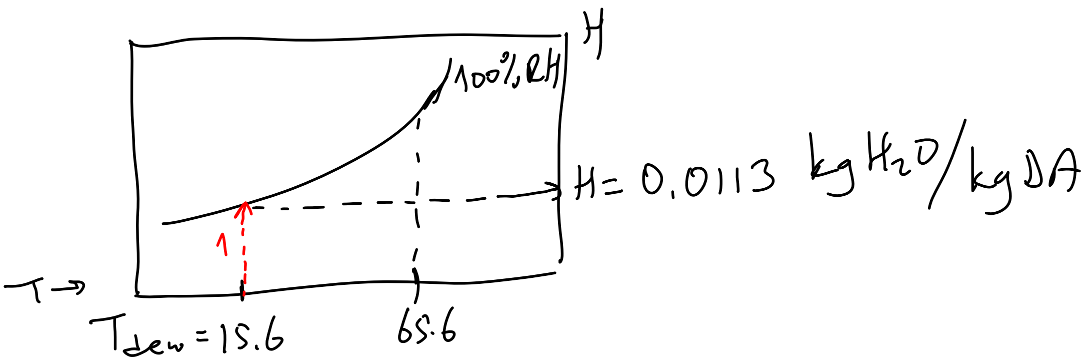
PROBLEMS

1) The air entering a dryer has a temperature of 65.6°C and dew point of 15.6°C. Calculate the humid volume and humid heat of this mixture.

Solution:

$$T = 65.6 + 273 = 338.6\ K$$



* Humid Volume, $\nu_H = (2.83 \times 10^{-3} + 4.56 \times 10^{-3} \times H) \times T$ (T → K)

$$\nu_H = (2.83 \times 10^{-3} + 4.56 \times 10^{-3} \times 0{,}0113) \times (338{,}8)$$

$$= 0{,}976\ m^3\ \text{wet air}/\text{kg DA}$$

* Humid Heat, $C_s = (1.005 + 1.88 \times H)$

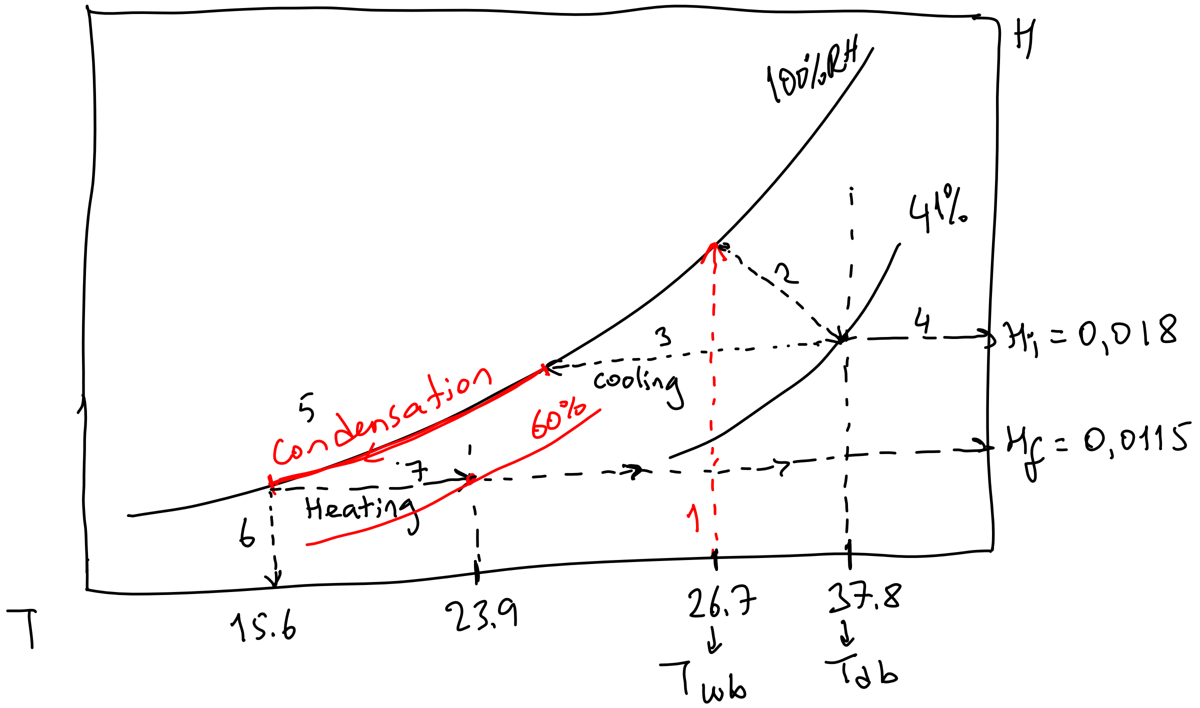
$$= 1.005 + 1.88 \times 0{,}0113 = 1{,}026\ \text{kJ}/\text{kg DA}$$

2) Air having a dry bulb temperature of 37.8°C and a wet bulb of 26.7°C is to be dried by first cooling to 15.6°C to condense water vapor and then heating to 23.9°C.

a) Calculate the initial absolute humidity and relative humidity

b) Calculate the final absolute humidity and relative humidity

Solution:



a) $H_i = 0{,}018 \ kgH_2O/kgDA$, $RH = 41\%$.

b) $H_f = 0{,}0115 \ kgH_2O/kgDA$, $RH = 60\%$

3) A tunnel dryer is being designed for drying apple halves from an initial moisture content of 70 % (wb) to a final moisture content of 5 % (wb). An experimental drying curve for the product indicates that the critical moisture content is 25 % (wb) and the time for constant rate drying is 5 min. Based on the information provided, estimate the total drying time for the product. Assume 1 kg of dry solids/m^2 of effective drying surface as the basis.

<u>Solution:</u>

$$X_1 = \frac{70}{30} = 2.33 \ kgH_2O/kgDS$$

$$X_c = \frac{25}{75} = 0{,}333 \quad ''$$

$$X_2 = \frac{5}{95} = 0{,}0526 \quad ''$$

$$t_c = 5 \ min \ (given), \quad \frac{L_s}{A} = 1 \ \frac{kgDS}{m^2} \ (given)$$

$$R_c = \frac{L_s \times (X_1 - X_2)}{A \times t_c} = 1 \times \frac{(2.33 - 0{,}333)}{5} \Rightarrow$$

$$R_c = 0{,}4 \ kg H_2O/(m^2 \cdot min)$$

$$t_f = \frac{L_s}{A} \times \frac{X_c}{R_c} \times \ln\frac{X_c}{X_2} = 1 \times \frac{0{,}333}{0{,}4} \times \ln\left(\frac{0{,}333}{0{,}0526}\right) \Rightarrow$$

$$t_f = 1.54 \ min$$

$$\text{Total drying time} = t_c + t_f = 5 + 1.54 = 6.54 \ min.$$

4) A bed of material consisting of wet granular solids is being dried in a current of heated air. The air is maintained at a temperature of 338 K (65°C) and a relative humidity of 15 %. Assuming that no shrinkage takes place, then, calculate the depth of a bed of this material which will take 12 hours to dry from an initial moisture content of 1.0 kg H_2O/kg dry solids to a final moisture content of 0.1 kg H_2O/kg dry solids.

Additional data:

Critical MC: **0.5 kg H_2O/kg dry solids**

Equilibrium MC: **0.02 kg H_2O/kg dry solids**

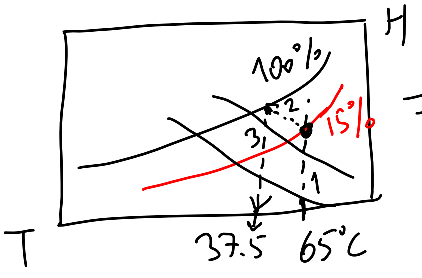
Bulk density of the dry solids: **1600 kg/m^3**

The heat transfer coefficient to the surface during the constant rate period was found to be 162 kJ/(h.m^2.K).

<u>Solution:</u>

For through circulation drying where the drying gas passes upward or downward through a bed of wet granular solids, both a constant rate period and a falling rate period of drying may result. Often the granular solids are arranged on a screen so that the gas passes through the screen and through the open spaces or voids between the solid particles.

<u>Solution:</u>



$\Rightarrow T_s = T_{wb} = 37.5°C$, $\lambda_w = ?$ at $37{,}5°C$

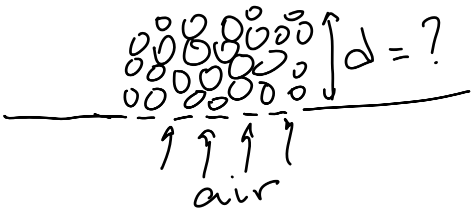
From saturated steam table;

$\lambda_w = 2410{,}3 \ kJ/kg H_2O$

For such drying processes $\Rightarrow$

$$t_c = \frac{\rho_s \times \lambda_w \times d \times (X_1 - X_c)}{(T - \underbrace{T_{wb}}_{T_s}) \times h} \quad , \; d: \text{depth of bed.}$$

$$t_f = \frac{\rho_s \times \lambda_w \times d \times (X_c - X_e)}{(T - T_{wb}) \times h} \times \ln\left[\frac{X_c - X_e}{X_2 - X_e}\right]$$



$$t_{total} = t_c + t_f = 12 \text{ hr (Given)} \Rightarrow$$

$$12 = \frac{1600 \times 2410{,}3 \times d \times (1 - 0{,}5)}{(338 - 310{,}5) \times 162} + \frac{1600 \times 2410{,}3 \times d \times (0{,}5 - 0{,}02)}{\underbrace{(338 - 310{,}5)}_{37.5^\circ C} \times 162} \times \ln\left[\frac{0{,}5 - 0{,}02}{0{,}1 - 0{,}02}\right]$$

$$\Rightarrow d = 0{,}0102 \text{ m} \equiv 1.02 \text{ cm}$$

5) 100 kg of food material are dried from an initial water content of 80 % on a wet basis and with an effective surface drying area of 12 m^2. Estimate the time needed to dry to 50 % moisture content on a wet basis, assuming constant rate drying period in air at a temperature of 120°C dry bulb and 50°C wet bulb. Under the conditions in the drier, measurements indicate the convective heat transfer coefficient to the food surface from the air to be 18 J/(m^2.s.°C).

<u>Solution:</u>

$$t_c = \frac{L_s \times \lambda_w \times (X_1 - X_2)}{A \times h \times (T - T_{wb})} \quad , \; T_{wb} \cong T_{sat}$$

$$X_1 = \frac{80}{100-80} = 4 \text{ kg}H_2O/\text{kg DS}$$

$$X_2 = \frac{50}{100-50} = 1 \text{ kg}H_2O/\text{kg DS}$$

$T_{wb} = 50°C \Rightarrow \lambda_w$ at $50°C = 2383 \frac{kJ}{kgH_2O}$ from sat'led steam table.

$$h = 18 \frac{J}{m^2 . s . °C} \times \frac{1 kJ}{1000 J} = 18 \times 10^{-3} kJ/(m^2 . s . °C)$$

$$L_s = 100 \times (1 - 0.8) = 20 \text{ kg DS.}$$

$$t_c = \frac{20 \cancel{kgDS} \times 2383 \frac{\cancel{kJ}}{\cancel{kgH_2O}} \times (4-1) \frac{kg\cancel{H_2O}}{\cancel{kgDS}}}{12 m^2 \times 18 \times 10^{-3} \frac{\cancel{kJ}}{m^2 . s . °\cancel{C}} \times (120-50)°\cancel{C}}$$

$$t_c = 9456 \cancel{s} \times \frac{1 hr}{3600 \cancel{s}} \cong 2.63 h$$

6) 2060 lb/h of dried product (with 4 % wet basis moisture) is produced from a co-current drier. Atmospheric air (75°F) of absolute humidity H_1=0.0095 kg water/kg dry air is heated to 350°F before entering the drier. Air is exhausted from the drying chamber at 176°F. Feed contains 45 % solids and pumped in to the dryer at 80°F. Dried product temperature is 115°F. What is the dry air flow rate and absolute humidity of air outlet if no heat loss from the drying system.

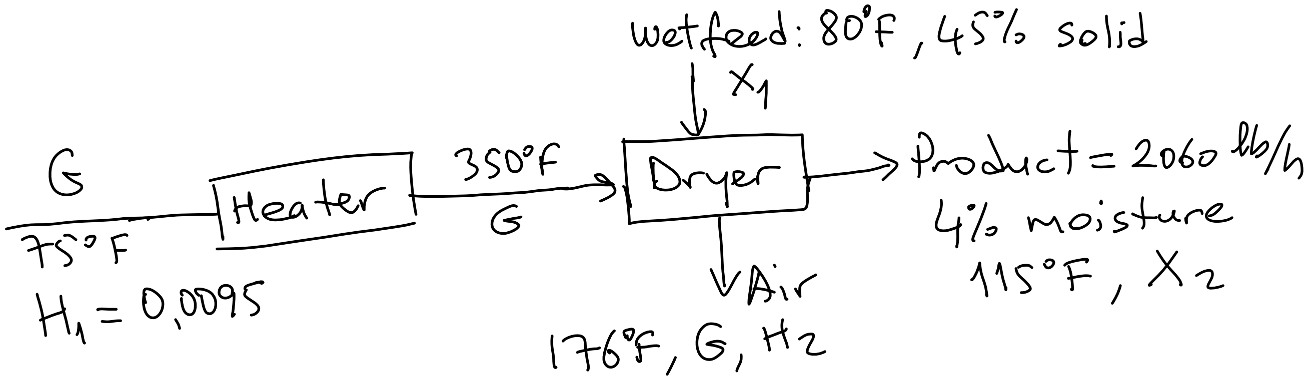
C_s = 0.24 + 0.45xH, Btu/(lbDA.°F)

Latent heat of water at 32°F: 1075 Btu/lb water

Specific heat of dry product: 0.40 Btu/(lb dry solids.°F)

Specific heat of water: 1 Btu/lb water.°F

Solution:



$$L_s = 2060 \frac{lb}{h} \times 0.96 = 1977.6 \ lb\,DS/h$$

$$X_1 (d.b.) = \frac{0.55}{1-0.55} = 1.22 \ lb\,H_2O/lb\,DS$$

$$X_2 (d.b.) = \frac{0.04}{1-0.04} = 0.0416 \ lb\,H_2O/lb\,DS$$

Material balance for H_2O on dryer:

$$G \times H_1 + L_s \times X_1 = G \times H_2 + L_s \times X_2$$

$$G \times 0.0095 + 1977.6 \times 1.22 = G \times H_2 + 1977.6 \times 0.0416 \Rightarrow$$

$$\boxed{0.0095\,G + 2330.4 = G H_2} \longrightarrow \text{eqn } 1$$

Heat balance on dryer:

$$H'_{G_1} = C_s(T_G - \underbrace{T_0}_{32°F}) + H \times \overbrace{\lambda_0}^{\text{at } 32°F} \rightarrow \text{for gas}$$

$$H'_s = C_{p_s}(T_s - T_0) + X \cdot C_{p_w}(T_s - T_0) \rightarrow \text{for solid.}$$

$$G \times H'_{G_1} + L_s \times H'_s = G \times H'_{G_2} + L_s \times H'_{s_2} + \cancel{Q_{Loss}}^{\,0}$$

$$G \times \left[(0.24 + 0.45 \times 0.0095)(350-32) + 0.0095 \times \overset{\lambda_0}{1075.2} \right] +$$

$$1977.6 \left[0.40(80-32) + 1.22 \times \overset{\rho_{cp}}{1} \times (80-32) \right] =$$

$$G \times \left[(0.24 + 0.45 \times H_2)(176-32) + H_2 \times 1075.2 \right] +$$

$$1977.6 \left[0.40 \times (115-32) + 0.0416 \times 1 \times (115-32) \right] \Rightarrow$$

$$87.8G + 153778.18 = G(34.56 + 64.8H_2 + 1075.2H_2) + 72484.5 \Rightarrow$$

$$87.8G + 81293.59 = 1140G \cdot H_2 + 34.56G$$

$$\boxed{53.24G + 81293.59 = 1140GH_2} \rightsquigarrow \text{eqn } 2$$

Substituting eqn 1 into eqn 2

$$53.24G + 81293.59 = 1140\left[0.0095G + 2330.4\right] \Rightarrow$$

$$42.41G = 2575362.2 \Rightarrow$$

$$G = 60725.35 \text{ lb dry air/h}$$

$$GH_2 = 0.0095 \times G + 2330.4 \rightsquigarrow \text{eqn } 1$$

$$\boxed{H_2 = 0.0478 \text{ lb } H_2O/\text{lb DA}}$$

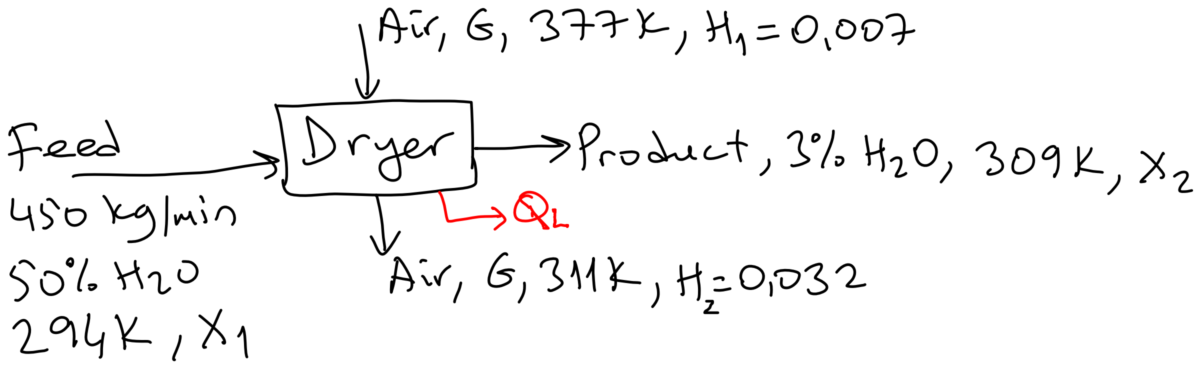
7) 450 kg/min of a feed material containing 50 % moisture (wet weight basis) enters a drier at 294K. The product containing 3 % moisture (wet weight basis) leaves the drier at 309K. The air enters the drier at 377K with an absolute humidity of 0.007 kg water/kg dry air. The air leaves the drier at 311K. Calculate heat loss, % heat loss and weight of dry air used per hour. The humidity of air leaving the drier is 0.032 kg water/kg dry air.

Cp (liquid water): 4.19 kJ/kg.K, Cp (solid): 0.83 kJ/kg.K

Cp (water vapor): 2 kJ/kg.K, Cp (air): 0.95 kJ/kg.K

Latent heat of vaporization of water at 273K: 2411 kJ/kg

Solution:



$Q_{Loss} = ?\,,\quad G = ?\ (kg/h)$

Dry solids, $L_s = 450 \times 0{,}5 = 225\ \frac{kg\,DS}{\cancel{min}} \times \frac{60\ \cancel{min}}{1\ hr} = 13500\ \frac{kg\,DS}{h}$

$$X_1 = \frac{0{,}50}{1-0{,}5} = 1\ kg\,H_2O/kg\,DS$$

$$X_2 = \frac{0{,}03}{1-0{,}03} = 0{,}0309\ kg\,H_2O/kg\,DS$$

Material balance for H_2O on dryer:

$$G \times H_1 + L_s \times X_1 = G H_2 + L_s \times X_2$$

$$G \times 0{,}007 + 225 \times 1 = G \times 0{,}032 + 225 \times 0{,}0309$$

$$0{,}025\,G = 218.05 \Rightarrow$$

$$G = 8722\ \frac{kg\,DA}{\cancel{min}} \times \frac{60\ \cancel{min}}{h} = 523320\ \frac{kg\,DA}{h}$$

Heat balance on dryer:

$$G \times H'_{G_1} + L_s \times H'_s = G \times H'_{G_2} + L_s \times H'_{s_2} + Q_{Loss}$$

$$523320 \times \left[(0{,}95 + 2 \times 0{,}007) \times (377-273) + 0{,}007 \times 2411\right] +$$

$$13500 \times \left[0{,}83(294-273) + 1 \times 4.19 \times (294-273)\right] =$$

$$523320 \times [(0{,}95 + 2 \times 0{,}032) \times (311 - 273) + 0{,}032 \times 2411] +$$

$$13500 \times [0{,}83\,(309 - 273) + 0{,}0309 \times 4.19\,(309 - 273)] + Q_{Loss}$$

$$\Rightarrow \quad 62718071 \ \frac{kJ}{h} = 61006053 \ \frac{kJ}{h} + Q_{Loss}$$

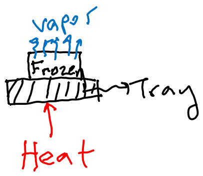
$$Q_{Loss} = 1712018 \ kJ/h$$

$$\% Q_{Loss} = \frac{1712018}{62718071} \times 100 \cong 2.73\%$$

8) A slab of frozen orange juice to be freeze dried, from a moisture content of 87 % to 3% (db). The slab, 1.2 cm thick, rests on a tray and is heated by raidation from upper surface. The source of radiation is regulated so as to maintain the surface temperature at 30ºC at all times. The frozen juice is at - 18ºC. The latent heat of sublimation is 3000 kJ/kg. The thermal conductivity of the dry layer at the pressure of operation is 0.09 W/(m.K). The density of the frozen juice is 1000 kg/m^3. Estimate the drying time.

<u>Solution:</u>

$$t = \frac{L_s \times \rho \times (X_o - X_f)}{k \times (T_s - T_f)} \times \frac{L^2}{2} \quad , \quad L = 1{,}2 \ cm = 0{,}012 \ m$$



$$= \frac{3000 \times 10^3 \ J/kg H_2O \times 1000 \ \frac{kg \ solid}{m^3} \times (0{,}87 - 0{,}03) \ \frac{kg H_2O}{kg DS} \times \frac{(0{,}012m)^2}{2}}{[30 - (-18)] \ K \times 0{,}09 \ \frac{J}{s.m.K}}$$

$$\Rightarrow t = 42000 \ s \cong 11.67 \ h$$

9) Slices of a food product 5 mm thick are freeze-dried from both major surfaces of the slices, kept at 50ºC, in the vacuum chamber. The chamber pressure is 60 Pa and pressure at ice front is 85 Pa. The temperature of ice

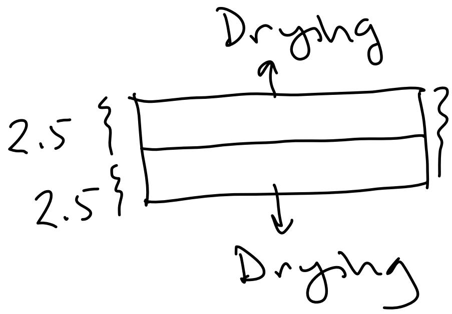
is - 22 ºC. Calculate the time to dry from 200 % (db) moisture content to 5 % (db).

k: 0.02 W/(m.K), b: 2x10^{-8} kg/(s.m.Pa)

Ls: 2.95x10^{6} J/kg, density: 500 kg/m^{3}.

<u>Solution:</u>

$$t = \frac{L_s \times \rho \times (X_0 - X_f)}{k \times (T_s - T_f)} \times \frac{L^2}{2}$$



5 mm $\Rightarrow$ L = 0,0025 m

$$t = \frac{2.95 \times 10^6 \times 500 \times (2 - 0{,}05)}{0{,}02 \times [50 - (-22)]} \times \frac{(0{,}0025)^2}{2} \Rightarrow$$

$$t = 5837 \text{ sec} \cong 1.62 \text{ h}$$

OR

$$t = \frac{\rho \times (X_0 - \overset{X_e}{X_f}) \times \frac{L^2}{2}}{b \times \underbrace{(P_i - P_D)}_{\Delta P}}$$

P_i: Vapor P at ice front (Surface)

P_D: " " " dried layer (Surface)

$$t = \frac{500 \times (2 - 0.05) \times (0.0025)^2/2}{2 \times 10^{-8} \times (85 - 60)} = 3808 \text{ sec} \cong 1.06 \text{ h}$$