注意：考試開始鈴響前，不得翻閱試題，

並不得書寫、畫記、作答。

國立清華大學 109 學年度碩士班考試入學試題

系所班組別：化學工程學系

科目代碼：0901

考試科目：輸送現象及單元操作

—作答注意事項—

1. 請核對答案卷（卡）上之准考證號、科目名稱是否正確。
2. 作答中如有發現試題印刷不清，得舉手請監試人員處理，但不得要求解釋題意。
3. 考生限在答案卷上標記「由此開始作答」區內作答，且不可書寫姓名、准考證號或與作答無關之其他文字或符號。
4. 答案卷用盡不得要求加頁。
5. 答案卷可用任何書寫工具作答，惟為方便閱卷辨識，請儘量使用藍色或黑色書寫；答案卡限用 2B 鉛筆畫記；如畫記不清（含未依範例畫記）致光學閱讀機無法辨識答案者，其後果一律由考生自行負責。
6. 其他應考規則、違規處理及扣分方式，請自行詳閱准考證明上「**國立清華大學試場規則及違規處理辦法**」，無法因本試題封面作答注意事項中未列明而稱未知悉。

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　　　*請在【答案卡】作答

Problem 1 (20%)

Each sub-question is 2% in score.

1. Apheresis is a process of removing specific blood cells of the blood while returning the remaining components in blood plasma (the yellowish liquid) into the body. The separated blood cells can be used for other medical applications such as cell therapy. This process can be performed using a continuous flow centrifuge. To understand the fundamental physics of the blood separation, the viscosity of blood, therefore, is a critical parameter to be addressed. Numerous empirical model for the viscosity of blood is proposed below:

$$\mu_B = \mu \exp\left(1 + \frac{6}{\gamma^{0.75}}\right)\frac{5H}{(1-H)^{0.5}}$$

where μ_B is the viscosity of blood, μ is the viscosity of plasma, γ is the shear rate, and H is the fractional volume concentration of cells or hematocrit. If the H and μ are constant, please identify the blood belongs to which fluid.
(A) Newtonian fluid, (B) Shear-thinning fluid, (C) Shear-thickening fluid,
(D) Bingham fluid, (E) None of the above.

2. The normal range for hematocrit is different between the sexes and is approximately 45% to 52% for men and 37% to 48% for women. Please choose the highest viscosity of blood based on the equation in Question 1 of Problem 1.
(A) The men's blood at 25°C, (B) The men's blood at 37 °C, (C) The women's blood at 25°C, (D) The women's blood at 37°C, (E) Not enough information to answer.

3. The sedimenting velocity (v_s) of a cell suspended in plasma at the infinite dilution can be determined from Stokes' Law. During the centrifugation process, a single cell (radius R, density ρ_s) suspended in the plasma (density ρ, viscosity μ) is under three different forces: buoyance force ($F_B = \frac{4}{3}\pi R^3 \rho a$), fluid drag force ($F_D = 6\pi\mu_B R v_\infty$), and centrifugal force ($F_C = \frac{4}{3}\pi R^3 \rho_s a$). The symbol "$a$" refers to the centrifugal acceleration. Assume the plasma around the cells is a creeping flow. Please identify v_s.

(A) $v_s = \dfrac{2R^2(\rho_s - \rho)a}{9\mu}$, (B) $v_s = \dfrac{4R^2(\rho_s - \rho)a}{9\mu}$, (C) $v_s = \dfrac{4R^3(\rho_s - \rho)a}{9\mu}$,

(D) $v_s = \dfrac{4R^3(\rho - \rho_s)a}{9\mu}$, (E) $v_s = \dfrac{4R^3(\rho_s + \rho)a}{9\mu}$.

4. If a single white blood cell (R = 6 μm, ρ_s = 1.062 g/cm^3) is centrifuged from a tube containing 10 cm-hight plasma solution (ρ = 1.024 g/cm^3, μ = 1.32 cp) at 500 RCF (g force), how much time does it take to centrifuge the cell down to the bottom of the tube? [Note: 1 RCF = 9.8 m/s^2]
(A) 1 min, (B) 1.5 min, (C) 2.5 min, (D) 5 min, (E) 10 min.

5. The sedimenting velocity of high concentrated white blood cells v_W can be expressed as the following equation:

$$v_w = v_s \times \frac{(1-\xi H)(1-H)^{0.5}}{6.6H}, \text{ where } \xi = \frac{\rho_R - \rho}{\rho_W - \rho}$$

Assume the density red blood cell ρ_R is 1.096 g/cm^3, the density of white blood cells ρ_W is 1.062 g/cm^3, and the density of plasma ρ is 1.024 g/cm^3. Hematocrit H is equal to 40%. Please calculate the required time to centrifuge a high concentration of white blood cells to the bottom of the 10-cm length tube.
(A) 5 min, (B) 10 min, (C) 15 min, (D) 20 min, (E) 25 min.

6. Another approach to obtain the single-cell sedimenting velocity is based on the plot of friction factor f (or drag coefficient) verse Reynolds number. Friction factor and Reynolds number can be derived as the following equation.

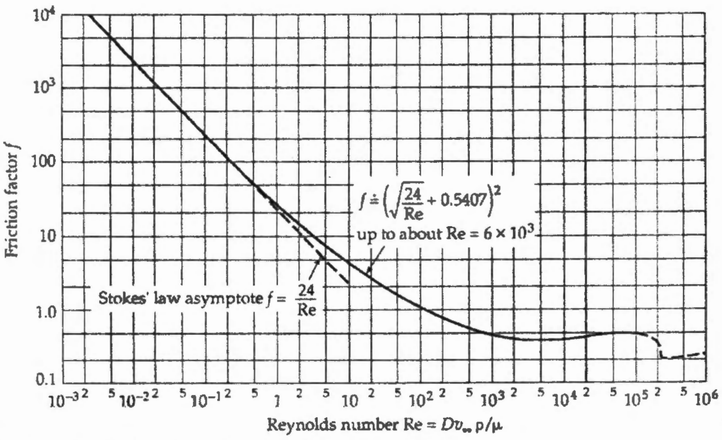
$$f = \frac{4}{3}\frac{aD}{v_s^2}\left(\frac{\rho_s - \rho}{\rho}\right), \quad \text{Re} = \frac{Dv_s\rho}{\mu}$$

To avoid the unknown v_s, a simple technique is used to obtain the relationship between f and Re by combining them to fit f-Re plot. Please identify which combination is an appropriate step.

(A) $\text{Re} f$, (B) $\frac{\text{Re}}{f}$, (C) $\frac{f}{\text{Re}}$, (D) $\frac{\text{Re}}{\sqrt{f}}$, (E) $\text{Re}\sqrt{f}$.

7. Continue the above question. Please calculate the number of the combination of Re and f. Assume all parameters are the same with Question 4 of Problem 1.
(A) 0.1, (B) 0.2, (C) 0.3, (D) 0.4, (E) 0.5

8. A straight line from the combination of Re and f can intersect with the curve of f-Re plot. Based on the intersection point, please identify actual Re from the f-Re plot illustrated below. [Hint] set f = 1 and 10^4 to obtain corresponding Re



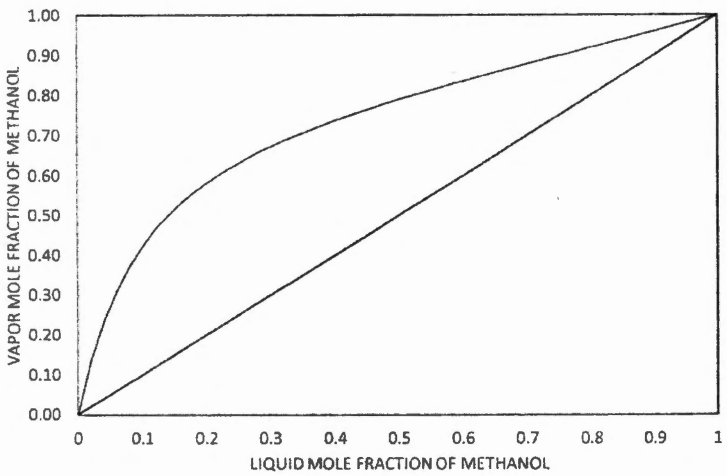
(A) 0.001, (B) 0.005, (C) 0.01, (D) 0.05, (E) 0.1

9. Using the friction factor correlation, the sedimenting velocity can be calculated from the obtained Re. What is the percentage difference between the sedimenting velocity of a single cell obtained from Stokes' Law and friction factor methods? Please choose the close answer.
(A) 1%, (B) 5%, (C) 10%, (D) 15%, (E) 20%.

10. Please choose the **WRONG** answer.
(A) Stoke's Law is the force required to move a sphere through a given viscous fluid at low uniform velocity is directly proportional to the velocity and radius of the sphere.
(B) For creeping flow, the convection can be ignored.
(C) Diffusion plays no role in centrifugal separations.
(D) Shear enhances the cell sedimentation process.
(E) For the flow around spheres, there is a well defined laminar-turbulent transition.

Problem 2 (20%)

Each sub-question is 2% in score.



The equilibrium curve of methanol and water is given as above.
It is necessary to separate a saturated liquid mixture of 10 kgmol/hr containing 50 mol% of methanol and 50 mol% of water into a distillate containing 95% of methanol and a bottom product containing 95 mol% of water

11. Which of the following is closest to the minimum number of stage required for this separation?
(A) 3, (B) 5,(C) 7,(D) 9, (E) 11

12. Which of the following is closest to minimum reflux required for this separation?
(A) 0.25, (B) 0.45, (C) 0.65, (D) 0.85, (E) 1.05

13. Which of the following is closest to the optimal reflux required for this separation?
(A) 0.1, (B) 0.5, (C) 1, (D) 5, (E) 10

14. Which of the following is closest to the actual the number of stage required if the reflux ratio is 1
(A) 3, (B) 5, (C) 7, (D) 9, (E) 11

In Question 15, 16, 17 and 18 of Problem 2: If feed is changed into a saturated vapor
15. What will happen to minimum number of stage required for this separation?
(A) Increase, (B) Decrease, (C) Unchanged.

16. What will happen to minimum reflux required for this separation?
(A) Increase, (B) Decrease, (C) Unchanged.

17. What will happen to condenser duty required for this separation?
(A) Increase, (B) Decrease, (C) Unchanged.

18. What will happen to reboiler duty required for this separation?
(A) Increase, (B) Decrease, (C) Unchanged.

In Question 19 and 20 of Problem 2: It was found that the latent heat of a liquid of 95 mol% methanol is about 40000 kJ/kgmol. The condensing temperature is about 65 °C. Given that the feed is saturated liquid and reflux ratio is 1 as in Question 14 of Problem 2:

19. What is the condenser duty required?
(A) 40000 kJ/hr, (B) 200000 kJ/hr, (C) 400000 kJ/hr, (D) 2000000 kJ/hr, (E) 4000000 kJ/hr

20. If cooling water at 25 °C is used and exit temperature is about 45 °C, which of the following is closest to the Log Mean Temperature Difference (LMTD) in the condenser?
(A) 20 °C, (B) 25 °C, (C) 30 °C, (D) 35 °C, (E) 40 °C

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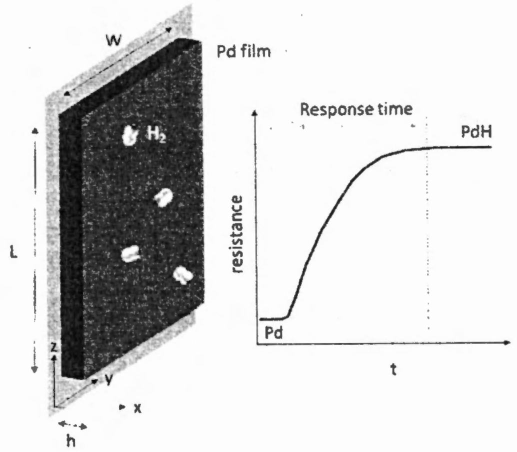
Problem 3 (10%)



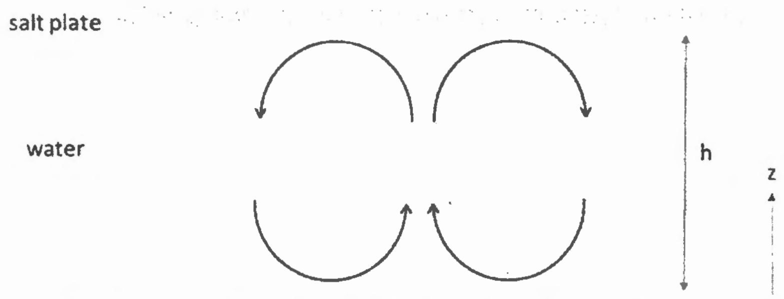
A 1-D hydrogen (H_2) sensor made of metallic palladium (Pd) thin film through the formation of palladium hydride (PdH). The amount of H_2 is reflected in the change in the measured resistance due to the lower conductivity of PdH compare with Pd. An important feature of H_2 sensor is the response time, *i.e.*, how fast the sensor respond to a certain concentration. The response of a Pd based hydrogen sensor is typically limited by the mass transfer of atomic hydrogen inside the Pd metal described by Fick's 2nd law of diffusion. With the aforementioned information, please answer the following:

(1) What is the mathematical form of Fick's 2nd law of diffusion in 1-D form? *(2%)*
(a) $j = -\mathfrak{D}\,\frac{d[H]}{d\ell}$, (b) $\frac{\partial[H]}{\partial t} = -\mathfrak{D}\,\frac{d^2[H]}{d\ell^2}$, (c) $\frac{\partial[H]}{\partial \ell} = \mathfrak{D}\,\frac{d^2[H]}{d\ell^2}$, (d) $\frac{\partial[H]}{\partial t} = -\mathfrak{D}\,\frac{d^2[H]}{dt^2}$

(2) Assuming the concentration of hydrogen at the surface is equal to the bulk concentration $[H_2]_{bulk}$. What are the boundary conditions best describing this problem? *(3%)*
(a) At y=0, $[H_2]=[H_2]_{bulk}$; at y=W, $[H_2]=[H_2]_{bulk}$
(b) At x=0, $[H_2]=[H_2]_{bulk}$; at y=h, $[H_2]=0$
(c) At z=0, $[H_2]=[H_2]_{bulk}$; at z=L, $[H_2]=[H_2]_{bulk}$
(d) At x=0, $[H_2]=0$; at x=h, $[H_2]=[H_2]_{bulk}$

(3) In order to accelerate the response (decrease response time), one can decrease the diffusion length (l) of hydrogen atom in Pd. How does response time (t_R) changes with film thickness l? *(5%)*
(a) $t_R \propto \ell$, (b) $t_R \propto \ell^2$, (c) $t_R \propto \frac{1}{\ell}$, (d) $t_R \propto \frac{1}{\ell^2}$

Problem 4 (10%)



An infinite large salt plate is placed above a stagnant water layer. The dissolved salt creates a concentration gradient in the z-direction. A density gradient is simultaneously created which may cause the denser water at the top to sink resulting in natural circulation.

(1) Assuming the concentration gradient is constant with fixed boundary conditions, under which situation would natural convection occur? *(1%)*

(2) Given the equation of motion: $\bar{\rho}\left(\frac{Dv_z}{Dt}\right) = -\frac{\partial P}{\partial z} - \mu\frac{\partial^2 v_z}{\partial r^2} + \bar{\rho} g_z \zeta (w - \bar{w})$ *(5%)*
In order to perform dimensional analysis, dimensionless quantities must be defined using the characteristic quantities. Please write down the expression for the dimensionless quantities listed below, using the following boundary conditions:

B.C.1: at z=0, v=0, $w=w_0$
B.C.2: at z=h, v=0, $w=w_h$ ($w_h>w_0$)

(a) Dimensionless length $\breve{z}$ *(1%)*
(b) Dimensionless time $\breve{t}$ *(1%)*
(c) Dimensionless differential operator $\frac{\breve{d}}{dz}$ *(1%)*
(d) Dimensionless concentration $\breve{w}$ *(1%)*
(e) Characteristic velocity v_0 *(1%)*

(3) The dimensionless form of equation of motion is given as:

$$\left(\frac{D\breve{v}_z}{D\breve{t}}\right) = -\frac{\partial \breve{P}}{\partial \breve{z}} - Sc\frac{\partial^2 \breve{v}_z}{\partial \breve{r}^2} - Gr_w Sc^2 \frac{\boldsymbol{g}}{g}\left(\breve{w} - \frac{1}{2}\right)$$

Please answer the following:
(a) What is the mathematical definition of the Schmidt number (Sc)? *(1%)*
(b) What is the mathematical definition of diffusional Grashof number (Gr_w)? *(1%)*
(c) If we assume steady state with no pressure gradient, how can the above expression be simplified and under what kind of fluid property would the favor the occurrence of natural convection? *(2%)*

Problem 5 (6%)

Surface-modified nanoparticles (NP) preserved in an aqueous solution were made to become pellet structure, which can be used to remove organic contaminants. The density of NP is 1.02 g/cm^3, and the weight concentration of NP preserved in the aqueous solution is 20 wt%. The rest (80 wt% of the aqueous solution) is assumed to be pure water.

During the industrial operation, Waste Water (WW) at a volumetric flow rate of 5.0 m^3/hour is generated. The majority of contaminants in WW is phenol, and the concentration of phenol in the WW is 0.5 wt%. Today, we use NP in pellet form to remove the phenol from WW via a batch layout: (1) Firstly 10 L of the NP aqueous solution was dried to become NP pellet for one batch reaction, and (2) WW was collected for 1 hour and react with NP pellet in a batch reactor. Presumably all of the particles are replaced with the fresh ones every batch reaction. For simplicity in calculation, we assume the density of WW and the aqueous solution to be the same with the pure water (i.e., 1.0 g/cm^3) during operation)

After 1 hour of operation in a batch reactor:

(a) What is the maximum amount of phenol can be removed to NP pellet? *(3%)*

(b) What is the concentration of phenol presenting in the WW? *(3%)*

From a literature study: a graduate student in NTHU has done an adsorption isotherm study, showing that the maximum capacity of NP for the adsorption of phenol (W_s) varies with the equilibrium concentration of phenol in the WW (C_s). The results show that W_s equals to 10 kg of phenol per kg of NP when C_s = 1.0 kg/m^3 of WW. By increasing C_s from 1.0 kg/m^3 of WW to 2.0 kg/m^3 of WW, W_s increases to 15 kg of phenol per kg of NP. With a further increase of C_s to 3.0 kg/m^3 of WW, W_s slightly increases to 17 kg of phenol per kg of NP. Here we identify that the increase of W_s is negligible when C_s > 3.0 kg/m^3 of WW.

Problem 6 (4%)

A (50wt% water + 50wt% ethanol) solvent is used to extract heat-sensitive vitamin X (molecular mass of 2000 g/mol) from a special seed. The amount of the vitamin X in the special seed is about 10 kg/kg of the seed. The vitamin X is shown to be more soluble in ethanol than in water with a boiling point of 80 °C. Using ICP-MS, the amount of the sodium in the special seed is 10 g/kg of the seed. After extraction the vitamin X for 10 hours, the amount of sodium in the extract increases from 0 g/L to 1 g/L.

If you want to effectively decrease the amount of the sodium in the extract after 8-h operation, what can you do based on the following suggestions from (a) to (k)? Also, please also provide your justification to the correct answer(s).

<u>The correct answer might be multiple answers</u>, and <u>no partial credit will be given</u>.

(a) Use a distillation process on the extracted product above 100 °C. (b) Use a spray-drying device on the seed prior to the solid extraction. (c) Use a low-pressure distillation process on the extracted product at a temperature above 100 °C. (d) Change to use another seed with lower concentrations of vitamin X and sodium. (e) Change to use another seed with higher concentrations of vitamin X and sodium. (f) Use a freeze vacuum-drying device on the seed prior to the solid extraction. (g) Use an ultracentrifugation device on the extract. (h) Use a membrane separation with a pore size of 0.1 mm. (i) Use mechanical filtration with a filter paper of 0.1 mm in pore size. (j) Use dialysis via a membrane with a pore size of 2 nm. (k) None of the above is working.

Problem 7 (5%)

Mechanical separation is often used to remove particles in the aqueous solution. In some cases, it can be used to classify particle or be used to study particle size distribution of particle suspension. Disc centrifugation is commonly used to measure particle size distribution of particle in the aqueous solution. A gradient solution having a viscosity of $2.5*10^{-4}$ Pa*s is used as the medium solution for this mechanical separation process. The injection point (i.e., entrance of the particle) is located close to the center of the disc, and the distance between the injection point and the center of the disc is assumed to be 0.5 cm. The discharge point of the disc (exit of the particle) is located at rim of the disc, and the distance between the discharge point and the center of the disc is 10.5 cm. The traveling distance from the injection point to the discharge point of the disc is 10.0 cm.

Based on vendor's information, the nominal size of the spherical particle product is about 30 nm, and the density of the spherical particle is 5.0 g/cm^3. We can operate at the centrifugation speed either 5000 revolutions/min or 20000 revolutions/min.

(a) Please choose a correct operating condition (centrifugation speed) based on your justification through detailed calculations. *(2%)*

The minimum operating time should be >2 min (to keep sufficient resolution), and the maximum operating time should be below 50 minutes (to have efficiency in the analysis).

(b) Followed on (a): At a constant centrifugation speed, particles with different diameter of the spherical particle will come out of the disc in sequence. Please draw a plot of the measured particle diameter versus operation time, *t* (i.e., from t = 0 min to t = 50 min; <u>You may only choose *t* = 4 min and 49 min</u>). *(2%)*

(c) Followed on (b): If the peak population is shown at *t* = 10 min, what is the actual measured peak diameter of the particle? *(1%)*

Problem 8 (5%)

After mechanical separation, a large particle-free aqueous solution containing the vitamin XX is formed. The density of the aqueous solution is assumed to be 1 g/cm^3, and the concentration of vitamin XX is 2 wt%. During the evaporation of the water in the solution, vitamin XX will start to precipitate to become dry powder.

Aerosol-based drying process, via a formation of fine spray in the air flow, is shown to be effective for the formation of powder vitamin XX via a fast removal of water. Using an aerosol-based measurement, the number concentration of dried vitamin XX particle is $10^8/cm^3$ of the air. The spray rate of the solution is then calculated based on the information by assuming that (1) the number of aerosol dried vitamin XX particles equals to the droplets generated, and (2) the diameter of the droplet is about 300 nm. Here the flow rate of the air is 10 L/min. The residence time defined for the constant heating process is 1 minute. A complete dried vitamin XX powder is formed.

(a) What is the actual drying rate in this system, in term of kg of solvent per minute? *(2%)*

(b) Followed on (a): If we increase the spray rate of the solution to be 5 times and still see a complete formation of dried vitamin XX powder under the same operation, what is the actual drying rate? *(1%)*

(c) Followed on (b): If the average drying rate at the first 5 minutes is 2X of the average drying rate during the 5-10 minutes: what is the average drying rate at the first 5 minutes? *(2%)*

Problem 9 (8%)

Answer the following problems relating to the fundamentals of energy transport.

(1) Temperature measurements taken in a complicated energy transport problem have been fitted with a polynominal with result $T = 60 + 0.2x^2 - 0.03x^4$, where T is in °C and x is in cm. If the thermal conductivity of the medium is 60 W/mK, what is the energy flux, q_x, at $x = 5$ cm? Is the medium where the measurements were taken, a gas, liquid or solid? *(4%)*

(2) Consider the following equation of change for temperature:

$$\rho Cp\frac{DT}{Dt} = k\nabla^2 T - \left(\frac{\partial \ln \rho}{\partial \ln T}\right)_p \frac{Dp}{Dt} + \mu\Phi_v$$

(a) Describe the physical meaning of substantial time derivative DT/Dt. *(2%)*

(b) What is the origin of the $\mu\Phi_v$ term in the equation? *(2%)*

Problem 10 (12%)

An annular chemical reactor consists of a packed bed of catalyst **between** two coaxial cylinders. The inner and outer cylinders have radii of R_0 and R_1, respectively. It is reasonable to assume that there is no heat transfer through the surface of the inner cylinder, which is at a constant temperature T_0. The catalytic reaction releases heat at a uniform volumetric rate $\boldsymbol{S}$ throughout the reactor, whose effective thermal conductivity k may be considered a function of temperature as $k = k_0 + AT$. Neglect the temperature gradients in the axial direction.

(a) Derive a second-order differential equation to describe the radial temperature distribution in the annular reactor starting with a shell energy balance. *(5%)*

(b) Establish the radial temperature distribution by solving the differential equation. *(4%)*

(c) Develop an expression for the temperature at the outer cylindrical wall of the reactor. *(3%)*