MASSEY UNIVERSITY
MANAWATU & ALBANY CAMPUSES

EXAMINATION FOR
280.371 PROCESS ENGINEERING OPERATIONS
Semester One – 2014

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

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

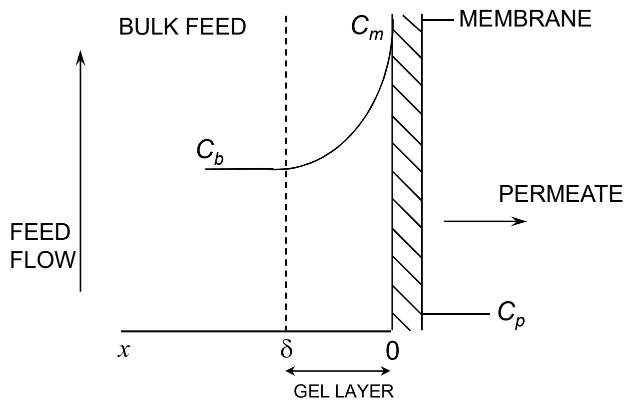
TOTAL: [100 marks]

Included with the examination paper are:
Graph paper
Steam Tables
A high temperature psychrometric chart

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

QUESTION 1 MEMBRANE SEPARATIONS

(a) The steady-state solute concentration profile in a filtration operation is shown below:



Here, C_b is the solute concentration in the bulk feed; C_m is the concentration of solute at the membrane on the feed side; C_p is the solute concentration in the permeate; and δ is the thickness of the "gel" layer.

Derive the relationship between the steady state permeate flux J and the polarization modulus (C_m/C_b). Assume $C_p = 0$.

[8 marks]

(b) The permeate flux in an ultrafiltration process being used to concentrate blood cells is being adversely affected by concentration polarization. List at least **five** methods that may be used to improve the flux.

[5 marks]

(c) Explain the following terms:
(i) Semipermeable membrane.
(ii) Solute rejection coefficient.
(iii) Permeate flux.
(iv) Hydraulic cleaning.
(v) Dead-end filtration.

[5 marks]

(d) During a steady-state ultrafiltration of a carbohydrate, the mass transfer coefficient is 1×10^{-6} m·s^{-1}. If the diffusion coefficient of the carbohydrate was 4.5×10^{-10} m^2·s^{-1}, what would be the expected thickness of the carbohydrate gel layer at the membrane?

[2 marks]

[Total: 20 marks]

QUESTION 2 HEAT EXCHANGER DESIGN

A plate heat exchanger (PHE) is being sized to pasteurise apple juice using hot water. The apple juice enters the PHE at 4°C with a volumetric flow rate of 10 L s^{-1}. It is required that the temperature of the apple juice be raised to 70°C using 90°C hot water coming in with the same volumetric flow rate as the apple juice. Assume the PHE has one pass on each side with perfect counter-current flow. The densities of the hot water and apple juice are 995 kg m^{-3} and 1050 kg m^{-3}, respectively. The heat capacity of the apple juice is 4.30 kJ kg^{-1} K^{-1} and of the hot water is 4.18 kJ kg^{-1} K^{-1}. The fouling resistance on the apple juice side is 0.00010 m^2 K W^{-1} and there is no fouling on the hot water side. The effective heat transfer coefficient on the hot water side (α_w) is known to be 5000 W m^{-2} K^{-1}.

(a) What is the temperature of the hot water coming out of the PHE after heating up the apple juice?

[4 marks]

(b) If the PHE has a total of 150 plates arranged to give one pass on each side, and each plate has a surface area of 0.50 m^2, what is the overall heat transfer coefficient (U)?

[3 marks]

(c) Find the effective heat transfer coefficient on the apple juice side (α_a) for the above set-up.

[2 marks]

(d) What are the pressure drops on the apple juice side and the hot water side for the set-up in (b)?

[4 marks]

(e) The calculations in (d) reveal that the PHE is not fully utilising the available pressure drops, and it is proposed that a configuration giving THREE passes on each side be used. For this setup, the pressure drops per pass have now increased to **THREE times** the pressure drop values found in (d). How many 0.50 m^2 plates will now be needed for this new set-up?

(Hint: Find the new effective heat transfer coefficient on each side of the PHE.)

[7 marks]

[Total: 20 marks]

Useful equations are listed on page 4 below

Question 2 continued Over…

…Question 2 continued

USEFUL EQUATIONS

$$\Phi = m\, C_p\, \Delta\theta = U\, n\, a\, F_T\, \nabla\theta_{LMTD} = U\, A\, F_T\, \nabla\theta_{LMTD}$$

$$\nabla\theta_{LMTD} = \frac{\nabla\theta_1 - \nabla\theta_2}{\ln\left(\frac{\nabla\theta_1}{\nabla\theta_2}\right)}$$

$$a = 2.68Q^{0.485}$$

$$\alpha = 3057(\Delta P_{pp})^{0.308}$$

$$\frac{1}{U} = \frac{1}{\alpha_a} + \frac{1}{\alpha_b} + R_a + R_b$$

Plate area (m^2)	Q_p
0.1	$Q_p = \left(\frac{\Delta P_{pp}}{3.73 \times 10^6}\right)^{0.633}$
0.2	$Q_p = \left(\frac{\Delta P_{pp}}{3.12 \times 10^6}\right)^{0.633}$
0.25	$Q_p = \left(\frac{\Delta P_{pp}}{2.79 \times 10^6}\right)^{0.633}$
0.5	$Q_p = \left(\frac{\Delta P_{pp}}{1.88 \times 10^6}\right)^{0.633}$
1.0	$Q_p = \left(\frac{\Delta P_{pp}}{1.59 \times 10^6}\right)^{0.633}$

QUESTION 3 EVAPORATION

A milk processing factory is trialling two evaporators for the production of condensed milk. One is a single-effect falling-film evaporator, the other is a double-effect feed-forward evaporator. Note that milk is a perishable and heat sensitive product, and is stored at 7°C before being processed.

Both evaporators use steam at 96°C as the heating medium and the **same overall temperature difference** will be used in both evaporators. The milk enters each evaporator at a flow rate of 2000 kg/h and on average has a water content of 87%. The target solids concentration for the condensed milk is 26%.

(a) With the aid of diagrams, draw the single-effect falling film evaporator, labelling the major parts and flows. Describe the primary function of each part.

[6 marks]

(b) Calculate the evaporation rate for the process.

[2 marks]

(c) The pressure inside the single-effect evaporator is set at 30 kPa.a. Calculate the energy efficiency of the evaporator, clearly stating your assumptions. Explain the significance of your answer. Assume the specific heat of the feed and product is the same and is 4.19 kJ kg^{-1} K^{-1}.

[5 marks]

(d) The double effect evaporator has milk entering at **its boiling point** and the pressure in the second-effect is 30 kPa.a. The heat transfer coefficients for each effect are 1750 and 1500 Wm^2K^{-1} for the first and second effects, respectively. Estimate the steam economy for the double-effect evaporator and based on this estimation calculate the heat transfer area for the first-effect, assuming the heat transfer area in each effect is the same. State your assumptions clearly.

[5 marks]

(e) Give one reason for choosing the single-effect evaporator and one reason for choosing the double-effect evaporator for producing the condensed milk.

[2 marks]

[Total: 20 marks]

Show your working for all calculations.
Steam tables are provided.
A useful equation is given on page 6 below.

Question three continued over …..

…Question 3 continued

Useful equation:

$$\Delta T_i = \frac{\frac{1}{U_i}}{\frac{1}{U_1} + \frac{1}{U_2}}(T_s - T_2)$$

QUESTION 4 DRYING

Green tea extract is spray dried to produce instant tea. The tea extract is sprayed as a fine mist into the top of the spray dryer together with hot air at 90°C dry bulb temperature and 32°C wet bulb temperature. Assume all drying is by convection only.

The flow rate of tea extract into the dryer is 500 kg h^{-1} and enters the dryer with a moisture content of 70% water. The instant tea powder exiting has a moisture content of 3.7% water, dry solid density of 650 kg m^{-3} and mean particle size of 300 µm. The critical moisture content for dried green tea extract is 1.5 kg water/kg dry solids.

(a) Determine the time required to dry green tea extract to a moisture content of 1.5 kg water/kg dry solids. The mass transfer coefficient k_H', during the constant rate drying period, is 9.25 kg m^{-2} s^{-1}.

[6 marks]

(b) Estimate the time required in the spray dryer to dry the green tea extract to a final m, moisture content of 3.7% water if capillary drying dominates in the falling rate period. The equilibrium moisture content for the dried green tea extract powder is 0.002 kg water/kg dry solids.
[Note: If you did not find R_C in part (a) use 0.2 kg $m^{-2}s^{-1}$.]

[4 marks]

Question 4 continued over…

… Question 4 continued

(c) Calculate the flow rate of air required in the dryer to dry 500 kg h^{-1} green tea extract solution to the final moisture content of 3.7% water if the exit air has a humidity of 0.015 kg kg^{-1}.

[4 marks]

(d) Based on a flow rate of 500 kg h^{-1}, how much water is evaporated in the dryer (kg s^{-1})?

[1 mark]

(e) What is the exit temperature of the air leaving the dryer?

[1 mark]

(f) If the dryer air is recycled back into the dryer, what impact will this have on the overall drying process?
[Note: No calculations required]

[2 marks]

(g) Recommend operating conditions or procedures to ensure the required drying rate is maintained with recycling of dryer air.

[2 marks]

[Total: 20 marks]

A high temperature psychrometric chart is provided on page14, if used, please attach it to your exam script.

Question 4 continued over…

…Question 4 continued

Useful Equations

$$mass\ of\ water\ evaporated = k_H^{'} A(H_{surface} - H_{air}) \quad (kg\ s^{-1})$$

$$R = \frac{mass\ of\ water\ evaporated}{area} \quad (kg\ m^{-2}\ s^{-1})$$

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

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

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

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

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

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

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

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

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

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 ($kg\ s^{-1}$)

$H_{surface}$ Humidity at the surface (kg water/kg dry air)

H_{air} Humidity of the air (kg water/kg dry air)

k'_H Mass transfer coefficient ($kg\ m^{-2}\ s^{-1}$)

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 ($kg\ m^{-3}$)

QUESTION 5 PROCESS COOLING

After being caught, the body temperature of blue fin tuna will rise to about 35°C. The fish are then immersed in an ice/sea water slush in which the surface heat transfer coefficient is about 250 W m^{-2} K^{-1} and the temperature is –1°C.

The fish have dimensions of 245 mm x 395 mm x 860 mm and the thermal properties of the fish are:

k_L = 0.53 W m^{-1} K^{-1}
c_L = 3,900 J kg^{-1} K^{-1}
ρ = 1020 kg m^{-3}

(a) Decide on an appropriate shape and calculate the shape factor for cooling time prediction. Compare the values of E0 and E∞ with E. What does that tell you about the problem?

[8 marks]

(b) It is required to reach a fish centre temperature of 5°C in no more than 15 hours. Is this possible?

[12 marks]

[Total: 20 marks]

Useful information is given below:

Shape	N	P_1	P_2	P_3	γ_1	γ_2	λ
Infinite slab ($\beta_1 = \beta_2 = \infty$)	1	0	0	0	∞	∞	1
Inf, rectangular rod ($\beta_1 \geq 1$, $\beta_2 = \infty$	2	0.75	0	-1	$4\beta_1/\pi$	∞	γ_1
Brick ($\beta_1 \geq 1$, $\beta_2 \geq \beta_1$)	3	0.75	0.75	-1	$4\beta_1/\pi$	$1.5\beta_2$	γ_1
Infinite cylinder ($\beta_1 = \beta_2 = \infty$)	2	1.01	0	0	1	∞	1
Infinite ellipse ($\beta_1 > 1$, $\beta_2 = \infty$)	2	1.01	0	1	β_1	∞	γ_1
Squat cylinder ($\beta_1 = \beta_2$, $\beta_1 \geq 1$)	3	1.01	0.75	-1	$1.225\beta_1$	$1.225\beta_1$	γ_1
Short cylinder ($\beta_1 = 1$, $\beta_2 \geq 1$)	3	1.01	0.75	-1	β_1	$1.5\beta_2$	γ_1
Sphere ($\beta_1 = \beta_2 = 1$	3	1.01	1.24	0	1	1	1
Ellipsoid ($\beta_1 \geq 1$, $\beta_2 \geq \beta_1$)	3	1.01	1.24	1	β_1	β_2	γ_1

Question five continued over …..

…Question 5 continued

Useful equations:

$$R = \frac{D_1}{2} \qquad \beta_1 = \frac{D_2}{D_1} \qquad \beta_2 = \frac{D_3}{D_1}$$

$$Bi = \frac{h_e R}{k_L}$$

Calculation of the equivalent heat transfer dimensionality at $Bi = 0$ (E_o) using:

(i) Ellipsoid or three-dimensional irregular shapes:

$$E_o = \frac{3\left[\beta_1 + \beta_2 + \beta_1^2(1+\beta_2) + \beta_2^2(1+\beta_1)\right]}{2\beta_1\beta_2(1+\beta_1+\beta_2)} - \frac{\left[(\beta_1-\beta_2)^2\right]^{0.4}}{15}$$

(ii) Ellipse or two-dimensional irregular shapes:

$$E_o = \left(1+\frac{1}{\beta_1}\right)\left(1+\left(\frac{\beta_1-1}{2\beta_1+1}\right)^2\right)$$

(iii) Finite cylinders, bricks, infinite rectangular rods:

$$E_o = 1 + \frac{1}{\beta_1} + \frac{1}{\beta_2}$$

(iv) sphere ($E_0 = 3$), infinite cylinder ($E_0 = 2$), infinite slab ($E_0 = 1$);

Calculation of the equivalent heat transfer dimensionality at $Bi = \infty$ (E_∞) using

$$E_\infty = 0.75 + P_1 f(\beta_1) + P_2 f(\beta_2)$$

where

$$f(\beta) = \frac{1}{\beta^2} + 0.01P_3 \exp\left(\beta - \frac{\beta^2}{6}\right)$$

$$E = \frac{Bi^{\frac{4}{3}} + 1.85}{\left(\frac{Bi^{\frac{4}{3}}}{E_\infty} + \frac{1.85}{E_o}\right)}$$

$$L_\infty = 1.271 + 0.305\exp\left(0.172\gamma_1 - 0.115\gamma_1^2\right) + 0.425\exp\left(0.09\gamma_2 - 0.128\gamma_2^2\right)$$

$$L_c = \frac{Bi^{1.35} + \frac{1}{\lambda}}{\left(\frac{Bi^{1.35}}{L_\infty} + \frac{1}{\lambda}\right)}$$

Question five continued over …..

…Question 5 continued

$$L_m = \mu L_c$$

$$\mu = \left(\frac{1.5 + 0.69Bi}{1.5 + Bi} \right)^N$$

$$t_c = \frac{3\rho c_L R^2}{\alpha^2 k_L E} \ln\left(\frac{\theta_{in} - \theta_a}{\theta_c - \theta_a} L_c \right)$$

$$\theta_c = L_c \exp\left(\frac{-k_L t_c E \alpha^2}{3\rho c_L R^2} \right)(\theta_{in} - \theta_a) + \theta_a$$

$$t_m = \frac{3\rho c_L R^2}{\alpha^2 k_L E} \ln\left(\frac{\theta_{in} - \theta_a}{\theta_c - \theta_a} L_m \right)$$

$$\theta_m = L_m \exp\left(\frac{-k_L t_m E \alpha^2}{3\rho c_L R^2} \right)(\theta_{in} - \theta_a) + \theta_a$$

A Table of B_i-α values follows on page 13.

Question five continued over …..

…Question 5 continued

Table of B_i-α values

Bi	α	*Bi*	α	*Bi*	α	*Bi*	α
0.01	0.173	0.60	1.264	1.80	1.959	8.50	2.786
0.02	0.244	0.65	1.310	2.00	2.029	9.00	2.804
0.03	0.299	0.70	1.353	2.20	2.092	9.50	2.821
0.04	0.345	0.75	1.393	2.40	2.148	10.00	2.836
0.05	0.385	0.80	1.432	2.60	2.200	11.00	2.863
0.06	0.422	0.85	1.469	2.80	2.246	12.00	2.885
0.08	0.486	0.90	1.504	3.00	2.289	13.00	2.904
0.10	0.542	0.95	1.538	3.20	2.328	14.00	2.921
0.12	0.593	1.00	1.571	3.40	2.364	15.00	2.935
0.14	0.639	1.05	1.602	3.60	2.397	16.00	2.948
0.16	0.682	1.10	1.632	3.80	2.427	18.00	2.969
0.18	0.722	1.15	1.661	4.00	2.456	20.00	2.986
0.20	0.759	1.20	1.689	4.50	2.518	25.00	3.017
0.25	0.845	1.25	1.716	5.00	2.570	30.00	3.037
0.30	0.921	1.30	1.741	5.50	2.615	35.00	3.052
0.35	0.990	1.35	1.766	6.00	2.654	40.00	3.063
0.40	1.053	1.40	1.791	6.50	2.687	50.00	3.079
0.45	1.111	1.45	1.814	7.00	2.717	60.00	3.089
0.50	1.16	1.50	1.837	7.50	2.742	80.00	3.102
0.55	1.27	1.60	1.880	8.00	2.765	100.00	3.110