Question Drying

(a) The critical moisture content (X_C) splits drying into a constant rate period and falling rate period.

  (i) Describe the mass and heat transfer mechanisms that occur during both these periods

  (ii) Draw a plot of drying rate versus moisture content (X), show where the critical moisture content (X_C) and equilibrium moisture content (X^*) are.

[6 marks]

(b) Wet paper is being dried in a continuous dryer with air recycle. The properties of the paper and process are known:

Initial moisture content	=	2.3 kg/kg
Critical moisture content	=	0.6 kg/kg
Equilibrium moisture content	=	0.01 kg/kg
Constant period drying rate	=	0.022 kg/m^2 s
Dry solid density	=	650 kg/m^3
Slab thickness	=	5 cm
Flowrate of wet paper	=	1200 kg/h
Hot air temperature into the dryer	=	130^{o}C
Make-up air temperature	=	21^{o}C
Make-up air relative humidity	=	10%
Moist air temperature leaving dryer	=	70^{o}C
Outlet air relative humidity	=	20%

  (i) Calculate the time required to dry wet paper from its initial moisture content to a moisture content of 0.05 kg/kg. Assume the paper is a slab, drying is from both sides, and mass transfer from the centre to the surface of the paper is dominated by capillary action.

[3 marks]

  (ii) Calculate the flow rate of dried paper leaving the dryer and the amount of water evaporated.

[2 marks]

  (iii) Calculate the required flow rate of make-up air and the flow rate of air passing through the dryer.

[5 marks]

  (iv) Calculate the heater duty required and the dryer efficiency.

[4 marks]

[Total 20 marks]

High and normal temperature psychrometric charts are provided, please attach charts to your exam script.

Useful Equations

$$t_d = \frac{s\rho_s}{R_c}(X_1 - X_2)$$

$$t_d = \frac{r\rho_s}{3R_c}(X_1 - X_2)$$

$$t_d = \frac{s\rho_s(X_c - X^*)}{R_c}\ln\left[\frac{(X_1 - X^*)}{(X_2 - X^*)}\right]$$

$$t_d = \frac{r\rho_s(X_c - X^*)}{3R_c}\ln\left[\frac{(X_1 - X^*)}{(X_2 - X^*)}\right]$$

$$t_d = \frac{4s^2}{\pi^2 D_v}\ln\left[\frac{8(X_1 - X^*)}{\pi^2(X_2 - X^*)}\right]$$

$$t_d = \frac{r^2}{\pi^2 D_v}\ln\left[\frac{6(X_1 - X^*)}{\pi^2(X_2 - X^*)}\right]$$

$$M_i \frac{1}{(1+X_i)} = M_o \frac{1}{(1+X_o)}$$

$$M_i \frac{X_i}{(1+X_i)} + F_{air}H_i = M_o \frac{X_o}{(1+X_o)} + F_{air}H_o$$

$$M_i \frac{X_i}{(1+X_i)} + (F+R)_{air}H_{FR} = M_o \frac{X_o}{(1+X_o)} + (F+R)_{air}H_o$$

$$F_{air}h_i = \phi + F_{air}h_o$$

$$\eta = \frac{\phi_{ideal}}{\phi_{actual}}$$

where:

A	Area (m^2)
D_v	Diffusivity ($m^2\ s^{-1}$)
F_{air}	Flow rate of air in the dryer ($kg\ s^{-1}$)
$(F+R)$	Flow rate of air entering the drying, including any recycled air ($kg\ s^{-1}$)
$H_{surface}$	Humidity at the surface (kg water/kg dry air)
H_{air}	Humidity of the air (kg water/kg dry air)
M_i, M_o	Mass flow rate of material in the dryer ($kg\ s^{-1}$)
r	Radius of particle (m)
R, R_C	Rate of drying ($kg\ m^{-2}s^{-1}$)
s	Characteristic dimension of slab (m)
t_d	Drying time (s)
X	Moisture content (kg water/kg dry solids)
ρ_S	Density of dry solid ($kg\ m^{-3}$)
ϕ	rate of heat transfer (kJ/s)
η	dryer efficiency

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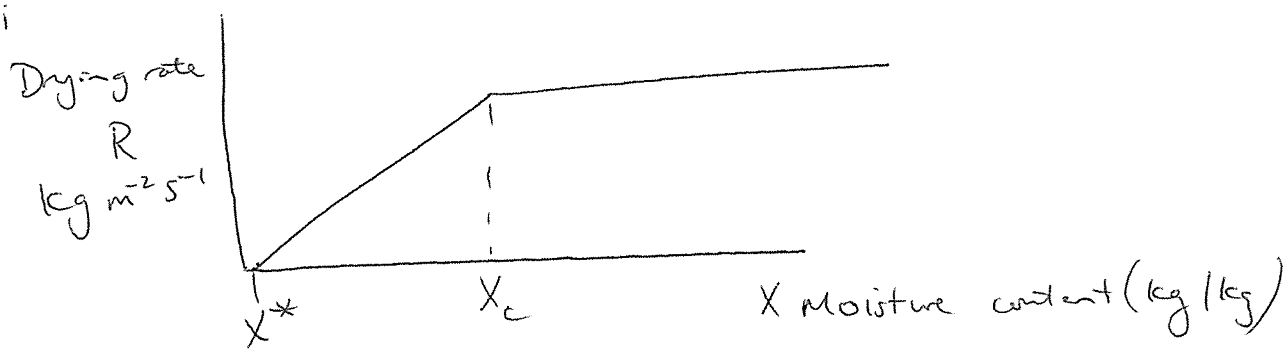
Answer Drying

(a) (i) Constant rate period

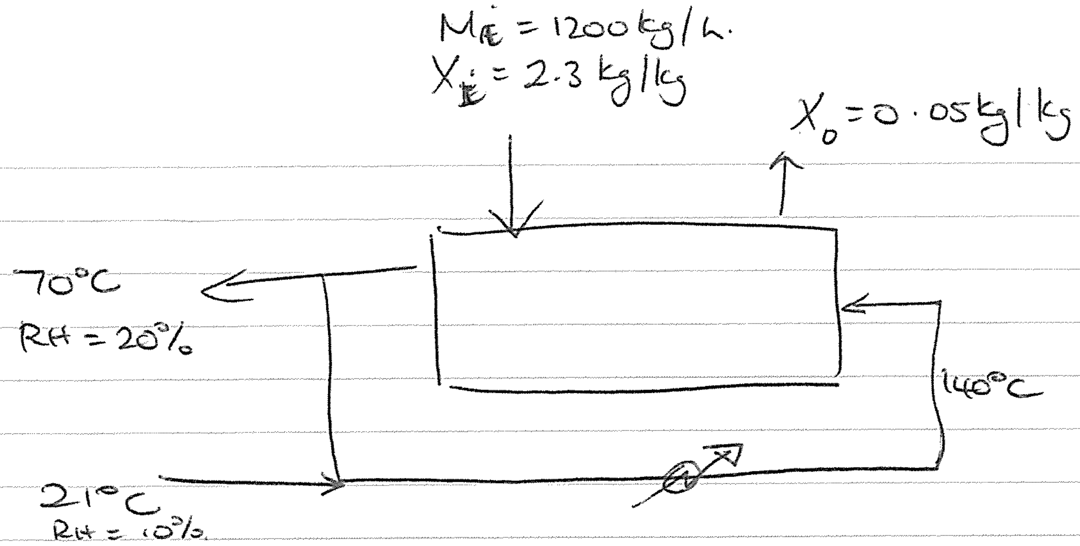
Mass transfer: from surface, from a wet surface, steady state
Heat transfer: steady state, product heats up plus evaporative cooling – no temperature change.
Controlled by dryer conditions

Falling Rate Period
Mass Transfer: unsteady state, diffusion or capillary movement of solvent to surface.
Controlled by material
Heat Transfer: Unsteady state, product heats up as evaporative cooling is less a rate of evaporation has reduced.

ii



(b)



$X_c = 0.6$ kg/kg

$X^* = 0.01$ kg/kg

$R_c = 0.022 \text{ kg m}^{-2} \text{s}^{-1}$

$\rho = 650 \text{ kg m}^{-3}$

$s = 2.5 \times 10^{-2}$ m

X 2.3 $\rightarrow$ 0.05 kg/kg constant + falling rates

(i) $$t = \frac{s\rho}{R_c}(X_1 - X_c) + \frac{s\rho}{R_c}(X_c - X^*) \ln\left[\frac{X_c - X^*}{X_2 - X^*}\right]$$

$$t = \frac{2.5 \times 10^{-2} \times 650}{0.022}(2.3 - 0.6) + \frac{2.5 \times 10^{-2}\ 650}{0.022}(0.6 - 0.01) \ln\left[\frac{0.6 - 0.01}{0.05 - 0.01}\right]$$

$$= 1255.7 + 1172.8$$

$$= 2428.5 \text{ s}$$

$$= 40.48 \text{ min}$$

(ii) solids balance

$$M_i \frac{1}{1 + X_i} = M_o \frac{1}{1 + X_o}$$

$$1200 \frac{1}{1 + 2.3} = M_o \frac{1}{1 + 0.05}$$

$$M_o = 382 \text{ kg h}^{-1} = 0.106 \text{ kg s}^{-1}$$

$$\text{water evaporated} = M_i \frac{X_i}{1+X_i} - M_o \frac{X_o}{1+X_o}$$

$$= 1200 \frac{2.3}{1+2.3} - 382 \frac{0.05}{1+0.05}$$

$$= 818 \text{ kg h}^{-1}$$
$$= 0.227 \text{ kg s}^{-1}$$

(iii)

$$M_i \frac{X_i}{1+X_i} + F_{air} H_i = M_o \frac{X_o}{1+X_o} + F_{air} H_o$$

$$M_i \frac{X_i}{1+X_i} - M_o \frac{X_o}{1+X_o} = F_{air} (H_o - H_i)$$

$H_i = 0.0015$ kg/kg $\qquad$ 21°C, RH = 10%
$H_o = 0.041$ $\qquad$ 70°C, RH = 20%

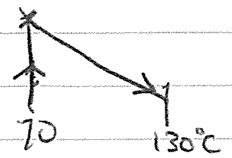
$$0.227 = F_{air} (0.041 - 0.0015)$$

$$F_{air} = 5.75 \text{ kg s}^{-1}$$

$$M_i \frac{X_i}{1+X_i} + (F+R) H_{FR} = M_o \frac{X_o}{1+X_o} + (F+R) H_o$$

$H_{FR} = 0.016$ $\qquad$ (130°C, constant enthalpy line)

$$0.227 = (F+R)(H_o - H_{FR})$$



$$0.227 = (F+R)(0.041 - 0.016)$$
$$(F+R) = 9.08 \text{ kg s}^{-1}$$

(iv) $\phi = F_{air}(h_o - h_i)$

$h_o = 181 \text{ kJ kg}^{-1}$

$h_i = 26 \text{ kJ kg}^{-1}$

$\phi_{actual} = 5.75\ (181 - 26) = 891 \text{ kJ s}^{-1}$

$\phi_{ideal} = \cancel{m h_{fg}}$

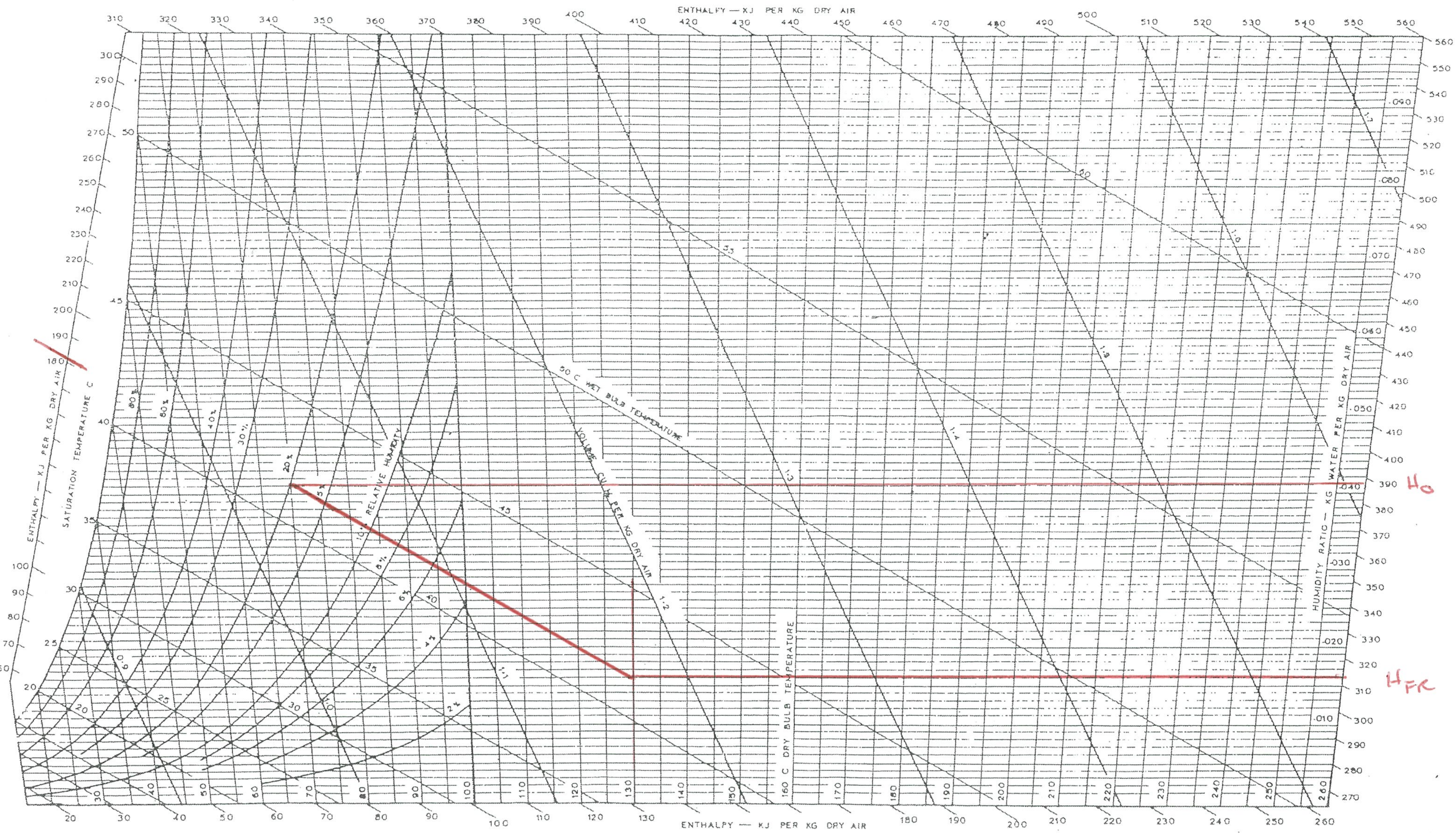
$$= \left[M_i \frac{x_i}{1+x_i} - M_o \frac{x_o}{1+x_o} \right] h_{fg} \quad @\ \theta_{WB} = 42^\circ$$

$h_{fg}\ @\ 42^\circ C = 2401 \text{ kJ/kg}.$

$$\eta = \frac{\phi_{ideal}}{\phi_{actual}} = \frac{0.227 \times 2401}{891} = 0.61$$

61%.

PSYCHROMETRIC CHART HIGH TEMPERATURES 1013.25 MILLIBARS



PSYCHROMETRIC CHART

NORMAL TEMPERATURES

1013.25 MILLIBARS