280.371 Process Engineering Operations
Assignment 2. Drying
Due Date: 9th May 2014
(Submission on Stream OR in Assignment boxes in B80)

Question 1.

Blackcurrant berries are a seasonal product. Drying is a process that can be used to make them shelf stable and available all year around. For dried berries, it is important to reduce the moisture content low enough to stop the growth of moulds, yeasts and bacteria.

As a recent graduate, you have convinced your boss to purchase a tray dryer. Before installing it, you have been asked to prove to the quality assurance manager that the product is in fact safe. To do so, you designed a drying experiment for the seller to conduct. The experiment consisted of drying samples of blackcurrants at three different temperatures and recording the weight loss as a function of time. The results of the drying experiment sent to you by the seller (after they kindly converted the weight data to moisture contents) are shown in Figure 1.1.

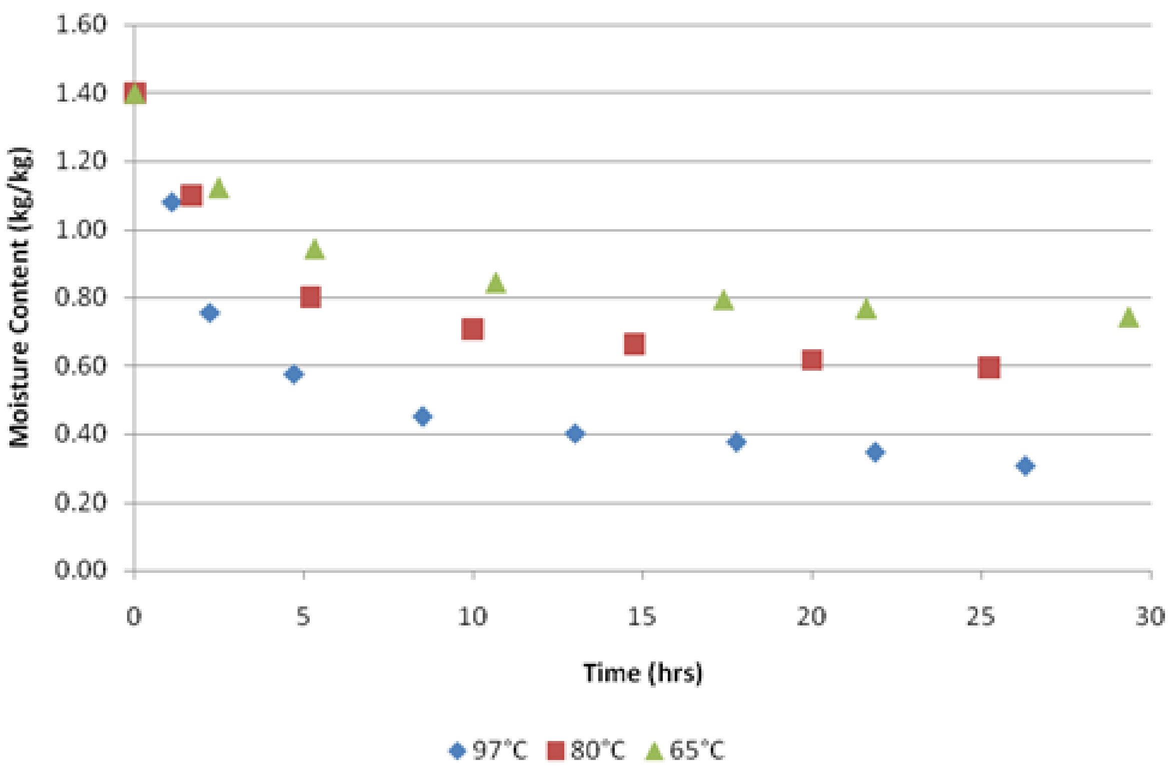


Figure 1.1. Drying experiment results.

(a)

(i) Using the 97°C data in Figure 1.1, sketch a plot of the drying rate versus moisture content.
Note: an accurate plot is not needed for this part.

(ii) On your sketch, clearly label the constant and falling drying rate regimes, and mark the point that separates the two drying regimes.

(iii) Is the drying mechanism in the falling rate period likely to be dominated by capillary or diffusion? Explain how you chose the mechanism.

(b) Knowing the equilibrium moisture content at 97°C is 0.2 kg/kg, convert the drying data in Figure 1.1 into free moisture content and plot the free moisture content versus time.

Note: A full plot is required. Use the graph paper supplied, remember to attach it to your assignment.

(c) Using your answer to (b), estimate the rate of drying (in free moisture content) during the constant drying rate period.

(d) The berries are to be packed tightly together in a single layer (10 mm) on a square drying tray. Assume that the tray is infinitely large and that the berries are dried from top and bottom only. The critical moisture content and diffusivity of water in the fruit was shown to be 0.52 kg/kg (free moisture) and 3×10^{-10} $m^2\ s^{-1}$, respectively. Calculate the moisture content in the centre of the fruit after 24 h of drying at 97°C.

(e) Explain why the equilibrium moisture contents for the 97°C, 80°C, and 65°C drying experiments are different.

Gurney Lurie Charts are provided. Include charts with your answer book.

[Total 20 marks]

Question 2.

Bruce's Butchery has found it difficult to sell lamb offal (lungs, heart etc.) to customers and so has decided that drying the offal and selling it as pet food is the best way to avoid wastage. Mr Bruce found a second-hand dryer that he has since bought and installed. He has hired you to analyse his dryer and to make recommendations as to how he may run the dryer to reduce the cost of operation.

Currently, the dryer is being run for 20 hours each day. Each day, 207 kg of dried offal is produced from 586 kg of feed. The feed offal is 80% water. Air at 81°C is being fed into the dryer at 1 $kg.s^{-1}$ and leaves the dryer at 65°C (dry bulb) with a relative humidity of 40%. The make-up air has a relative humidity of 60% and a dry bulb temperature of 24°C.

(a) Calculate the moisture content of the offal leaving the dryer and the rate of moisture removed from the offal.

(b) Estimate the following:
   a. Humidity of the air leaving the dryer,
   b. Humidity of the air entering the dryer,
   c. Humidity of the make-up air.

(c) Determine the flow rates of make-up and recycled air

(d) Calculate the efficiency of the dryer.

(e) Suggest two changes to the dryer system in which the product throughput of the dryer could be increased and explain how these suggested changes will increase product throughput.

Mr Bruce has noted that the rate of drying during the first half of the day is relatively fast but decreases during the second half of the day. He can't understand why this is the case as the dryer settings remain the same throughout the day.

(f) Explain, with the use of a carefully labelled diagram, why the rate of drying is not constant throughout the entire day (20 hours of drying) and what drying mechanisms may be occurring.

Psychrometric charts must be included with your answer

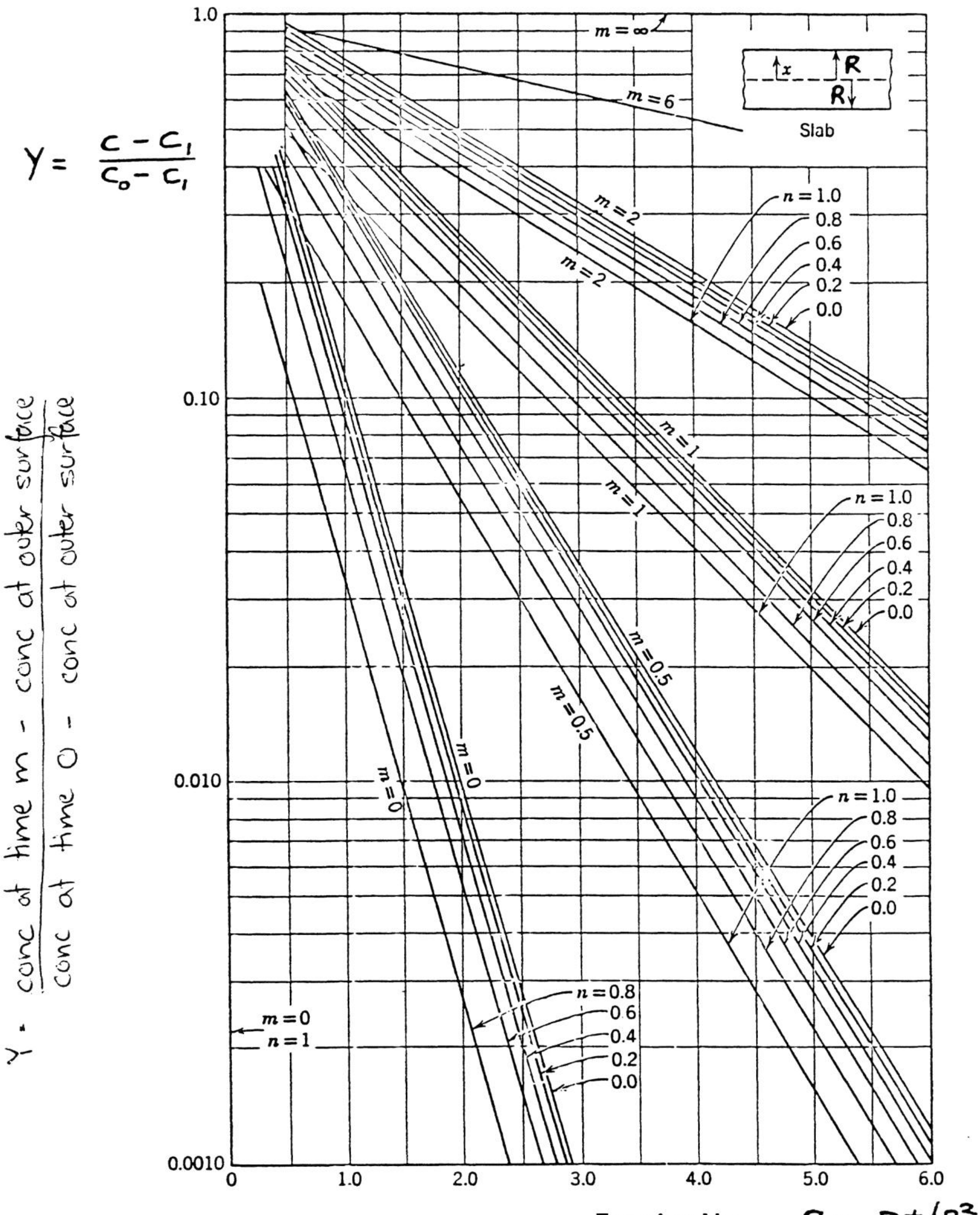
[Total 20 marks]

Normal Graph Paper

Normal Graph Paper

Figure 1

POINT LOCATION IN A SLAB



Unsteady-state transport in a large flat slab.

$n = \frac{x}{R}$

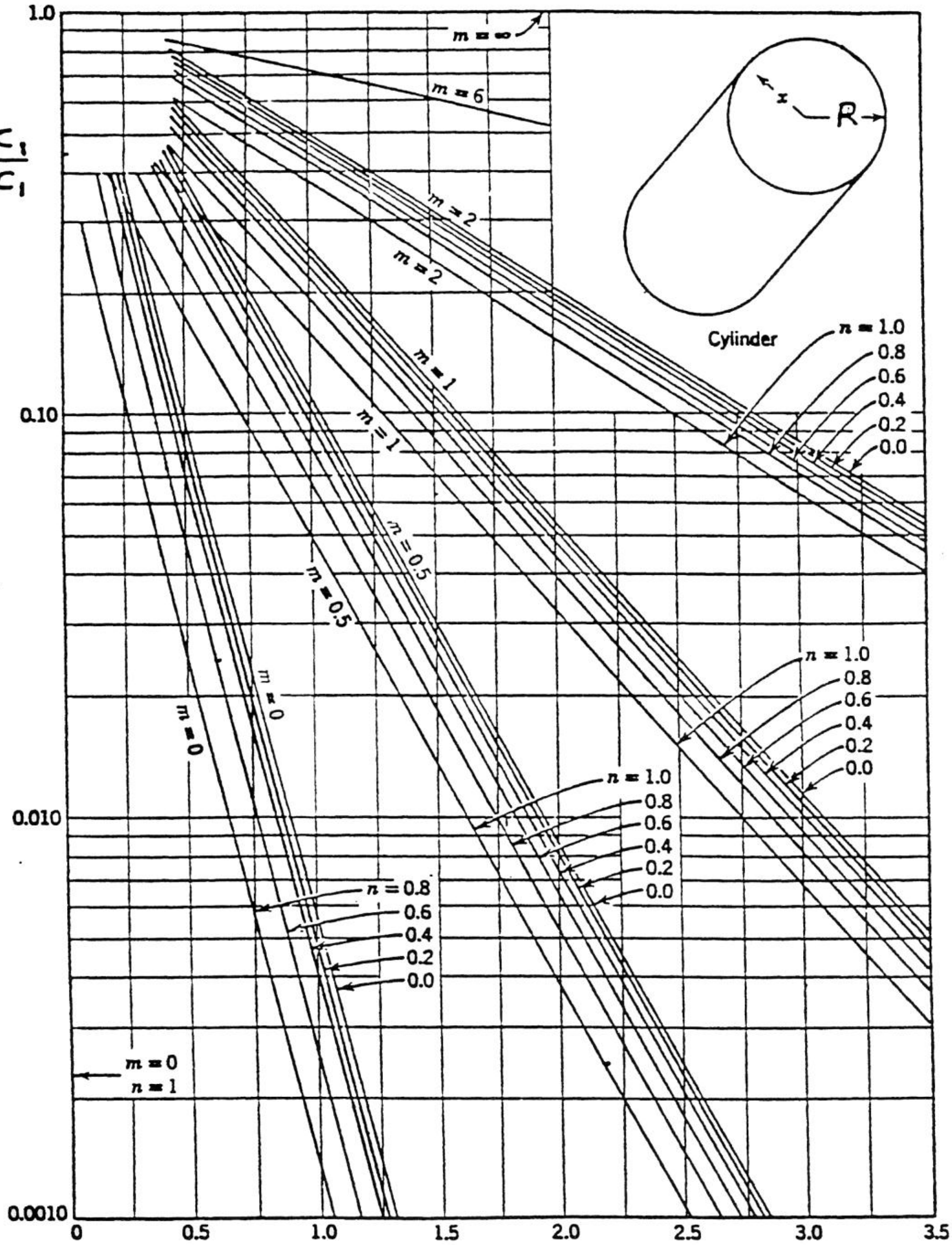
$m = 1/Bi$

Figure 2

POINT LOCATION IN A CYLINDER

$$Y = \frac{c - c_1}{c_0 - c_1}$$

$$Y = \frac{\text{conc at time } m - \text{conc at outer surface}}{\text{conc at time } 0 - \text{conc at outer surface}}$$



Fourier No. $= \beta = Dt/R^2$

Unsteady-state transport in a long cylinder.

$$n = \frac{x}{R}$$

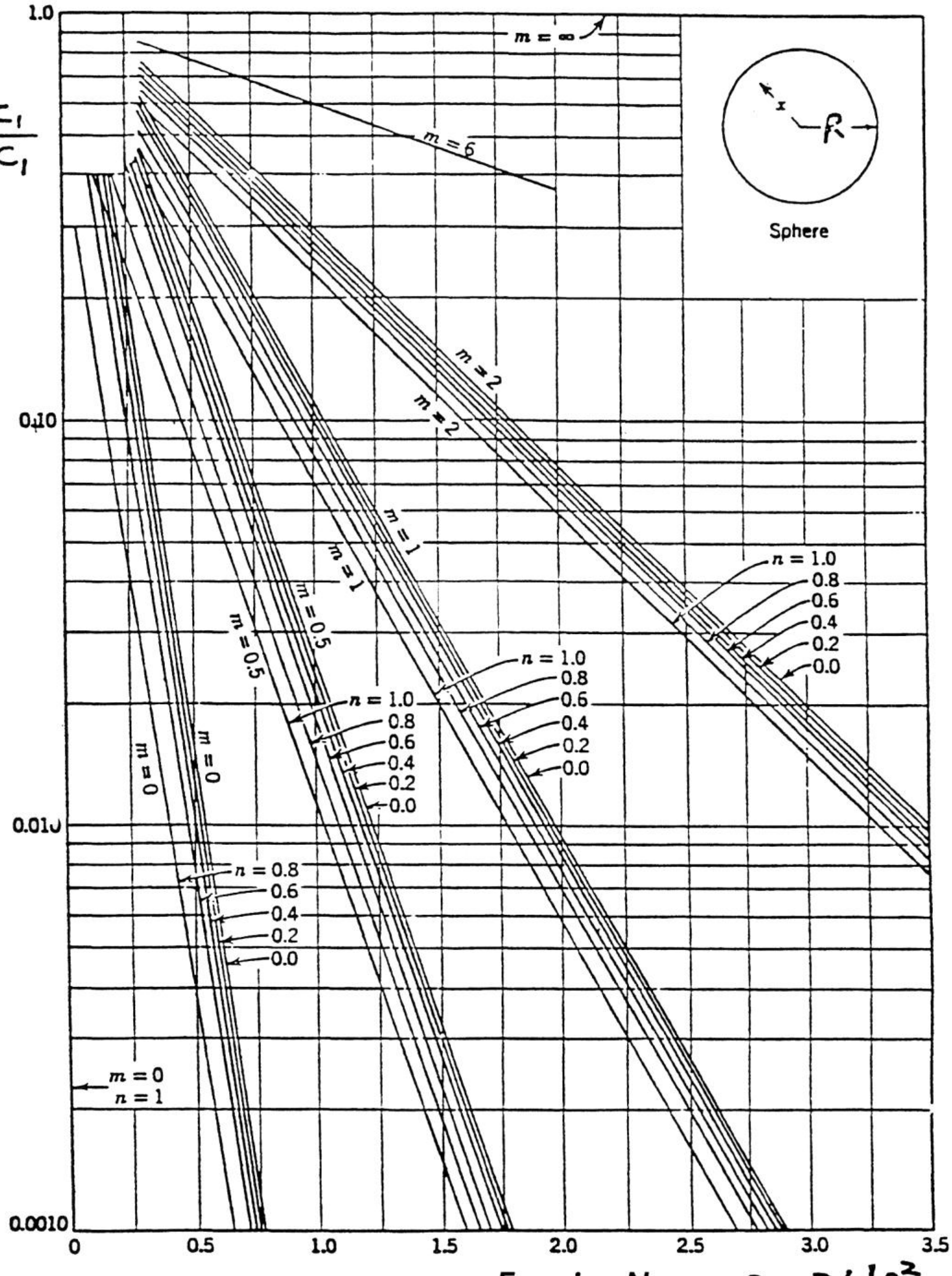
$$m = 1/Bi$$

Figure 3

POINT LOCATION IN A SPHERE

$$Y = \frac{c - c_1}{c_o - c_1}$$

$$Y = \frac{\text{conc at time m} - \text{conc at outer surface}}{\text{conc at time 0} - \text{conc at outer surface}}$$



Fourier No. = $\beta = Dt/R^2$

Unsteady-state transport in a sphere.

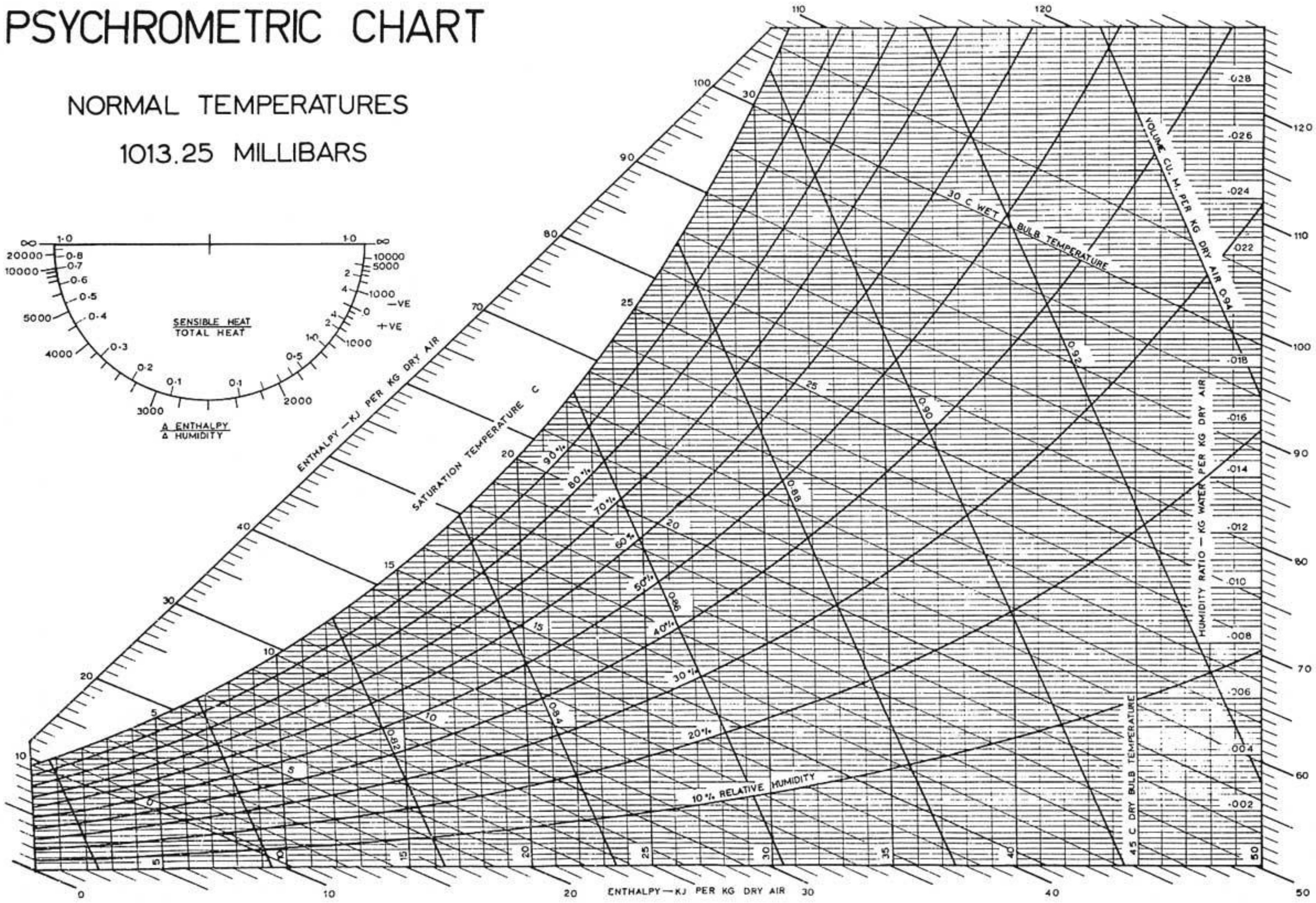
$$n = \frac{x}{R}$$

$$m = 1/Bi$$

PSYCHROMETRIC CHART

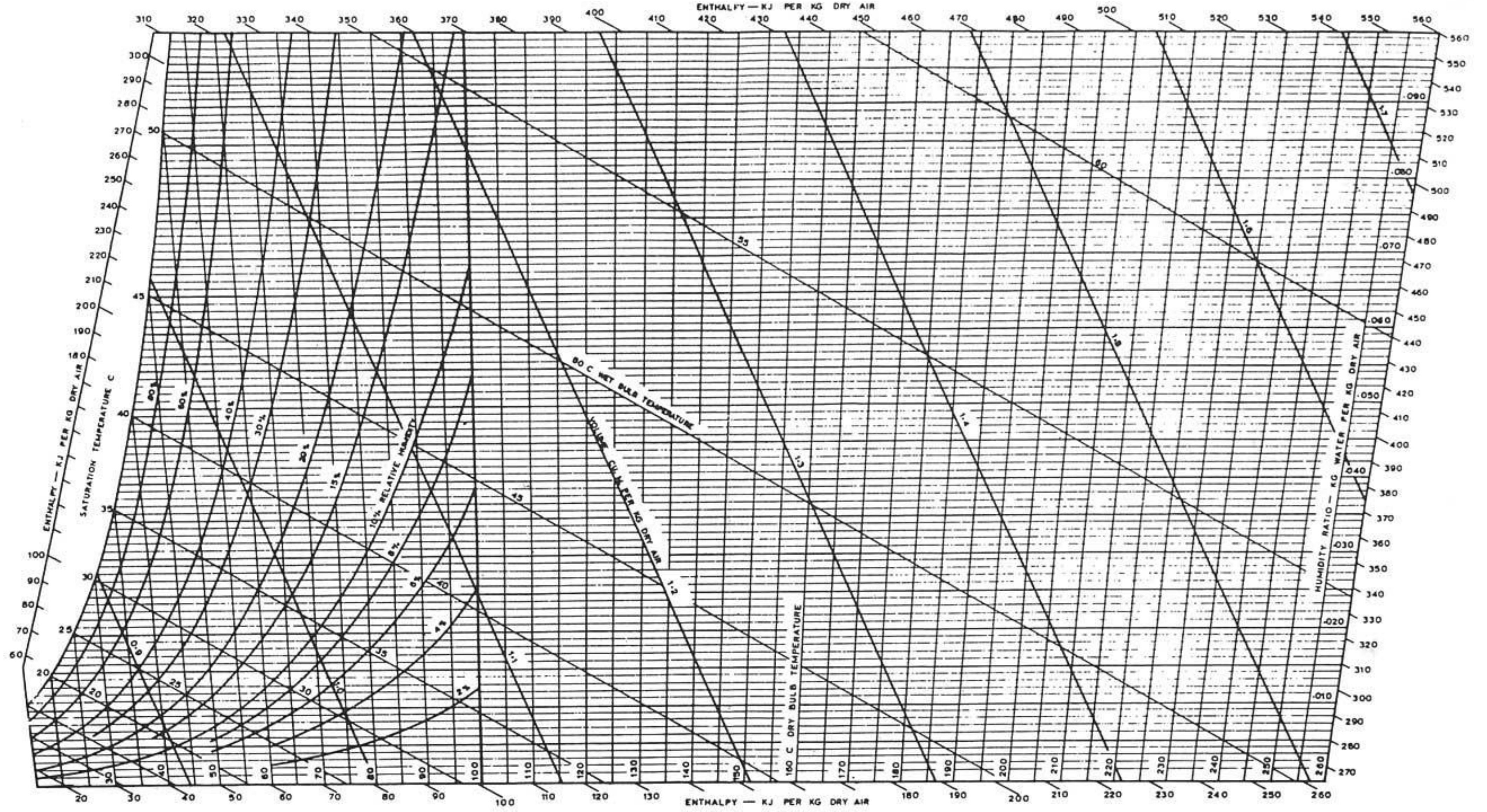
NORMAL TEMPERATURES

1013.25 MILLIBARS



PSYCHROMETRIC CHART

HIGH TEMPERATURES 1013.25 MILLIBARS



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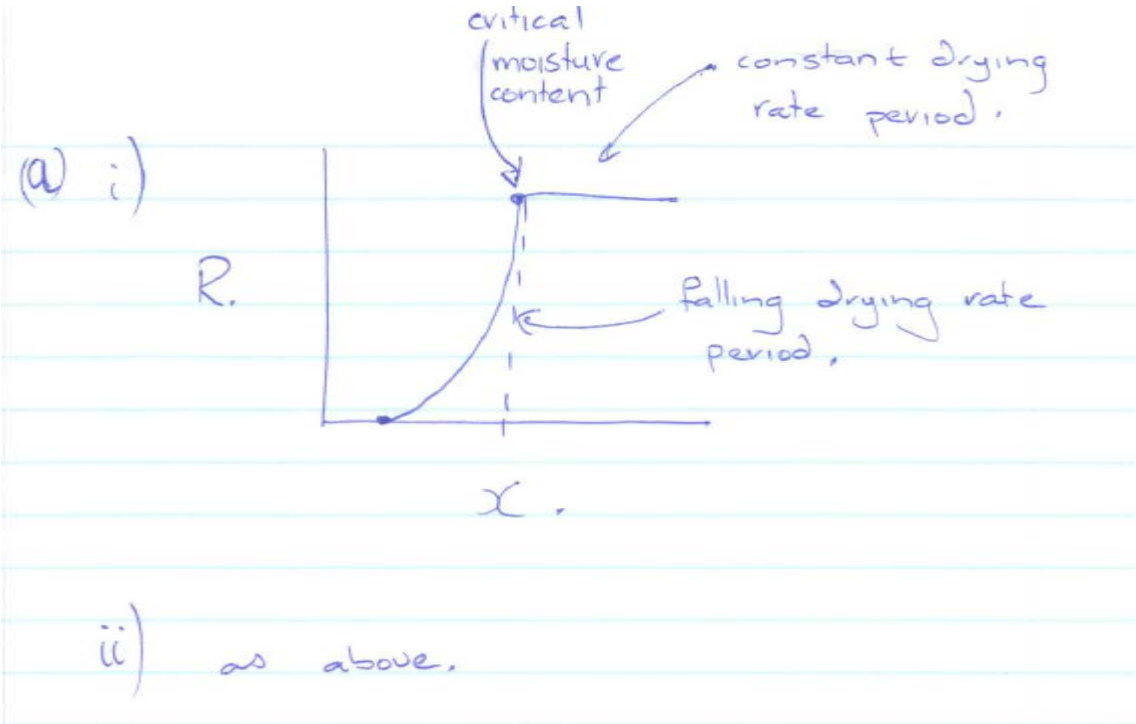
2014

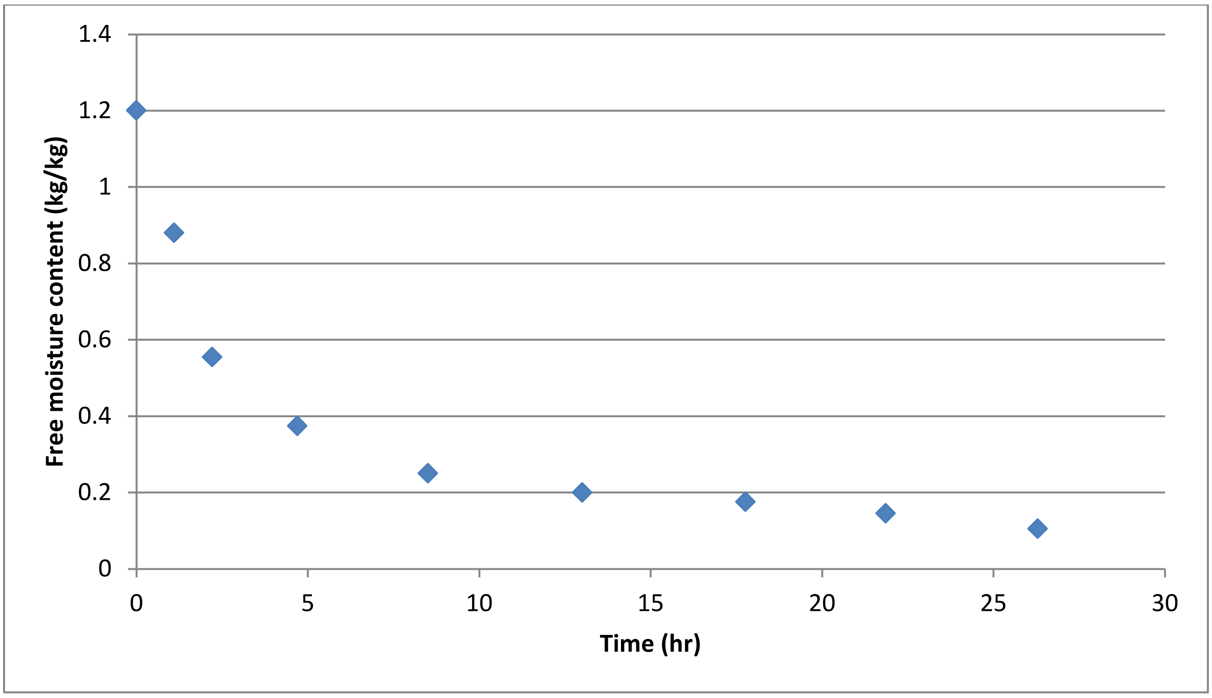
Model Answers

Question 1.



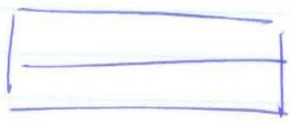
iii) Diffusion. The rate of drying in the falling rate drying period is not linearly related to the moisture content. Instead, the rate of drying decreases as the moisture content decreases.

b) Free moisture content =X-X*



c) Slope of first three points (give or take) = (1.2-0.55)/2.21=0.29kg/hr = 8.17x10^{-5}kg/s

d)



↕ 5mm.

$$D = 3 \times 10^{-10} \; \frac{m^2}{s}$$

Total Drying Time = 24 hrs.
Time in constant rate period ≈ 2.2 hrs

∴ Time in falling rate period = 21.8 hrs
= 78480 s.

$X_1 = X_c = 0.52 \; \frac{kg}{kg}$

$X_2 = 0.15 \; \frac{kg}{kg}$. (from plot)

$$\text{Fourier \#} = \frac{3\times10^{-10} \times 78480}{(5\times10^{-3})^2} = 0.942$$

$m = \frac{1}{Bi} = 0 \qquad x = 0 \qquad \therefore \; n = 0.$

(about)

$$y = 0.12 = \frac{C - 0.15}{0.52 - 0.15}$$

$$\therefore \; C = 0.1944 \; \frac{kg}{kg}$$

e) Driving force for heat/mass transfer is reduced at different temperatures. The humidity of the cooler air is higher than the hotter air. Or similar answer.

(1) Question 2.

ANSWER: DRYING QUESTION.

(a) $M_i = \frac{586}{20 \times 3600} = 0.008139 \frac{kg}{s}$.

$M_o = \frac{207}{20 \times 3600} = 0.002875 \frac{kg}{s}$.

(1)

$X_i = \frac{0.8}{1 - 0.8} = 4 \frac{kg\,w}{kg\,DS}$,

$X_o \Rightarrow$

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

$X_o = 0.766 \frac{kg\,w}{kg\,DS}$.

Rate $M_i \frac{X_i}{1+X_i} - M_o \frac{X_o}{1+X_o}$

rate of water removed

$= 0.005264 \frac{kg}{s}$.

(2) (b) H_o @ 65°C (θ_{DB}) and RH = ~~$\$0$~~% from chart.

$H_o = 0.07 \frac{kg}{kg}$.

$H_{RF} \Rightarrow$

$$m_i \left(\frac{X_i}{1+X_i}\right) + (F+R) H_{FR} = M_o \frac{(X_o)}{(1+X_o)} + (F+R) H_o.$$

$$H_{FR} = \frac{M_o \frac{X_o}{(1+X_o)} + (F+R)H_o - m_i\left(\frac{X_i}{1+X_i}\right)}{F+R}$$

$$= \frac{0.002875 \times \frac{0.766}{1.766} + \cancel{22}\,1 \times 0.07 - 0.008139 \frac{4}{5}}{\cancel{22}\,1}$$

$= 0.0674 \frac{kg}{kg}$.

(Note can also be found on psychrometric chart along line of constant enthalpy, extrapolate line back to 81C)

(2)

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

H_i = humidity air in (make up air).

H_i @ 24°C (θ_{DB}) and RH = 60% from chart.

$$H_i = 0.017 \frac{kg}{kg}.$$

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

$$= \frac{0.008139 \times \frac{4}{5} - 0.002875 \left(\frac{0.766}{1.766} \right)}{0.07 - 0.017}$$

$$= 0.0993 \frac{kg}{s} \quad \text{or appox } 10\% \text{ of } (F+R)$$

$$R = (F+R) - F$$

$$= 1 - 0.993 \simeq 0.9 \ kg/s$$

(d) $$F_{air} h_i + \phi_{in} = F_{air} h_o.$$

~~eg.~~

$$\phi_{in} = 0.1 \times (h_o - h_i)$$

~~(F+R)x~~

h_o = from chart = $255 \frac{kJ}{kg}$

h_i = from chart = $54 \frac{kJ}{kg}$

ϕ_{in} = $\cancel{19.96}$ 20.1 kW.

(3)

$$\eta_E = \frac{\phi_{evap}}{\phi_{in}}$$

$$= \frac{\left[0.008139 \times \frac{4}{5} - 0.002875 \times \frac{0.766}{1.766}\right] h_{fg}}{\cancel{19.96 \times 10^3}\ (20.1 \times 1000)}$$

h_{fg} @ θ_{WB} of air out

$\theta_{WB} = 48°C \qquad h_{fg} = 2387 \times 10^3 \frac{J}{kg}$.

$\eta_E = 0.625$ or $62\frac{1}{2}\%$

(5) • ~~Decrease the flowrate of makeup air i.e. increase recycle.~~

• ~~Increase~~

(e)

- Increase allowable moisture content in product. - less water to remove.
- Increase dryer temp. - higher driving force)
- Increase flowrate of air - higher heat transfer rate

etc.....

(f) The rate of drying changes during the day as drying moves from the constant rate to falling rate period.
Drawing drying rate curve and explain what is happening during drying of the offal in relation to this graph.