MASSEY UNIVERSITY
MANAWATU & ALBANY CAMPUSES

EXAMINATION FOR
280.371 PROCESS ENGINEERING OPERATIONS
Semester One – 2015

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
A low temperature psychrometric chart
A heat exchanger chart

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

QUESTION 1 MEMBRANE SEPARATIONS

(a) Pure water flux through a microfiltration membrane operating at a transmembrane pressure of 5×10^{5} Pa is 1×10^{-4} $m^3\cdot m^{-2}\cdot s^{-1}$. A slurry of yeast cells in water is filtered through this membrane at a transmembrane pressure of 6×10^{5} Pa. The measured steady-state water flux is now 5×10^{-6} $m^3\cdot m^{-2}\cdot s^{-1}$. The viscosity of the water at the processing temperature is 1.2×10^{-3} Pa·s.

(i) What is the resistance of the membrane?

[4 marks]

(ii) Calculate the resistance of the cake of yeast cells.

[4 marks]

(iii) What would be the thickness of the deposited cake if its specific resistance is 2×10^{18} m^{-2}?

[2 marks]

(b) A steady-state ultrafiltration process is being used to concentrate a protein. The concentration of the protein in the feed is 0.05 $kg\cdot m^{-3}$. If the feed flow rate is 10 $m^3\cdot h^{-1}$ and the volume concentration factor *VCF* is 8, calculate:

(i) The flow rates of the permeate and the retentate.

[2 marks]

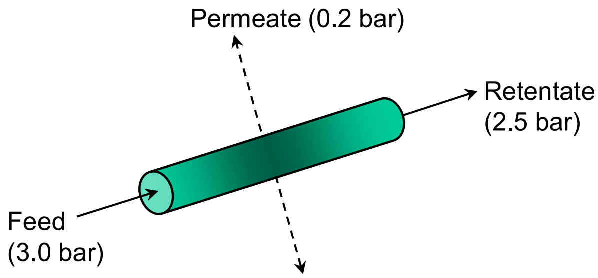
(ii) The protein concentration in the retentate if the solute rejection coefficient (*SRC*) is 0.96.

[3 marks]

Question 1 continued over …….

……. Question 1 continued

(c) "The transmembrane pressure for the case shown below is …"



Select **one** of the options (i) to (v) below for correctly completing the above statement.

(i) 5.30 bar.

(ii) 2.55 bar.

(iii) 0.30 bar.

(iv) 2.58 atm.

(v) 0.30 atm.

[2 marks]

(d) In microfiltration of a slurry of yeast cells, what would be the expected effects on limiting flux, of the following:

(i) A lowering of temperature.

(ii) An increase in cross flow rate.

(iii) Dilution of the cell slurry with water.

[3 marks]

[Total 20 marks]

QUESTION 2 HEAT EXCHANGER DESIGN

A Thailand-based beverage company has a shell and tube heat exchanger with 1 shell passes and 2 tube passes to heat a coconut milk product from 20°C to 80°C. The coconut milk product will flow through the tubes at 10,000 L h^{-1} with a bulk density of 950 kg m^{-3}. Hot water with a specific heat capacity of 4180 J kg^{-1} K^{-1} and density 990 kg m^{-3} is available for the shell at a flow rate of 25,000 L h^{-1} and a temperature of 100°C.

The coconut milk product has a fat content of 10% and a total solids content of 15%. The remainder of the product is effectively water.

(a) Calculate the amount of heating required (kW) to bring the temperature of the coconut milk product to 80°C?

The specific heat capacity of the milk product can be estimated using Eq (2A):

$$C_{p\ \text{coconut milk}} = 4180W + 1400S + 1900F \qquad (2A)$$

where:

$C_{p\ \text{coconut milk}}$ = specific heat capacity of coconut milk (J kg^{-1} K^{-1})
W = water fraction
F = fat fraction
S = non-fat solids fraction

[3 marks]

(b) If the full available heating water flow rate is used, what is the required UA value of the heat exchanger? The F_T vs S diagram for the heat exchanger is shown in Figure 2A (attached).

[5 marks]

(c) The shell side heat transfer coefficient is estimated to be 5000 W m^{-2} K^{-1} and the tube side heat transfer coefficient is estimated to be 2800 W m^{-2} K^{-1}. The available heat exchanger has 32 tubes/pass. The tubes have a length of 4 m, an external diameter of 20 mm, a wall thickness of 1.5 mm and a thermal conductivity of 20 W m^{-1} K^{-1}. Is the existing heat exchanger in its current configuration suitable for this duty?

Assume that there is no fouling resistance on the hot water side and the fouling factor is 0.00015 m^2 K W^{-1} on the tube side.

[5 marks]

Question 2 continued over …….

……. Question 2 continued

(d) Estimate the frictional pressure drop on the tube side. The bulk viscosity of the coconut milk product is 1.0 x 10^{-3} Pa s. Assume the ratio of wall to bulk viscosity is 1.

[4 marks]

(e) The coconut milk feed pump is capable of generating 50 kPa pressure across the tube side of the heat exchanger. The baffle number and spacing can be modified if necessary or the ends can be modified to change the number of tube passes. How would you modify the current design to make a small increase (5-10%) in the heat transfer capacity of the heat exchanger? (No calculations are required but explain your reasoning).

[3 marks]

[Total 20 marks]

USEFUL EQUATIONS **(**The equations are the same, but are written with different symbols for Albany and Palmerston North)

Albany

$$\phi = mc_p\Delta\theta = UAF_T\Delta\theta_{LMTD}$$

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

$$\frac{1}{U} = \frac{1}{h_t} + \frac{r_2 - r_1}{\lambda_w} + \frac{1}{h_{ss}} + R$$

$$A = 2\pi\left(\frac{r_1 + r_2}{2}\right)L\,N$$

$$v_t = \frac{Q_t}{\frac{\pi D^2}{4}N_{t/pass}}$$

$$f_{F,t} = 0.25(1.82\log_{10}(Re_t) - 1.64)^{-2}$$

$$\Delta P_t = \frac{2f_{F,t}\rho LN_p v_t^2}{D}\left(\frac{\mu_w}{\mu}\right)^{0.14} + 2\rho v_t^2 N_p$$

$$Re_t = \frac{Dv_t\rho}{\mu}$$

Palmerston North

$$q = mc_p\Delta T = UAF_T\nabla T_{lm}$$

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

$$\frac{1}{U} = \frac{1}{h_t} + \frac{r_o - r_i}{k_w} + \frac{1}{h_{ss}} + R$$

$$A = 2\pi\left(\frac{r_o + r_i}{2}\right)LN$$

$$v_t = \frac{Q_t}{\frac{\pi D^2}{4}N_{t/pass}}$$

$$f_{F,t} = 0.25(1.82\log_{10}(Re_t) - 1.64)^{-2}$$

$$\Delta P_t = 4f_{F,t}\frac{LN_p}{D}\frac{\rho v_t^2}{2} + 4N_p\frac{\rho v_t^2}{2}$$

$$Re_t = \frac{Dv_t\rho}{\mu}$$

QUESTION 3 EVAPORATION

A New Zealand dairy factory is considering installing a new evaporator to reduce the effluent volumes for final disposal. The daily volume of waste to be evaporated is 620 m^3, and its density is 1003 $kg.m^{-3}$; the waste is to be concentrated from 3.5 % (w/w) solids to 30 % (w/w) solids in 16 hours. Process steam is available at 220 kPa.a. The waste contains both dissolved and particulate solids and is known to be moderately fouling and viscous when heated in concentrated form. The evaporator system must be housed within the existing dairy factory building.

(a) Two second-hand falling film evaporators have been found at the back of the factory, left-over after a major refurbishment. Explain the key operating features of this type of evaporator including its advantages and disadvantages. Would they be a suitable choice for the required application?

[4 marks]

(b) A two-effect feed-forward evaporator is proposed, using the same area in each stage. Steam evaporated in stage 1 is used as the heat source for stage 2. Boiling point elevation can be ignored and the vapour flow rates can be assumed to be the same in each stage. The evaporation temperature in the second stage is to be 105°C. The overall heat transfer coefficient, *U,* depends on the product concentration, x_{Li}, of the product leaving an evaporation stage and is given by Equation 3 below.

Calculate:

(i) The mass flow rates of feed, final product and the vapour flow rates removed in each stage.
(ii) The intermediate product concentration leaving stage 1.
(iii) The *U* values for each stage and the evaporation temperature in stage 1.
(iv) The required steam flow rate to the first stage and its steam economy ($kg.kg^{-1}$).

[14 marks]

(c) If boiling point elevation had been significant in this case, what would the major consequence(s) be?

[2 marks]

[Total 20 marks]

Useful equations are given below; the symbols are defined in the list of Notation.

Question 3 continued over …….

…….. Question 3 continued

You must show and explain all your working, and justify any assumptions you make.

Steam tables are provided.

Useful Equations

$$m_F x_F = m_{L_i} x_{Li} \tag{1}$$

$$m_F = \sum m_{Vi} + m_L \tag{2}$$

$$U = 1900\exp(-4\, x_{Li}) \tag{3}$$

$$(\theta_i - \theta_{i+1}) = \frac{\frac{1}{U_{i+1}}}{\frac{1}{U_1} + \frac{1}{U_2}}(\theta_s - \theta_2) \tag{4}$$

Notation

m_{Li}	mass flow rate of product leaving stage *i* [kg s^{-1}]
m_F	mass flow rate of feed entering the first stage [kg s^{-1}]
m_{Vi}	mass flow rate of vapour leaving stage *i* [kg s^{-1}]
U_i	Overall heat transfer coefficient in stage *i* [W m^{-2} k^{-1}]
x_F	Concentration of solids entering stage 1 [kg kg^{-1}]
x_{Li}	Concentration of solids leaving stage *i* [kg kg^{-1}]
θ_i	Temperature of boiling liquid in stage *i* [°C]
θ_s	Temperature of primary steam entering stage 1.

QUESTION 4 DRYING

After graduating from a well known University, you immediately find employment with a company manufacturing food products.

In one of their processes, a particulate feedstock containing significant amounts of moisture is dried before further processing.

One of your first tasks is to carry out preliminary calculations on the performance of the dryer.

You are given the following information and guidelines:

- The configuration of the dryer is as depicted in Figure 1; the symbols are defined in the list of Notation below.
- The Make-up air is at 30°C, dry bulb, and its wet bulb temperature is 15 °C.
- The Dryer air Feed is at 85°C, dry bulb, and its wet bulb temperature is 41 °C.
- The Purge air leaving the dryer is at 55°C, dry bulb.
- In a test to measure the mass flow rate of the dry solids, 4.8 kg are collected in one minute.
- The moisture content of the solids leaving the dryer is 0.028 kg kg $^{-1}$.
- The ratio of the moisture content of the solids entering the dryer to the moisture content of the solids leaving the dryer is 100:1.

(a) Calculate the mass flow rate of the wet solids entering the dryer; give your answer in kg s^{-1}.

[4 marks]

(b Calculate the flow rate of the Make-up air; give your answer in kg s^{-1-}.

[6 marks]

Question 4 continued over …….

…….. Question 4 continued

(c) Calculate the flow rate of the Recycle air; give your answer in kg s^{-1}.

[6 marks]

(d) Calculate the heat input to the dryer, Φ_{in} ; give your answer in kW. (In your calculations you can assume that there are no heat losses).

[4 marks]

[Total 20 marks]

Useful equations are given below; the symbols are defined in the list of Notation.

You must show and explain all your working, and justify any assumptions you make.

A psychrometric chart is provided. You must attach the chart to your exam script and hand it in with your answer; any lines you draw on the chart, and any points you mark on the chart must be clearly visible.

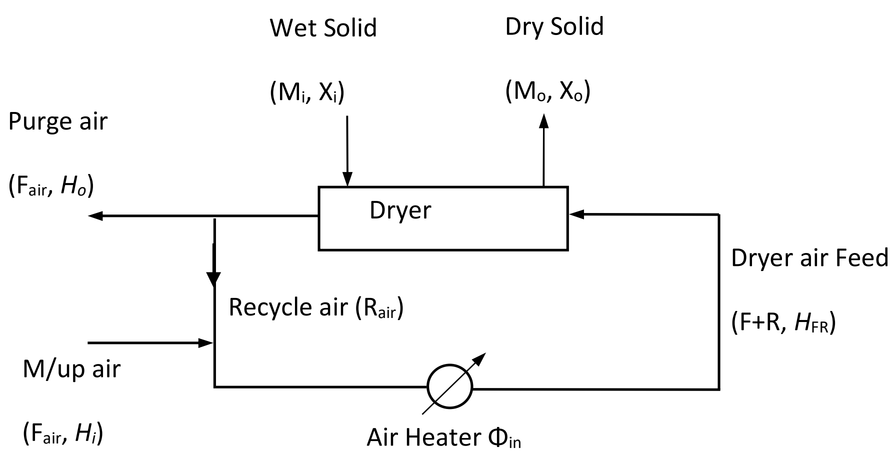


Figure 1 Schematic diagram of Dryer

Question 4 continued over …….

…….. Question 4 continued

Useful equations:

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

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

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

$$F_{air} h_i + \phi_{in} = F_{air} h_o$$

Notation

F_{air}	Flow rate of Make-up air [kg s^{-1}]
h_i	Specific enthalpy of Make-up air [kJ kg^{-1}]
h_o	Specific enthalpy of Purge air [kJ kg^{-1}]
H_i	Humidity of Make-up air [kg kg^{-1}]
H_o	Humidity of Purge air [kg kg^{-1}]
H_{FR}	Humidity of air entering dryer [kg kg^{-1}]
M_i	Flow rate of wet solids [kg s^{-1}]
M_o	Flow rate of dry solids [kg s^{-1}]
R_{air}	Flow rate of Recycle air [kg s^{-1}]
X_i	Moisture content of solid feed [kg (kg dry solid)$^{-1}$]
X_o	Moisture content of solid Product [kg (kg dry solid)$^{-1}$]

QUESTION 5 PROCESS COOLING

You are working for a company that produces beef stock in 1 kg stand-up pouches. The pouches are ellipsoidal in shape with dimensions of 60, 130 and 260 mm. The product is hot filled at 75°C vacuum sealed into plastic pouches (200 μm thick) and then cooled to 15°C in a continuous immersion cooler. The product is then frozen to -18°C in a continuous blast freezer.

The thermal and physical properties for the beef stock are:

Unfrozen specific heat:	3690 J $kg^{-1}K^{-1}$
Frozen specific heat:	1900 J $kg^{-1}K^{-1}$
Unfrozen thermal conductivity:	0.60 W $m^{-1}K^{-1}$
Frozen thermal conductivity:	1.5 W $m^{-1}K^{-1}$
Density:	1030 kg m^{-3}
Latent heat of Freezing:	215000 J kg^{-1}

Thermal conductivity of the plastic pouch material is 0.1 W $m^{-1}K^{-1}$

The immersion cooler will operate with brine at 0°C and a heat transfer coefficient to the surface of the package is estimated to be 150 W $m^{-2}K^{-1}$.

The blast freezer will operate with an air velocity of 6 m s^{-1} and an air temperature of -35°C.

(a) Calculate the product heat load, in Watts, that needs to be removed by the immersion chiller if 1000 pouches are to be processed per hour.

[3 Marks]

(b) Calculate the required residence time in the blast freezer in minutes.

[15 Marks]

(c) Identify four (4) heat loads that are usually relevant for the blast freezer.

[2 Marks]

[Total 20 marks]

Question 5 continued over …….

…….. Question 4 continued

Useful information

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

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

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

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

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

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

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

$$E = 1 + \frac{1 + \frac{2}{Bi}}{\beta_1^2 + \frac{2\beta_1}{Bi}} + \frac{1 + \frac{2}{Bi}}{\beta_2^2 + \frac{2\beta_2}{Bi}}$$

$$\beta_1 = \frac{A}{\pi R^2}$$

$$\beta_2 = \frac{3V}{4\pi R^3 \beta_1}$$

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

$$\frac{1}{h_e} = \frac{1}{h_a} + \frac{x_p}{k_p} + \frac{x_a}{k_a}$$

For large oval objects (R > 0.05m): $h_e = 12.5v^{0.6}$

For large planar objects (R > 0.05m): $h_e = 7.3v^{0.8}$

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