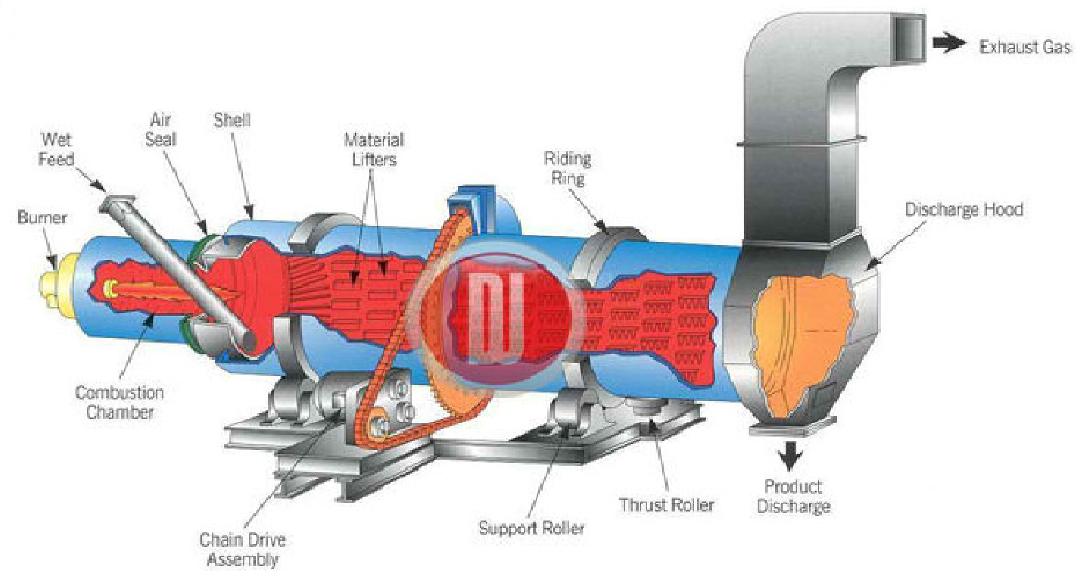
- after substituting the above values in the steady state heat balance:

$$82.51G - 2572GH_1 = 22199$$ **Eq. (2)**

- **Solve Eqns. (1) and (2) simultaneously to get:**

G = 1171.8 kg dry air/h , H_1= 0.0247 kg water /kg air

Analysis and design of countercurrent continuous dryers



Rotary dryer

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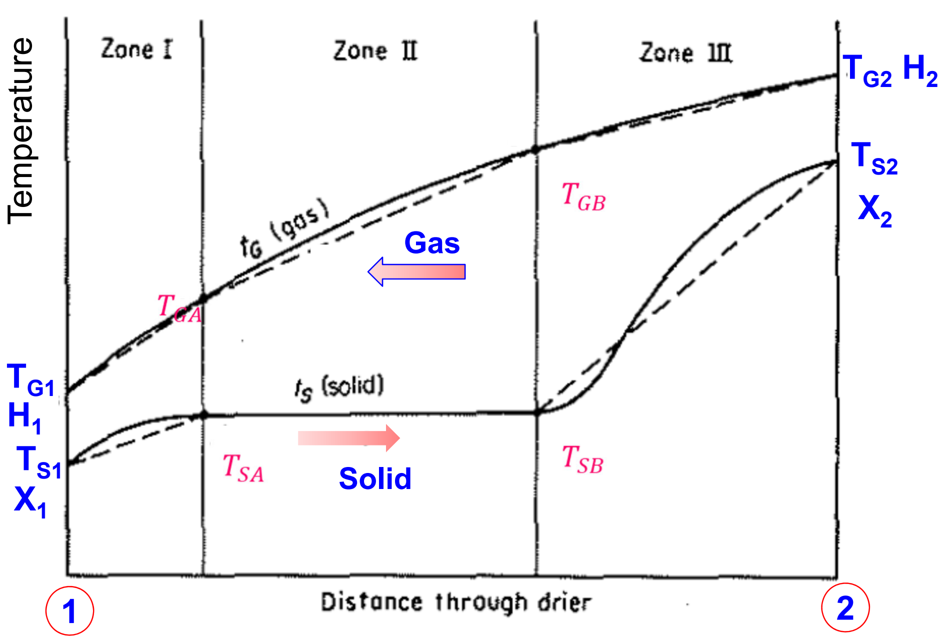
Analysis and design of countercurrent continuous dryers



Typical gas and solid temperature profiles in a countercurrent rotary dryer

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Analysis and design of countercurrent continuous dryers

Zone I (Preheat zone):

- The solid is heated up to the wet bulb or adiabatic saturation temperature (rate of heat transfer to the solid is balanced by the heat requirements for evaporation of moisture).
- Little evaporation occurs, thus this zone is usually ignored when drying performed at relatively low temperatures

Zone II:

- The equilibrium temperature of the solid remains substantially constant (at the wet bulb temperature of the air at location between III & II) while surface and unbound moisture are evaporated.
- At point B, the critical moisture of the solid is reached

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Analysis and design of countercurrent continuous dryers

Zone III,

- Unsaturated surface drying and evaporation of bound moisture occur.
- Assuming that the heat-transfer coefficients remain essentially constant, the decreased rate of evaporation in zone iii results in increased solid temperature,
- The discharge temperature of the solid approaches the inlet temperature of the gas.

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Analysis and design of countercurrent continuous dryers

Assumptions:

- Adiabatic operation (*the losses Q = 0.0)*
- Heat transfer only from the gas, and neglecting any indirect heat transfer between the solid and the drier itself,

→ Then, the loss in heat from the gas is equal to dq_G to that which is transferred to the solid dq *and the losses Q*.

$$dq_G = dq + dQ$$

$$dq = U\,dS\,(T_G - T_S) = Ua(T_G - T_S)\,\mathrm{dZ}$$

Where:

U = overall heat-transfer coefficient between gas and solid
T_G - T_s = temperature difference for heat transfer
S = interfacial surface/drier cross section
a = interfacial surface/drier volume

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Analysis and design of countercurrent continuous dryers

Also, $$dq_G = -\,G\,c_s dT_G$$

For adiabatic process, *the losses Q = 0.0*

$$dq_G = dq$$

where → $$-G\,c_s dT_G = Ua(T_G - T_S)\,\mathrm{dZ}$$

dT_G: is the temperature drop experienced by the gas as a result of transfer of heat to the solid only,

c_s: is the humid heat.

$$dN_{tOG} = \frac{dT_G}{T_G - T_S} = \frac{Ua\,\mathrm{dZ}}{G\,c_S}$$

- if the heat-transfer coefficient is constant

$$N_{tOG} = \frac{\Delta T_G}{\Delta T_m} = \frac{L}{H_{tOG}}$$ and $$H_{tOG} = \frac{G\,c_S}{Ua}$$

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Analysis and design of countercurrent continuous dryers

where

N_{tOG} = Number of heat-transfer units

H_{tOG} = Length of heat-transfer unit

ΔT_G = change in gas temperature owing to heat transfer to solid only

ΔT_m = appropriate average temperature difference between gas and solid (Log mean average)

- The volumetric heat transfer coefficient is calculated using the correlation

$$Ua\ (\frac{W}{m^3.K}) = 237\,\frac{G^{0.67}}{d}$$

where

G = gas mass flow rate (kg/m^2.s), d = dryer diameter (m)

Analysis and design of countercurrent continuous dryers

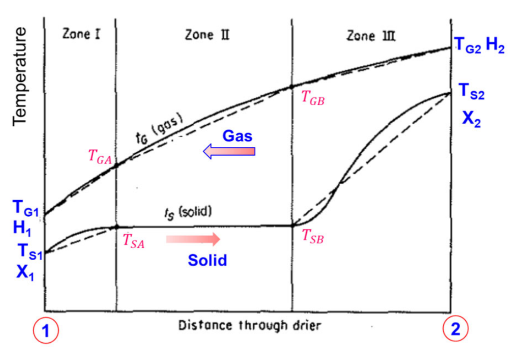
The total length of dryer is given by

$$\rightarrow \quad \boxed{L = N_{tOG} \times H_{tOG}}$$

- For the zone II, for example, the number of heat transfer units is given by

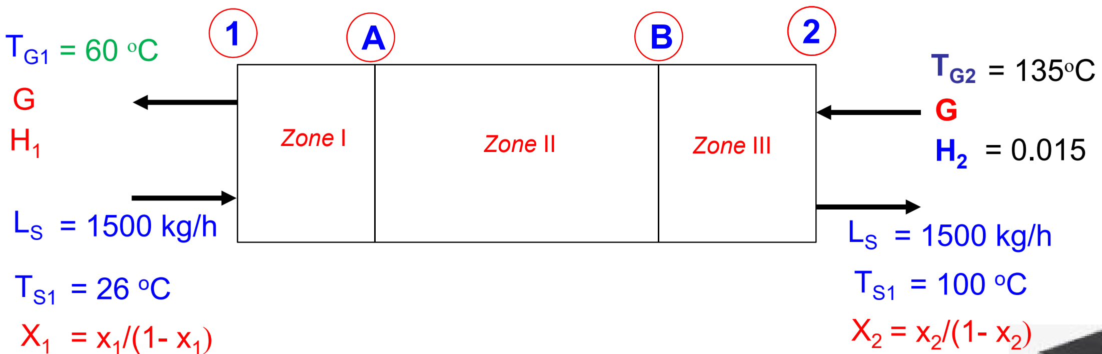
$$(N_{tOG})_{II} = \frac{T_{GB} - T_{GA}}{(\Delta T_m)_{II}}$$

$$(\Delta T_m)_{II} = \frac{(T_{GB}-T_{SB}) - (T_{GA}-T_{SA})}{\ln\dfrac{(T_{GB}-T_{SB})}{(T_{GA}-T_{SA})}}$$



Example: Analysis and design Rotary dryers

A moist non hygroscopic granular solid at 26°C is to be dried from 20% initial moisture to 0.3% final moisture in a rotary dryer at a rate of 1500 kg/h. The hot air enters the dryer at 135°C with a humidity of 0.015 and leaves at 60 °C . With condition that the temperature of the solid leaving the dryer must not exceed 100°C and the air velocity must not exceed 1.5 m/s in order to avoid dust carry over. C_{ps} = 0.85 kJ/kg.K. Recommend the diameter, length and other parameters of the dryer



Solution Cont.d

Solid contains 20% initial moisture:

Mass flow of dry solid: L_S = 1500 (1-0.2) = 1200 kg/h,

Moisture in the wet solid: X_1 = 0.20/(1-0.20) = 0.25

Moisture in the dry solid: X_2 = 0.003/(1-0.003) = 0.00301

Water evaporated, $m_{w\_evaporated} = L_S (X_1 - X_2)$

= 1200 (0.25 – 0.00301) = 296.4 kg

Now enthalpy of different streams (suppose ref temp = 0°C)

$$H'_{S1} = C_{pS}(T_{S1} - T_0) + X_{T,1}C_L(T_{S1} - T_0) \rightarrow H'_{S1} = C_{pS}T_{S1} + X_{T,1}C_L T_{S1}$$

T_0 = 0 °C

$$H'_{S2} = C_{pS}(T_{S2} - T_0) + X_{T,2}C_L(T_{S2} - T_0) \rightarrow H'_{S2} = C_{pS}T_{S2} + X_{T,2}C_L T_{S2}$$

Solution Cont.d

H'_{S1} = 0.85 (26) + 4.187 (0.25) (26) = 49.31 kJ/kg DA

H'_{S2} = 0.85 (100) + 4.187 (0.00301) (100) = 86.2 kJ/kg DA

$$c_{S2} = 1.005 + 1.88 H_2$$

= 1.005 + 1.88 (0.015) = 1.0332 kJ/kg DA.K

$$H_{y2} = c_{S2}(T_{G2} - T_0) + \lambda_0 H_2$$

= 1.0332 (135-0) + 0.015 (2500) = 177 kJ/kg DA

$$c_{S1} = 1.005 + 1.88 H_1$$

$$H_{y1} = c_{S1}(T_{G1} - T_0) + \lambda_0 H_1$$

= (1.005 + 1.88 H_1) (60)+ 2500 H_1 = 60.3 + 2613 H_1

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Solution Cont.d

- Steady-state moisture material balance:

$L_S(X_1 - X_2) = G(H_1 - H_2)$ → 1200 (0.25 - 0.00301) = G (H_1 – 0.015)

→ G H_1 – 0.015 G = 296.4 kg **Eq. (1)**

- Steady-state heat balance:

$$L_S(H'_{S1} - H'_{S2}) = G(H_{y1} - H_{y2})$$

→ 1200 (49.31 - 86.2) = G (60.3 + 2613 H_1 – 177) **Eq. (2)**

- **Solve Eqns. (1) and (2) simultaneously to get:**

G = 10560 kg dry air/h , H_1= 0.04306 kg water /kg air

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Solution Cont.d

Calculation of the shell diameter

Humid volume of the inlet gas (135°C, $Y_2 = 0.015$), $v_{H2} = 1.183\ \text{m}^3/(\text{kg dry air})$

Humid volume of the exit gas (60°C, $Y_1 = 0.04306$), $v_{H1} = 1.008\ \text{m}^3/(\text{kg dry air})$

The maximum volumetric gas flow rate (this occurs at end 2)

$$= G_s v_{H2} = (10{,}560)(1.183) = 12{,}490\ \text{m}^3/\text{h} \Rightarrow 3.47\ \text{m}^3/\text{s}$$

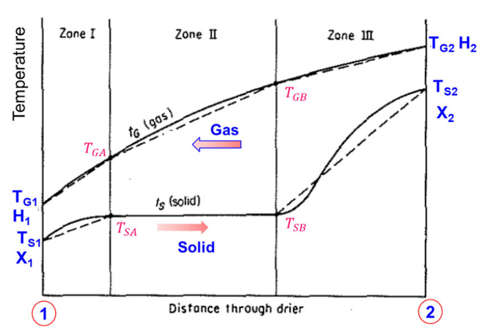
- Take the maximum superficial air velocity to be 1.2 m/s (this is 20% less than the maximum allowable velocity since part of the dryer is filled with the moving solid, and the entire crosssection is not available for gas flow).

$$(\pi d^2/4)(1.2) = 3.686 \Rightarrow d = 1.98\ \text{m}$$ Select a 2-m diameter shell

Solution Cont.d

Calculation of the number of heat transfer units

- The dryer is considered to consist of three zones as shown in the Figure.
- The stage wise calculation of temperature and humidity or moisture content of the streams can be obtained by material and energy balance



Zone III:

- Only heating of the solid occurs in this zone; there is little water left for vaporization.
- At the boundary between zones III and II, the solid is at T_{SB}, the wet-bulb temperature of the air at that location.

Solution Cont.d

Assume $T_{SB} (= T_{SA}) = 41\ ^oC$ (this value is T_{WB} at H = 0.015 (inlet humidity, only heating in zone III, i.e. H = constant) and air temperature close to the inlet, i.e. 115 °C)

T_{DA} = 115 °C

H = 0.015 kg/kg DA

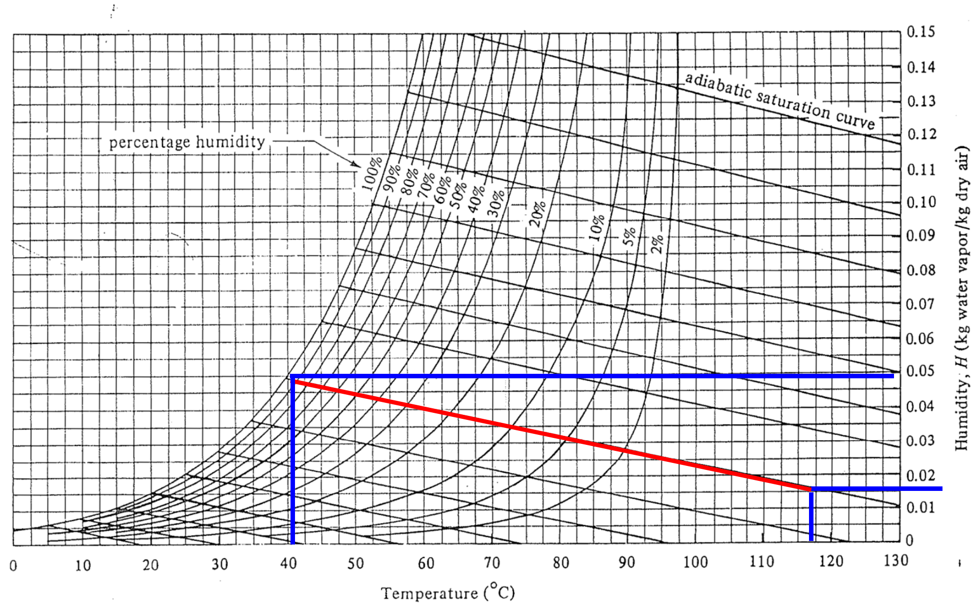


FIGURE 9.3-2. Humidity chart for mixtures of air and water vapor at a total pressure of 101.325 kPa (760 mm Hg). (From R. E. Treybal, Mass-Transfer Operations, 3rd ed. New York: McGraw-Hill Book Company, 1980. With permission.)

Solution Cont.d

Enthalpy of the solid at the inlet to zone III

$$H'_{sB} = [0.85 + (0.00301)(4.187)](41 - 0) = 35.37 \text{ kJ/(kg dry solid)}$$

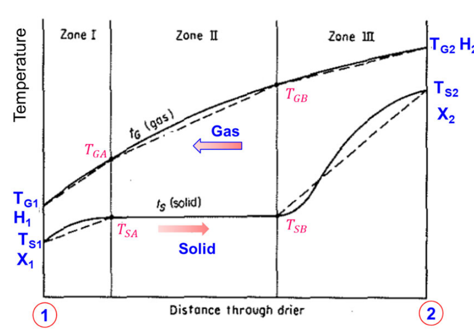
Humid heat of the gas entering zone III

$$c_{sB} = [1.005 + (1.88)(0.015)] = 1.033 \text{ kJ/kg·K}$$

(this remains constant in zone **III**, since the humidity does not change in this section).

Heat balance over zone III

$$L_s(H'_{s2} - H'_{sB}) = G\, c_{sB}\, (T_{G2} - T_{GB})$$



$$\Rightarrow \quad (1200)(86.2 - 35.37) = (10{,}560)(1.033)(135 - T_{GB}) \Rightarrow T_{GB} = 129°C$$

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Solution Cont.d

The wet bulb temperature of air entering zone II (129 °C and humidity of 0.015) is 41.3 °C.

This is fairly close to the guess value of 41 °C and T_{SB} (= T_{SA}) = 41 °C is not changed.

At the boundary B, $\Delta T_B = 129 - 41 = 88°C$; at end 2, $\Delta T_2 = 135 - 100 = 35°C$

$$\text{Log mean temperature in zone III, } (\Delta T)_m = \frac{88-35}{\ln(88/35)} = 57.5°C$$

$$\text{Number of heat transfer units, } (N_{tG})_{III} = \frac{T_2 - T_{GB}}{(\Delta T)_m} = \frac{135-129}{57.5} = 0.104$$

Solution Cont.d

Zone II: In order to calculate $(N_{tG})_{II}$, we need the value of T_{GA}. This can be obtained by heat balance.

$$H_{yB} = [1.005 + 1.88Y_B](129 - 0) + (2500)(Y_B) = 170.8 \text{ kJ/kg.} \quad (\text{since } Y_B = 0.015)$$

$$H'_{sA} = [0.85 + c_{ps}X_1](T_{sA} - 0) = [0.85 + (4.187)(0.25)](41) = 77.77 \text{ kJ/(kg dry solid)}$$

$$\text{Enthalpy balance: } L_s(H'_{sB} - H'_{sA}) = G(H_{yB} - H_{yA})$$

$$(1200)(35.37 - 77.77) = (10{,}560)(170.8 - H_{yA})$$

$$\Rightarrow H_{yA} = 175.6$$

$$= [1.005 + (0.04306)(1.88)](T_{GA} - 0) + (0.04306)(2500)$$

$$\Rightarrow T_{GA} = 63°C$$

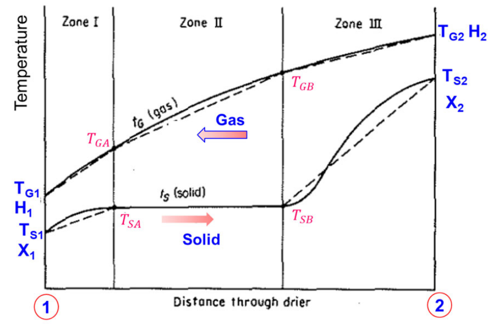
Solution Cont.d

Temperature differences: At section A, $(\Delta T)_A = 63 - 41 = 22°C$; $(\Delta T)_B = 88°C$

$$(\Delta T)_m = \frac{88-22}{\ln(88/22)} = 47.6$$

Number of heat transfer units,

$$(N_{tG})_{II} = \frac{T_{GB} - T_{GA}}{(\Delta T)_m} = \frac{129-63}{47.6} = 1.386$$



Zone I: $(\Delta T)_1 = 60 - 26 = 34°C$; $(\Delta T)_A = 22°C$; $(\Delta T)_m = \frac{34-22}{\ln(34/22)} = 27.5$

Number of heat transfer units, $(N_{tG})_I = \frac{T_{GA} - T_{G1}}{(\Delta T)_m} = \frac{63-60}{27.5} = 0.109$

Solution Cont.d

Total number of heat transfer units $N_{tG} = 0.104 + 1.386 + 0.109 = 1.53$

Length of a transfer unit calculation

$$H_{tOG} = \frac{G\, c_s}{Ua}$$

Average gas mass flow rate

$$= [(10{,}560)(1.015) + (10{,}560)(1.04306)]/2 = 10{,}867 \text{ kg/h}$$

The gas mass flow rate, $G' = (10{,}867/3600)/(\pi/4)(2)^2 = 0.961 \text{ kg/m}^2\cdot\text{s}$

Volumetric heat transfer coefficient

$$U\bar{a} = \frac{237(G')^{0.67}}{d} = \frac{(237)(0.961)^{0.67}}{2} = 115 \text{ W/m}^3\cdot\text{K}$$

Solution Cont.d

Humid heats at the ends:

$$c_{S2} = 1.005 + 1.88 H_2$$

$$= 1.005 + 1.88\ (0.015) = 1.0332 \text{ kJ/kg DA.K}$$

$$c_{S1} = 1.005 + 1.88 H_1$$

$$= 1.005 + 1.88\ (0.04306) = 1.083 \text{ kJ/kg DA.K}$$

Average humid heat

$$c_S = (1.033 + 1.083)/2 = 1.058 \text{ kJ/kg·K} = 1058 \text{ J/(kg dry air)(K)}$$

$$H_{tOG} = \frac{G' c_H}{U \bar{a}} = \frac{(0.961)(1058)}{115} = 8.84 \text{ m}$$

Length of the dryer, $L = (N_{tG})(L_t) = (1.56)(8.84) = 13.8$ m

Select a 2 m diameter, 15 m long dryer

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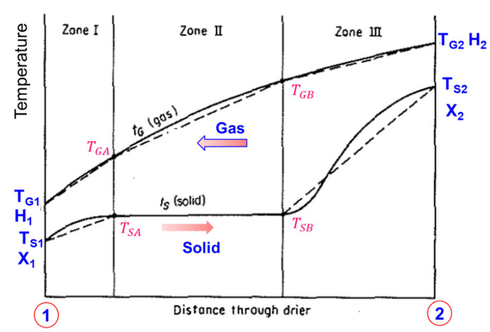
Drying time in countercurrent continuous dryers:

Zone III:

- The terminal conditions (temperature and moisture content) of the two streams are either given or can be obtained by overall material and energy balance.
- The heat load Q_3 for raising the temperature of the 'dry solid' from T_{sB} ($= T_{WB}$) to T_{s2} and the temperature driving forces at the boundaries are



$$Q_3 = L_s c_{ps} (T_{S2} - T_{sB})$$

$$= G\, c_s (T_{G2} - T_{GB})$$

$$\Delta T_B = T_{GB} - T_{SB} \quad , \quad \Delta T_2 = T_{G2} - T_{S2}$$

If ΔT_m is the log-mean temperature difference,

the heating time in this zone is given by
$$t_{III} = \frac{Q_3}{A\, h_c \Delta T_m}$$

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Drying time in countercurrent continuous dryers:

✓ T_{GB} and T_{sB} are determined as discussed in the previous example

$$L_s(H'_{s2} - H'_{sB}) = G\, c_{sB}\,(T_{G2} - T_{GB})$$

➢ **Alternative analysis: Zone III (falling rate zone):**

- Linear drying rate: $R = R_c X / X_C$
- Convection heat transfer : $R_c = h(T\text{-}T_w)/\lambda_w = k_y M_B (H_w\text{-}H)$
- Differential material balance of moisture: $L_s dX = GdH$

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Drying time in countercurrent continuous dryers:

- Drying time is:

$$t = -\frac{L_s}{A}\int_{X_c}^{X_2}\frac{dX}{R} = -\frac{X_C L_s}{A}\int_{X_c}^{X_2}\frac{dX}{R_c} = -\frac{GX_C}{Ak_y M_B}\int_{H_c}^{H_2}\frac{dH}{X(H_w - H)}$$

- Moisture material balance over the zone from X_2 to X:

$$L_S(X - X_2) = G(H - H_2) \rightarrow X = X_2 + \frac{G}{L_S}(H - H_2)$$

$$t = -\frac{GX_C}{Ak_y M_B}\int_{H_c}^{H_2} dH \Big/ \left[\left(X_2 + \frac{G}{L_S}(H - H_2)\right)(H_w - H) \right]$$

- Integrate to get :

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Drying time in countercurrent continuous dryers:

$$t = \frac{GX_C}{Ak_y M_B} \frac{1}{(H_W - H_2)G/L_s + X_2} \ln \frac{X_C(H_W - H_2)}{X_2(H_W - H_C)}$$

- Again, H_c can be calculated from:

$$H_C = H_2 + \frac{L_S}{G}(X_C - X_2)$$

Drying time in countercurrent continuous dryers:

Zone I:

- The heat load Q_1 for raising the temperature of the 'dry solid' from T_{s1} to T_{sA} (= T_{WB}) and the temperature driving forces at the boundaries are

$$Q_3 = L_s c_{ps} (T_{SA} - T_{s1}) = G c_s (T_{GA} - T_{G1})$$

$$\Delta T_A = T_{GA} - T_{SA} \quad , \quad \Delta T_1 = T_{G1} - T_{S1}$$

If ΔT_m is the log-mean temperature difference,

the heating time in this zone is given by

$$t_I = \frac{Q_I}{A\, h_c \Delta T_m}$$

Drying time in countercurrent continuous dryers:

- **Zone II (constant rate zone):**
- If heat is transferred by convection only, the drying rate is:

$$R_c = h(T\text{-}T_w)/\lambda_w = k_y M_B (H_w\text{-}H)$$

- Differential material balance on moisture:

$$L_s dX = G dH$$

- Drying time is:

$$t = -\frac{L_s}{A}\int_{X_1}^{X_C}\frac{dX}{R_C} = -\frac{G}{Ak_y M_B}\int_{H_1}^{H_C}\frac{dH}{H_w - H}$$

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Drying time in countercurrent continuous dryers:

- H_W is constant since Tw is constant. Thus, the above Eq. can be integrated to have:

$$t = \frac{G}{Ak_y M_B}\ln\frac{H_W - H_C}{H_W - H_1} = \frac{G}{Ak_y M_B}\frac{H_1 - H_C}{\Delta H_{LM}}$$

$$\Delta H_{LM} = \frac{(H_W - H_C) - (H_W - H_1)}{\ln\dfrac{H_W - H_C}{H_W - H_1}}$$

Log mean humidity difference

- Apply moisture material balance over the whole Zone II to get H_c:

$$L_S(X_C - X_2) = G(H_C - H_2) \longrightarrow H_C = H_2 + \frac{L_S}{G}(X_C - X_2)$$

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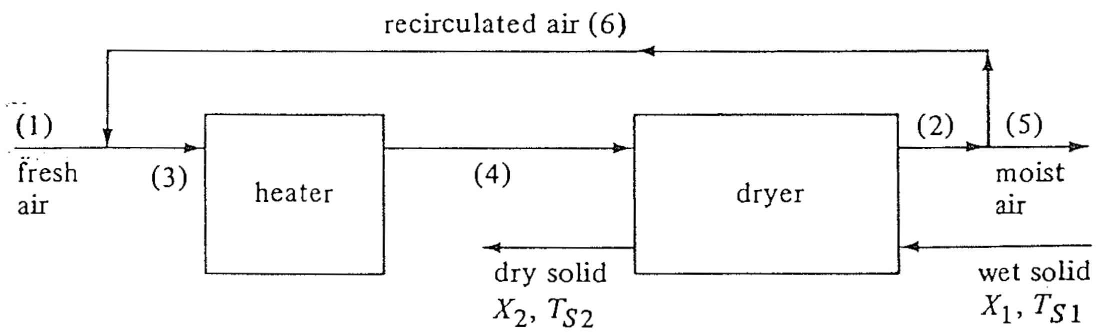
Air circulation in countercurrent continuous dryers:



- **Purpose of air circulation:**

  to control the humidity of the entering air and the wet bulb temperature in order to minimize heating cost of air.

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