MASSEY UNIVERSITY
MANAWATU & ALBANY CAMPUSES

EXAMINATION FOR
280.371 PROCESS ENGINEERING OPERATIONS
Semester One – 2016

Time allowed: **THREE (3)** hours

FIVE (5) Questions

All questions are **COMPULSORY**

Each question is worth **TWENTY (20)** marks

This is a **CLOSED BOOK** examination

Calculators are permitted, no restrictions on type of calculator

FIVE (5) compulsory questions each worth 20 marks	**[100 marks]**
TOTAL:	**[100 marks]**

Included with the examination paper are:

Graph paper
Steam Tables
A high temperature psychrometric chart, A3
A low temperature psychrometric chart, A3
A Moody plot
A Dühring chart

At the conclusion of the exam, tie all charts to the back of the examination booklet

QUESTION 1 MEMBRANE SEPARATIONS

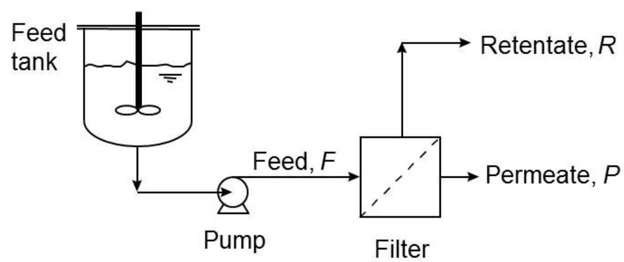
i. An ultrafiltration process is being used to concentrate a protein solution. The retentate volume after 5 h of operation is 0.5 m^3 and the retentate is four times more concentrated than the feed. If there was no leakage of protein through the membrane, the initial protein concentration in the feed was 34 kg m^{-3}, the initial permeate flux was 0.045 $m^3 m^{-2} h^{-1}$ and the final flux was 0.006 $m^3 m^{-2} h^{-1}$, determine the following:

a) the mass transfer coefficient (k) at the membrane;

b) the protein concentration (C_m) at the surface of the membrane.

[6 marks]

ii. A steady-state filtration operation as shown below is being used to concentrate a solute.



Calculate:

a) the flow rate of the retentate (R);

b) the flow rate of the permeate (P);

c) the concentration of the solute (C_p) in the permeate; and

d) the concentration of the solute (C_r) in the retentate.

Assume the following: a feed flow rate of 50 m^3/h; a solute concentration C_f in the feed of 1 g/L; a volume concentration factor of 1.5; and a solute rejection coefficient of 0.98.

[5 marks]

Question 1 continued over …….

…….. Question 1 continued

iii. The permeate flux in a microfiltration process being used to concentrate a slurry of yeast cells is being adversely affected by concentration polarization. List at least five methods that may be used to improve the flux.

[5 marks]

iv. Explain the following terms:

a) Concentration polarization.

b) Hydraulic diameter.

c) Backflushing.

d) Diafiltration.

[4 marks]

[Total 20 marks]

QUESTION 2 HEAT EXCHANGER DESIGN

A proposed counterflow double-pipe heat exchanger design has a stainless steel ($k = 16.3\ W\ m^{-1}\ K^{-1}$) inner tube with an outside diameter of 69 mm and an inside diameter of 60 mm. This is surrounded by a shell of 117 mm inside diameter. Ethylene glycol flowing in the tube at a rate of 2.0 kg/s is heated from 40°C to 60°C by hot water in the annulus, cooling from 95°C to 85°C. The tube side heat transfer coefficient is given as 650 $W\ m^{-2}\ K^{-1}$. Assume fouling resistances are negligible.

i. Calculate the length of the heat exchanger required to achieve the given temperatures.

[11 marks]

ii. Calculate the pressure drop on the annulus side. (A Moody plot is attached)

[4 marks]

iii. If the pressure drop on the annulus side is 10% greater than that available, suggest a design modification that will bring it within bounds. No calculations are required but you need to justify your answer by discussing the effect of the change on all relevant parameters.

[5 marks]

[Total 20 marks]

Question 2 continued over ……

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Fluid properties:

Ethylene glycol		
	density	1087 kg m^{-3}
	viscosity	5.15 x 10^{-3} Pa s
	heat capacity	2562 J kg^{-1} K^{-1}
	thermal conductivity	0.259 W m^{-1} K^{-1}
Water		
	density	967 kg m^{-3}
	viscosity	0.318 x 10^{-3} Pa s
	heat capacity	4205 J kg^{-1} K^{-1}
	thermal conductivity	0.675 W m^{-1} K^{-1}

Useful equations:

$$q = m_a c_a \Delta T_a = m_b c_b \Delta T_b$$

$$q = UA\nabla T_{tm}$$

$$\nabla T_{tm} = \nabla T_{lm} = \frac{\nabla T_1 - \nabla T_2}{\ln\left(\frac{\nabla T_1}{\nabla T_2}\right)}$$

$$\nabla T_{tm} = F_T \nabla T_{lm}$$

$$\frac{1}{U} = \frac{1}{h_a} + \frac{x_w}{k_w} + \frac{1}{h_b} + R_a + R_b$$

$$\frac{hD}{\lambda} = 0.023\left(\frac{Dv\rho}{\mu}\right)^{0.8}\left(\frac{c_p\mu}{\lambda}\right)^{0.4}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$\Delta P = 4 f_F \frac{L}{D}\frac{\rho v^2}{2}$$

$$A_a = \frac{\pi}{4}\left(D_o^2 - D_i^2\right) \qquad \text{(area of an annulus)}$$

$$D_h = D_o - D_i \qquad \text{(for an annulus)}$$

QUESTION 3 EVAPORATION

A single effect evaporator, which operates under vacuum at a gauge pressure of negative 0.081 MPa, is used to concentrate a Lithium Chloride solution containing 0.05 kg/kg Lithium Chloride; the product solution is quite concentrated and boiling point rise cannot be ignored. The flow rate into the evaporator is 1000 kg/h and water vapor is removed at a rate of 0.244 kg/s. Atmospheric pressure is 101.3 kPa.

The temperature difference between the condensing steam used to provide heat to the process and the boiling Lithium Chloride in the evaporator is 21°C, the energy efficiency, η, is 97.5%, and the overall heat transfer coefficient, U, is 1950 W/m^2 °C.

Calculate the heat exchanger area. [20 Marks]

You must show all your calculations and state all assumptions you make. A Dühring chart is provided to assist you. All working and line connections on the Dühring chart must be clearly shown, and the chart must be attached to your answer book and handed in with it. Steam tables are provided.
Useful equations:

$$m_F x_F = m_L x_L \qquad (1)$$

$$m_F = m_L + m_V \qquad (2)$$

$$\eta = \frac{m_V h_{fg\ vapour}}{\phi} \qquad (3)$$

$$\phi = UA(\theta_S - \theta_1) \qquad (4)$$

Notation

A	heat exchanger area, [m^2]
$h_{fg\ vapour}$	latent heat of steam, [J/kg]
m	mass flow rate, [kg/s] or [kg/h]
U	overall heat transfer coefficient, [W/m^2 °C]
x	mass fraction, [kg/kg]
φ	rate of heat transfer, [W]
η	efficiency, [-]
θ_1	temperature of boiling liquid, [°C]
θ_s	temperature of condensing steam [°C]
Subscripts	
F	feed
L	concentrate
V	vapour
S	steam

QUESTION 4 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.

[7 marks]

(iv) Calculate the heater duty required.

[2 marks]

[Total 20 marks]

Question 4 continued over …….

…….. Question 4 continued

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

Useful Equations

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

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

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

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

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

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

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

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

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

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

Question 4 continued over …….

…….. Question 4 continued

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_i	Humidity of the air at the inlet to the dryer system (make up air) (kg water/kg dry air)
H_o	Humidity of the air leaving the dryer system (purge air) (kg water/kg dry air)
H_{FR}	Humidity of air entering the dryer (make up air and recycle 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

QUESTION 5 PROCESS COOLING

A multi stage hydro cooler is used to cool corn on the cob leaving a blancher from a mass average temperature of 63°C to a mass average temperature of 15°C. The cooler uses cold water sprayed over the corn on a conveyer and the cooling time is found to be 28 minutes.

a) Calculate the product heat load for the cooler? [4 Marks]

b) What are two other heat loads for the cooler? [2 Marks]

An air blast freezer is proposed for the freezing operation. Assume the cob enters at a uniform temperature of 15°C following cooling and is required to leave with a centre temperature of -18ºC. The air temperature onto the product is -31ºC. The surface heat transfer coefficient for the proposed air flow through the bed of corn is estimated at 50 W/m^{2}K. The corn on the cob can be approximated by an infinite cylinder that has a shape factor of 2.

c) Calculate the required residence time for the corn to freeze. [12 Marks]

d) What could be altered in the freezer in order to reduce the freezing time? [2 Marks]

[Total 20 marks]

Corn on the cob data

diameter = 47 mm
length = 130 mm
mass = 0.227kg per cob
density = 1040 kg/m^3
initial freezing temperature = -1.1°C
frozen thermal conductivity = 1.633 W/m K
unfrozen thermal conductivity = 0.527 W/m K
frozen specific heat capacity = 2.0227 kJ/kg K
unfrozen specific heat capacity = 3.608 kJ/kg K
bulk density = 450 kg/m^3
Latent heat of freezing = 233.5 kJ/kg

[Total 20 marks]

Useful equations:

Chilling

$$\phi_p = \frac{m_p c_L (\theta_{in} - \theta_{out})}{t}$$

Freezing

$$t_f = \frac{1}{E}\left(\frac{\Delta H_1}{\Delta\theta_1} + \frac{\Delta H_2}{\Delta\theta_2}\right)\left(\frac{R}{h_e} + \frac{R^2}{2k_s}\right)$$

$$\Delta H_1 = \rho c_l \left(\theta_{in} - \theta_{fm}\right)$$

$$\Delta H_2 = \rho c_s \left(\theta_{fm} - \theta_{out}\right) + \rho \Delta h_f$$

$$\Delta\theta_1 = \frac{\left(\theta_{in} + \theta_{fm}\right)}{2} - \theta_a$$

$$\Delta\theta_2 = \theta_{fm} - \theta_a$$

$$\theta_{fm} = 1.8 + 0.263\theta_{out} + 0.105\theta_a$$

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