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 110 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. 考試開始後，請於作答前先翻閱整份試題，是否有污損或試題印刷不清，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。

Problem 1 (40%)

Multiple choice: Pick only one answer for each problem. Each problem is 2 points.

1. The outbreak of coronavirus disease 2019 (COVID-19) has caused a global pandemic and significant impact on society, economy, and human life. To combat the virus, wearing the mask and keep a safe social distance can help prevent the spread of COVID-19. However, it was still broadly debated regarding "what is the safe social distance". Some studies recommended that at least 2 m of physical distance should be kept from others, while others suggested that 2 m may not be adequate. To answer this question, it is vital to fully understand the mechanism of virus spreading. The respiratory infections occur usually through the transmission of virus-containing droplets and aerosols exhaled from infected individuals during breathing, speaking, coughing, and sneezing. Therefore, we can assume the spreading of the droplet is similar to a falling particle in the air. Please identify the kinetic force (F_k) acting on the droplet. Assume μ is the dynamic viscosity of airflow, R is the radius of the droplet, v_t is the falling (terminal) velocity.

(A) $F_k = \pi\mu R v_t$, (B) $F_k = 2\pi\mu R v_t$, (C) $F_k = 4\pi\mu R v_t$, (D) $F_k = 6\pi\mu R v_t$,

(E) $F_k = 8\pi\mu R v_t$

2. Please obtain the falling velocity of the droplet. [Hint] Use the force balance of gravity force, buoyance force, and kinetic force. ρ_d is the density of the droplet and ρ is the density of the air.

(A) $v_t = \dfrac{R^2(\rho_d - \rho)g}{3\mu}$

(B) $v_t = \dfrac{R^2(\rho_d - \rho)g}{6\mu}$

(C) $v_t = \dfrac{4R^2(\rho_d - \rho)g}{3\mu}$

(D) $v_t = \dfrac{2R^2(\rho_d - \rho)g}{3\mu}$

(E) $v_t = \dfrac{2R^2(\rho_d - \rho)g}{9\mu}$

3. Assume the diameter, density, viscosity of the droplet is 5 μm, 0.997 g/cm^3, and 1.86×10^{-5} kg/m·s, respectively. The density of the air is 1.184 kg/m^3 and gravity is 9.8 m/s^2. If the initial height of the droplet is set as 1.5 m, please calculate the falling time of the droplet. Choose the closest answer.

(A) 1 min, (B) 2 min, (C) 10 min, (D) 30 min, (E) 60 min

4. If the evaporation of the droplet is considered, obviously, the small droplets would evaporate first before falling on the ground. However, the evidence demonstrates that large droplets are not affected by evaporation. Please calculate the minimum size (in diameter) of the droplet before it falls on the groud. Assume the initial horizontal velocity of the droplet is 2 m/s and the initial height of the droplet is set as 1.5 m. The transmission distance is 2 m.
(A) 134 μm, (B) 226 μm, (C) 474 μm, (D) 508 μm, (E) 668 μm

5. As we know, the falling velocity of the particle can also be determined by introducing the friction factor f concept when we assume kinetic force $F_k = AKf$. A is a characteristic area and K is a characteristic kinetic energy. D is the diameter of the particle. Please identify the correct answer.
(A) $f=\frac{1}{3}\frac{gD}{v_\infty^2}\left(\frac{\rho_d-\rho}{\rho}\right)$, (B) $f=\frac{1}{6}\frac{gD}{v_\infty^2}\left(\frac{\rho_d-\rho}{\rho}\right)$, (C) $f=\frac{4}{3}\frac{gD}{v_\infty^2}\left(\frac{\rho_d-\rho}{\rho}\right)$,
(D) $f=\frac{2}{3}\frac{gD}{v_\infty^2}\left(\frac{\rho_d-\rho}{\rho}\right)$, (E) $f=\frac{2}{9}\frac{gD}{v_\infty^2}\left(\frac{\rho_d-\rho}{\rho}\right)$

6. If we try to introduce the kinetic force F_k from question 1, the correlation between f and Re can be:
(A) $f=\frac{8}{\mathrm{Re}}$, (B) $f=\frac{16}{\mathrm{Re}}$, (C) $f=\frac{24}{\mathrm{Re}}$, (D) $f=\frac{32}{\mathrm{Re}}$, (E) $f=\frac{36}{\mathrm{Re}}$

7. Please calculate the falling time of the droplet using the equation from question 5. The initial height of the droplet is set as 1.5 m. Please choose the closest answer.
(A) 1 min, (B) 2 min, (C) 10 min, (D) 30 min, (E) 60 min

8. The falling velocity of the droplet may or may not be the same when using the force balance method or friction factor method. If not the same, there should be a reason behind that. Please choose the CORRECT answer.
(A) The falling velocities are the same, so there is no reason behind that.
(B) The falling velocities are not the same because the airflow is the creeping flow.
(C) The falling velocities are not the same because the air friction is dominant.
(D) The falling velocities are not the same because the density of the air can be ignored.
(E) The falling velocities are not the same because the viscosity of the air is not considered when using the friction factor method.

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9. Cough can increase the initial horizontal velocity of the droplets, allowing the longer travel distance of the droplets. Usually, the average velocity of cough flow is 10 m/s. Please calculate the Reynolds number of the cough flow. Assume the opening of the mouth is 1 cm in diameter. Choose the closest answer.
(A) 500, (B) 1000, (C) 3000, (D) 5000, (E) 6000

10. Wearing the face mask can provide a critical barrier, reducing most infectious viruses during coughing, especially of asymptomatic people and those with mild symptoms of COVID-19. Please calculate the force of cough flow acting on the mask. Assume the mask perfectly covers the mouth. The velocity of cough flow is 10 m/s and the opening of the mouth is 1 cm in diameter.
(A) 0.001 N
(B) 0.01 N
(C) 0.1 N
(D) 1 N
(E) 10 N

11. What is the SI unit of mass flux?
(A) Kg/s, (B) g/(s cm^2), (C) Kg/(s m^2), (D) g/s

12. Concerning the SI units of kinematic viscosity, thermal diffusivity, and mass diffusivity, which of the following statements is true?
(A) All three are different.
(B) All three are the same as m^2/s.
(C) All three are the same as s/m^2.
(D) All three are the same as s/cm^2.

13. For the following mixtures, (a) H_2-O_2 at 1 atm and 273 K, (b) N_2-O_2 at 1 atm and 273 K, (c) dilute aqueous ethanol solution at 298 K, and (d) Cd in Cu at 293 K, place them in the order of increasing mass diffusivity.
(A) (a)(b)(c)(d), (B) (c)(d)(a)(b), (C) (d)(c)(a)(b), (D) (d)(c)(b)(a)

14. For flow of a binary gas mixture over a flat plate, boundary layers of velocity and concentration develop. Which of the following statements concerning the thicknesses of the velocity (δ) and concentration (δ_c) boundary layers is true?
(A) $\delta << \delta_c$, (B) $\delta \sim \delta_c$, (C) $\delta >> \delta_c$, (D) none of the above

15. Consider a spherical particle A of radius R dissolving in a stagnant liquid B. Once dissolved, A and B react to form C with an irreversible first-order reaction (reaction rate constant k_1). The solubility of A in B, C_{A0}, is small and the system can be approximated as a dilute binary system. The diffusivity of A in B is D_{AB}. The system can be treated as in a pseudo-steady state. Let b^2 denote (k_1R^2/D_{AB}). What is the molar flux of A at the particle surface?
(A) $\frac{D_{AB}C_{A0}(1+b)}{R}$, (B) $\frac{D_{AB}C_{A0}}{R(1+b)}$, (C) $\frac{D_{AB}C_{A0}R}{(1+b)}$, (D) $\frac{D_{AB}R}{C_{A0}(1+b)}$

16. Continued from the above problem, what is dm_A/dt? (M_A=molecular weight of A, m_A=mass of particle A)
(A) $-4\pi RM_AD_{AB}C_{A0}/(1+b)$
(B) $4\pi RM_AD_{AB}C_{A0}(1+b)$
(C) $4\pi RM_AD_{AB}C_{A0}/(1+b)$
(D) $-4\pi RM_AD_{AB}C_{A0}(1+b)$

17. Consider the absorption of gas A by a laminar falling film of liquid B. Gas A is only slightly soluble in B, and the diffusion takes place so slowly in the liquid film that A will not penetrate very far into B. The concentration of A at the interface is maintained at C_{A0} and the maximum velocity of the fluid is V_{max}. Let x be the coordinate into the liquid film, z the coordinate down the liquid film, and D_{AB} the mass diffusivity of A in B. The molar concentration of A, C_A, is a function of x and z. Which of the following statements is true?
(A) C_A increases with increasing x.
(B) C_A decreases with increasing z.
(C) C_A increases with decreasing V_{max} at fixed x and z.
(D) C_A decreases with increasing D_{AB} at fixed x and z.

18. Continued from the above problem, what is the molar absorption rate of A at the gas/liquid interface? Here, W and L are the width and length of the liquid film exposed to gas A.

(A) $WLC_{A0}\sqrt{\frac{4D_{AB}V_{max}}{\pi L}}$

(B) $WLD_{AB}\sqrt{\frac{4C_{A0}V_{max}}{\pi L}}$

(C) $WLC_{A0}\sqrt{\frac{4V_{max}}{D_{AB}\pi L}}$

(D) $WLD_{AB}\sqrt{\frac{4V_{max}}{C_{A0}\pi L}}$

19. The equation of continuity of A in a dilute binary solution can be written as

$$\frac{\partial C_A}{\partial t} + \underline{v} \cdot \underline{\nabla} C_A = D_{AB} \nabla^2 C_A + R_A,$$

Here, $\underline{v}$ is the mass average velocity and R_A is the molar reaction rate of A. For the situation of pure diffusion in solids, what will the above equation be reduced to?

(A) $\underline{v} \cdot \underline{\nabla} C_A = D_{AB} \nabla^2 C_A + R_A$

(B) $\frac{\partial C_A}{\partial t} + \underline{v} \cdot \underline{\nabla} C_A = 0$

(C) $\frac{\partial C_A}{\partial t} = D_{AB} \nabla^2 C_A + R_A$

(D) $\frac{\partial C_A}{\partial t} = D_{AB} \nabla^2 C_A$

20. Which of the following statements is true?
(A) Eddy diffusivity is a physical property of a fluid.
(B) Eddy diffusivity depends on turbulent intensity of the flow.
(C) Nusselt number of heat transfer is analogous to Schmidt number of mass transfer.
(D) Chilton-Colburn analogy applies to laminar tube flow.

Problem 2 (9%)

Answer the following questions regarding the fundamentals of energy transport.

(a) Provide the definitions of forced convection and natural (free) convection. *(4%)*

(b) Give the definitions and physical meanings of Prandtl number (*Pr*), Nusselt number (*Nu*), and Grashof number (*Gr*). *(3%)*

(c) What are the important dimensionless groups governing the Nusselt number in forced convection? *(2%)*

Problem 3 (11%)

A sphere of radius R and thermal conductivity k_1 is embedded in an infinite solid of thermal conductivity k_0. The center of the sphere is located at the origin of coordinates and there is a constant temperature gradient A in the positive z direction far from the sphere. The temperature at the center of the sphere is T^o.

The steady-state temperature distribution in the sphere T_1 and in the surrounding medium T_0 have been shown to be:

$$T_1(r,\theta) - T^o = \left[\frac{3k_0}{k_1+2k_0}\right] Arcos\theta \qquad r \le R \qquad (1)$$

$$T_0(r,\theta) - T^o = \left[1 - \frac{k_1-k_0}{k_1+2k_0}\left(\frac{R}{r}\right)^3\right] Arcos\theta \qquad r \ge R \qquad (2)$$

(a) What are the partial differential equations that must be satisfied by Eq. (1) and (2) ? *(2%)*

(b) Write down the boundary conditions that apply at r = R. *(3%)*

(c) Show that T_1 and T_0 satisfy their respective partial differential equations in (a). *(3%)*

(d) Show that Eqs. (1) and (2) satisfy the boundary conditions in (b). *(3%)*

THE EQUATION OF ENERGY FOR PURE NEWTONIAN FLUIDS WITH CONSTANT* ρ AND k

$[\rho\hat{C}_p DT/Dt = k\nabla^2 T + \mu\Phi_v]$

Cartesian coordinates (x, y, z):

$$\rho\hat{C}_p\left(\frac{\partial T}{\partial t} + v_x\frac{\partial T}{\partial x} + v_y\frac{\partial T}{\partial y} + v_z\frac{\partial T}{\partial z}\right) = k\left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right] + \mu\Phi_v$$

Cylindrical coordinates (r, θ, z):

$$\rho\hat{C}_p\left(\frac{\partial T}{\partial t} + v_r\frac{\partial T}{\partial r} + \frac{v_\theta}{r}\frac{\partial T}{\partial \theta} + v_z\frac{\partial T}{\partial z}\right) = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2}\right] + \mu\Phi_v$$

Spherical coordinates (r, θ, ϕ):

$$\rho\hat{C}_p\left(\frac{\partial T}{\partial t} + v_r\frac{\partial T}{\partial r} + \frac{v_\theta}{r}\frac{\partial T}{\partial \theta} + \frac{v_\phi}{r\sin\theta}\frac{\partial T}{\partial \phi}\right) = k\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta\frac{\partial T}{\partial \theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2 T}{\partial \phi^2}\right] + \mu\Phi_v$$

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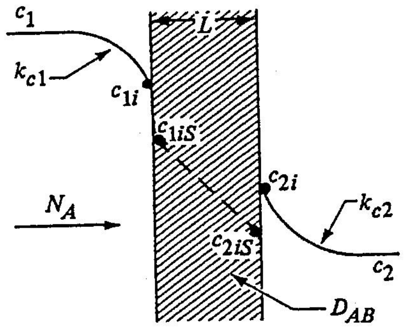
Problem 4 (12%)

Diffusion through a dialysis membrane.

A dialysis process is designed to recover solute A from a solution of 0.02 M (c_1). The end product contains A at the concentration of 0.003 M (c_2). The membrane thickness (L) is 1.59 x10^{-5} m, the distribution (partition) coefficient K_D is 0.7 and the effective diffusivity of A in membrane D_{AB} is 3.5 x 10^{-11} m^2/s. The mass transfer coefficients in the solution on both sides of the membrane are k_{c1} = 3.5 x 10^{-5} m/s and k_{c2} = 2.1 x 10^{-5} m/s. ($K_D = c_{iS}/c_i$)



(a) Calculate the membrane coefficient, k_{mA} *(=$D_{AB}K_D/L$). (2%)*

(b) Calculate the overall mass transfer coefficient, K and the percent resistance of membrane. *(3%)*

(c) Calculate the flux, N_A (kg mol/m^2-s). The area required (m^2) for a transfer rate of 0.001 kg mol of A/s. *(4%)*

(d) By increasing the mixing intensity of both liquid phases, we manage to increase the mass coefficients k_{c1} and k_{c2} to double their current values. What will be the percent increase in N_A? *(3%)*

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Problem 5 (8%)

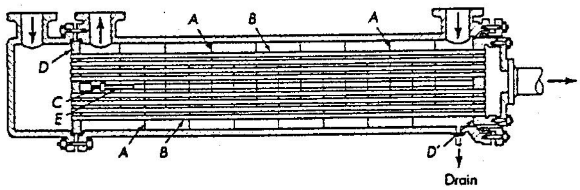
A therapeutic protein (at 1.0 mg/ml) is purified by an adsorption column. The breakthrough curve can be represented by the following data:

x-axis time (hr)	0	5	6	7	8
y-axis (mg/ml)	0	0	0.5	1.0	1.0

If the breakthrough concentration is 0.05 mg/ml, what is the fraction capacity used at break point?

Problem 6 (8%)

A silicone oil having a temperature of 185 °C, heat capacity of 5.0 kJ/(kg K) and a flow rate of 150 kg/min is used for pre-heating the soybean oil (i.e., for biodiesel production) by using the following heat exchanger (see the plot shown below).



Based on the design, the temperatures of the silicone oil leaving the shell is preferred (but not necessary) to be ≦170 °C. The temperature of the soybean oil entering the pipes is 20 °C, and the target temperature of the soybean oil at the exit of the tubes/pipes is ≧80 °C. Here, the heat capacity of soybean oil is assumed to be 80% of the heat capacity of silicone oil regardless of the variation in their temperatures. The flow rate of soybean oil is targeted to be at least 3600 kg/hour.

(a) What is the name of this heat exchanger shown above? *(2%)*

(b) To simplify the analysis, we choose the method for the study of a double pipe heat exchanger. The cold flow (in the tubes/pipes) is assumed to be in the inner pipe (10 cm in diameter) of this double pipe heat exchanger, and the hot flow in the shell is assumed to be in the outer tube (20 cm in diameter) of this double pipe heat exchanger. The overall heat transfer coefficient is 1000 W/m^2*K. The streams of silicone oil and soybean oil are counter-current.

What is the heat transfer area required to achieve the minimum target temperature of the soybean oil at the exit of the pipes (i.e., 80 °C, when flow rate of soybean oil is at the minimum value)? *(2%)*

Is the final temperature of the silicone oil leaving the shell below 170 °C? Full derivations to the answers are required. *(2%)*

(c) (Continued on (b)) Fouling is a severe issue to this heat exchanger, resulting in a decline of overall heat transfer coefficient. Through an operation under the minimum flow rate of soybean oil, the predicted overall heat transfer coefficients are linearly decreased to 900 W/m^2*K and 800 W/m^2*K in the first and the second months, respectively. What is the minimum heat transfer area required to achieve the target temperature of the soybean oil at the exit of the heat exchanger during the 2-month operation (i.e., 80 °C)? *(2%)*

Problem 7 (12%)

A chemical engineer designs a continuous unit for separating a liquid feed with a flow rate of 200 kg/min. The compositions (in weight percentage, wt%) of the feed are constant with time: 50.0 wt% of Component A, 48.0 wt% of Component B, 1.5 wt% of Component C and 0.5 wt% of other traceable components (denoted as Component D). A fractionation distillation column is employed for this separation, and the target composition of the overhead product, as collected by a total condenser, is 95 mol% of Component A and the target composition of the bottom product is 95 mol% of Component B.

The molecular masses of Component A, B and C are 100 g/mol, 150 g/mol and 32 g/mol, respectively. Component D is mainly CH_2O with an estimated molecular mass of 30 g/mol. Knowing that Component C and Component D are relatively more volatile than Component A and B, the engineer chooses to use a flash distillation to completely remove Component C and D prior to the fractionation distillation column.

The equilibrium data, based on a binary system of Component A and Component B, are summarized in a record book, showing the temperatures of bubble points are 120 °C, 110 °C, 100 °C, 90 °C, 85 °C and 80 °C when the molar fractions of A (x_A) are 0, 0.2, 0.4, 0.6, 0.8 and 1.0, respectively. The temperatures of dew points are 120 °C, 115 °C, 110 °C, 100 °C, 95 °C and 80 °C when the molar fractions of A (x_A) are 0, 0.2, 0.4, 0.6, 0.8 and 1.0, respectively.

Please provide your answers to the followings:

(a) What is the reflux ratio for having the minimum number of stages *(1%)*? What is the value of minimum number of stages *(1%)*?

(b) If the liquid feed is pre-heated to become a saturated vapor, please determine (1) the flow rates of the distillate and the bottom products *(2%)*, and (2) number of actual plates required if the plate efficiency is 60% of the ideal plate. The reflux ratio is set at 2 times the minimum reflux ratio *(4%)*.

(c) Continued on (b): Due to the demand from the customer, the chemical engineer further increases the targeted molar concentration of the Component A to be 98% in the overhead product by increasing the reflux ratio. The target composition in the bottom product is the same (i.e., 95 mol% of Component B). (1) What is the new reflux ratio, if the reflux ratio is set at 2.5 times the minimum reflux ratio *(2%)*? (2) What are the production rates of the overhead and bottom products after the tuning to the new reflux ratio *(2%)* ?