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 114 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 ：1001
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 (10%)

Multiple choice: (Pick only one answer for each problem. Each sub-question is **2%**) Darcy's Law describes the relationship between the superficial velocity (v) and viscosity (μ) of a fluid and the permeability (k) and pressure drop (ΔP) across a packed bed with length (L). Please answer the following questions.

1. Which of the following equations represents Darcy's Law?

   (A) $v = \frac{k\mu}{\Delta PL}$ (B) $v = \frac{k\Delta P}{\mu L}$ (C) $v = \frac{\mu\Delta P}{kL}$ (D) $v = \frac{\mu}{kL\Delta P}$ (E) $v = \frac{\Delta P}{k\mu L}$

2. Continued from above. The equation in the previous question can be derived from the Navier-Stoke Equation with several assumptions. Examine the following statements and choose the option that includes all the **correct** statements.
   a. The equation above assumes a steady-state motion.
   b. The equation above applies to both incompressible and compressible fluid.
   c. The inertia force of the fluid should be neglected.
   d. The fluid passing the packed bed is assumed turbulent.

   (A) ac (B) acd (C) abc (D) bcd (E) bd

3. Superficial velocity (v) and interstitial velocity (v_i) both can be used to describe the velocity of flow through a packed bed, but one of them considers the porosity (ϵ) of the packed bed to reflect the velocity at the pores. Which of the following equations represents the correct relationship between v and v_i?

   (A) $v = v_i\epsilon$ (B) $v = \frac{v_i}{\epsilon}$ (C) $v = v_i(1-\epsilon)$ (D) $v = \frac{v_i}{1-\epsilon}$

   (E) $v = \frac{v_i}{\epsilon}(1-\epsilon)^2$

4. Coffee espresso is usually extracted at 9 bar with a constant volumetric flow rate set by the espresso machine. The coffee ground can be viewed as a granular, porous packed bed composed of spherical particles. The Blake-Kozeny Relation, as shown below, suggests that the permeability (k) depends on the diameter of spherical particles (d_p) and the porosity (ϵ) of the packed bed. If the particle size of the coffee ground decreases by 20%, how would the extraction pressure change if the flow rate remains constant?

   $$k = \frac{\epsilon {d_p}^2}{180(1-\epsilon)^2} \quad \text{(The Blake-Kozeny Relation)}$$

   (A) Increase by ~60% (B) Increase by ~40% (C) Increase by ~20%
   (D) Decrease by ~20% (E) Decrease by ~40%

5. Flow instabilities can occur when brewing coffee espresso, significantly affecting the extraction process and the flavor of coffee. Select the option that includes all the **correct** statements.
   a. Decreasing the particle size of the coffee ground likely increases flow instabilities.
   b. Wall effect is a type of channeling due to the lower flow resistance near the wall.
   c. Local high permeability in a coffee bed leads to the channeling effect.
   d. When the particle size distribution of a coffee bed is non-uniform, one strategy to reduce channeling is to pack a coffee bed tighter to reduce the average porosity.

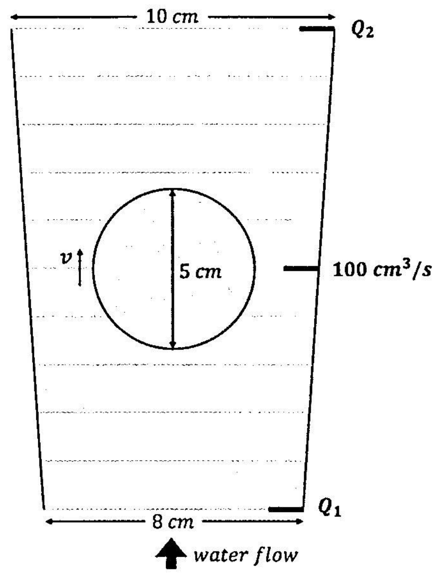
   (A) ac　(B) acd　(C) abc　(D) bcd　(E) cd

Problem 2 (10%)

A rotameter is a common device for measuring the volumetric flow rate of fluid, indicated by the position of the float inside. The working principle of the rotameter is the force balance of the float, which depends on several factors, such as the mass and size of the float and the kinetic force driven by the flow. The scheme on the next page shows a cylindrical rotameter whose upper and lower diameters are 10 cm and 8 cm, respectively, and the diameter of cylinder changes proportionally with the position. A spherical float with a diameter of 5 cm is used in this rotameter. Currently, the float is positioned in the <u>middle</u> of the rotameter, suggesting that the volumetric flow rate of water is 100 cm^3/s. Assume that the density and viscosity of water are 1000 kg/m^3 and 0.001 Pa·s, respectively, gravitational acceleration is 9.8 m/s^2, and the wall of the rotameter is hydrodynamically smooth.

Note: when Re < 6000, the friction coefficient (f) for the flow over a sphere can be estimated:

$$f = \left(\sqrt{\frac{24}{Re}} + 0.5407\right)^2$$



Scheme. Rotameter with a spherical float

Please pick only one answer for each problem .

6. What is the mass of the float? Select the closest value from the options below. **(4%)**
   (A) 25 g (B) 35 g (C) 45 g (D) 55 g (E) 65 g

7. What is the value of Q_2 on the rotameter? Select the closest value from the options below. **(4%)**
   (A) 110 cm^3/s (B) 122 cm^3/s (C) 134 cm^3/s (D) 1146 cm^3/s (E) 158 cm^3/s

8. Now, if you use this rotameter to estimate the flow rate of seawater flow and you adjust the valve to position the float at label 100 cm^3/s, what is the actual flow rate of the seawater compared to 100 cm^3/s? (Assume that the viscosity does not change significantly) **(2%)**
   (A) Greater than 100 cm^3/s.
   (B) Lower than 100 cm^3/s.
   (C) Remains at 100 cm^3/s.
   (D) Cannot be determined without additional information.

Problem 3 (20%)

Multiple choice: (Pick only one answer for each problem. Each sub-question is **2%**)

As artificial intelligence (AI) technology advances, the performance of AI chips has dramatically increased, enabling faster computation, larger model training, and real-time data analysis. However, this progress comes with a significant challenge: thermal management. AI chips are characterized by high power density and miniaturized designs, resulting in substantial heat generation in a confined area. This excess heat, if not effectively dissipated, can lead to reduced performance, reliability issues, and even hardware failure. Traditional cooling methods, such as air cooling, are often insufficient to handle the thermal loads of modern AI systems. Advanced solutions like liquid cooling, heat pipes, microchannel cooling, and immersion cooling have emerged as alternatives, but each approach faces limitations in terms of cost, complexity, and efficiency.

9. A metal rod with thermal conductivity $k = 200$ W/m·K, density $\rho = 7800$ kg/m^3, and specific heat $c_p = 500$ J/kg·K is exposed to a sudden temperature drop at its surface. The thermal diffusivity α of the rod is:
   (A) 4.2×10^{-5} m^2/s (B) 5.1×10^{-5} m^2/s (C) 6.4×10^{-5} m^2/s (D) 7.8×10^{-5} m^2/s (E) 2.3×10^{-4} m^2/s.

10. A small sphere with radius $R = 1$ cm is suddenly placed in an environment at T_∞ = 500°C. If the sphere's Biot number is calculated as Bi = 0.01, which of the following is **NOT** an appropriate assumption for heat transfer analysis?
   (A) Transient conduction with spatial temperature variation.
   (B) Steady-state conduction with negligible convection.
   (C) Conduction inside the sphere is negligible.
   (D) Radiation dominates the heat transfer.
   (E) Internal generation of heat dominates.

11. In a liquid-cooled system, a cold plate is attached to an AI chip with thermal conductivity k_{chip}=150 W/m·K, thickness L = 0.002 m, and surface area A = 0.01 m^2. The convective heat transfer coefficient between the cold plate and coolant is h = 2000 W/m^2·K. What is the Bi of the chip?
   (A) 0.002 (B) 0.027 (C) 0.133 (D) 0.267 (E) 2.667

12. The Nusselt number (Nu) is a dimensionless parameter that describes the ratio of convective to conductive heat transfer. In a microchannel cooling system with laminar flow, which of the following statements about the Nu is NOT appropriate?
   (A) The Nu increases with higher Reynolds number (Re) and Prandtl number (Pr) for fully developed laminar flow.
   (B) For fully developed laminar flow in a circular tube, the Nu can be constant under certain boundary conditions.
   (C) The Nu represents the enhancement of heat transfer due to convection over pure conduction.

(D) The Nu is constant in laminar flow, regardless of the geometry or flow conditions.

(E) For laminar flow, the Nu is always influenced by both thermal and velocity boundary layers.

13. A coolant flows through a microchannel with a hydraulic diameter of $D_h = 2$ mm. The Re of the flow is 1500 (laminar), and the Pr is 4. The channel wall maintains a constant heat flux boundary condition. Given the relationship for fully developed laminar flow with constant heat flux, Nu = 4.36, calculate the heat transfer coefficient (h) if the thermal conductivity of the coolant is $k = 0.6$ W/m·K.
(A) 600 W/m^2·K　(B) 872 W/m^2·K　(C) 1308 W/m^2·K　(D) 1744 W/m^2·K
(E) 2616 W/m^2·K

14. Selecting the right coolant is crucial for optimizing the performance of a liquid cooling system for high-power AI chips. Which of the following considerations is **NOT** appropriate when choosing a coolant?

(A) The coolant should have a high specific heat capacity to absorb more heat with minimal temperature rise.

(B) The coolant should exhibit low viscosity to reduce pumping power and improve flow efficiency.

(C) The coolant should be chemically stable and non-corrosive to avoid degrading the cooling components.

(D) The coolant should have a high boiling point to prevent phase change during operation.

(E) The coolant should have a low thermal conductivity to minimize heat transfer to the environment.

15. The new cooling structure consists of a hybrid system combining microchannel cooling and phase-change materials (PCM) embedded within the chip substrate. The microchannels circulate a liquid coolant, while the PCM absorbs heat during phase transition to stabilize temperature during peak loads. Key parameters:

- AI chip generates 300 W of heat.
- The coolant has a specific heat capacity $c_p = 4200$ J/kg·K.
- Coolant mass flow rate: $w = 0.05$ kg/s.
- PCM latent heat: $H = 250$ kJ/kg.
- PCM mass: 0.1 kg.
- Heat transfer coefficient of microchannels: $h = 1000$ W/m^2·K.
- Heat exchange area: $A = 0.02$ m^2.

If the coolant enters the microchannels at $T_{\text{inlet}} = 30^{\circ}\text{C}$, what is the heat transfer rate to the coolant when the outlet temperature is $T_{\text{outlet}} = 40^{\circ}\text{C}$?

(A) 200 W (B) 210 W (C) 250 W (D) 2000 W (E) 2100 W

16. Following the above question, how long can the PCM stabilize the chip temperature before it is fully melted?

(A) 8 s (B) 50 s (C) 125 s (D) 175 s (E) 200 s

17. Following the above question, if the total heat flux removed by the coolant is 200 W and the convective heat transfer coefficient is $h = 1000\ \text{W/m}^2\cdot\text{K}$, what is the surface temperature of the chip (T_{chip}) if the coolant bulk temperature is $T_{\text{coolant}} = 40^{\circ}\text{C}$?

(A) 41°C (B) 42°C (C) 44°C (D) 46°C (E) 50°C

18. Following the above question, what is the total heat transfer efficiency of the hybrid cooling system if the coolant removes 200 W and the PCM absorbs an additional 50 W during phase change?

(A) 50% (B) 66.7% (C) 75% (D) 80% (E) 100%

Problem 4 (8%)

A single-pass countercurrent shell-and-tube heat exchanger is used to cool a hot hydrocarbon stream with water as the coolant. The hydrocarbon enters at 120°C and must be cooled to 60°C. The hydrocarbon flowrate is 100 kg/h, and its average specific heat capacity is 2.5 kJ/kg·K (assumed constant). The cooling water is available at 25°C at a flowrate of 150 kg/h, with a specific heat capacity of 4.2 kJ/kg·K (assumed constant). The overall heat transfer coefficient (U) is estimated to be 300 W/m²·K.

19. Calculate the Log-Mean Temperature Difference (LMTD), assuming no phase change and constant specific heats. **(2%)**

(A) 45 K (B) 48 K (C) 51 K (D) 54 K (E) 57 K

20. Calculate the required heat transfer area of the exchanger given that it must handle the calculated duty at $U = 300\ \text{W/m}^2\cdot\text{K}$. **(2%)**

(A) 0.35 m² (B) 0.45 m² (C) 0.55 m² (D) 0.65 m² (E) 0.75 m²

21. If, over time, fouling reduces the overall heat transfer coefficient to 200 W/m²·K (with the same heat transfer area and flowrates), determine the new outlet temperature of the hydrocarbon stream. **(4%)**

(A) 50°C (B) 55°C (C) 60°C (D) 65°C (E) 70°C

Problem 5 (10%)

Please indicate whether each of the following statements is **correct** or **incorrect**. If incorrect, provide the corrected version.

(a) The Schmidt number (Sc) is defined as the ratio of mass diffusivity to momentum diffusivity. **(2%)**

(b) When diffusion occurs through a composite wall with two layers of different diffusivities D_1 and D_2, the total resistance to diffusion is equal to the resistance of the layer with the lower diffusivity. **(2%)**

(c) For mass transfer in laminar flow over a flat plate, the mass transfer coefficient decreases with increasing boundary layer thickness. **(2%)**

(d) For one-dimensional steady-state diffusion in a planar medium with constant diffusion coefficient, the concentration profile is parabolic. **(2%)**

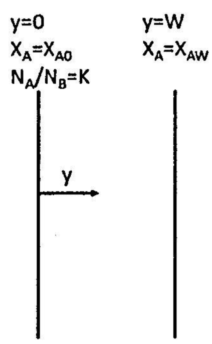
(e) For steady-state diffusion through a thin film with constant thickness L, the flux J is proportional to $1/L^2$. **(2%)**

Problem 6 (10%)

Please solve the following problems.

(a) Consider a binary system. Prove that the mass diffusivity of species A in species B is equal to the mass diffusivity of species B in species A. **(3%)**

(b) In a one-dimensional binary diffusion system of A in B, consider a film of width W, as shown below. At $y = 0$, the ratio of the molar flux of A to the molar flux of B is a constant K. Assuming the total concentration remains constant, derive the relationship between the mole fraction of A (X_A) and the position y. **(7%)**



Problem 7 (20%)

We use hydrothermal synthesis to fabricate metal-organic framework (MOF) particle, in the form of colloid, with a nominal diameter (i.e., assuming to be spherical) of 1.0 μm and a density of 1.1 g/cm^3. After the 1-h synthetic process, the MOF particles are required to be separated from the product solution (Stage 1), followed by the drying process to become dried powder (Stage 2). To achieve the goal of separating MOF particle from the product solution containing a massive amount of precursor, disc centrifugation is a useful approach. Therefore, we use disc centrifugation in Stage 1 and choose water as the medium for disc centrifugation.

(a) Please determine the required time for MOF particle to travel from the inner surface to the outer wall of the disc based on the following descriptions. **(5%)**

- The dimension of the disc: r_1 (inner surface, the solution entrance) = 2.0 m, r_2 (disc wall) = 5.0 m.
- The centrifugal speed is 20000 revolutions per minute.
- Viscosity of water is ≈ 1.0×10^{-3} Pa·s, and the density of water is 1.0 g/cm^3.

(b) Continue on (a): If the volume of MOF particle increases by 2 times: what is the required time for MOF particle to travel from the inner surface to the outer wall by using the disc centrifugation in Stage 1? Presumable the density of the MOF particle is the same. **Details of the calculations starting from the Stokes' law are required. (5%)**

(c) Wet powder of MOF particles can be obtained after the disc centrifugation process. In Stage 2, these MOF powders with a free moisture content of 0.10 kg H_2O/kg dry solid are delivered to an oven for drying. The goal is to have the almost completely dried powder, and we choose 0.00001 kg H_2O/kg dry solid as the target. Based on the information, please calculate the amount of time required for the drying in Stage 2.

The drying rate curve of the MOF powder is determined based on the previous experimental data in a similar case, showing the drying rate was 0, 1, 2, 4, 4, and 4 kg H_2O/kg dry solid when the free moisture content was 0, 0.02, 0.04, 0.08, 0.12 and 0.16 kg H_2O/(m^2·h), respectively. The weight of the dry MOF powder is 0.5 kg, and the area of the MOF powder used for drying is approximately 500 m^2/g of dry powder. **Details of the calculations starting from drying rate are required. (5%)**

(d) The MOF powders can be used as the adsorbent for CO_2 capture, to achieve the goal of carbon reduction and sustainable chemical engineering. Firstly, 5 g of MOF particles are placed as small fixed bed. A gas flow containing 20% of CO_2 in volume C_0 is flowing through the fixed bed, in which CO_2 will adsorb on the MOF by design. The flow rate of the gas is 5.0 L/min. The temperature and pressure are set at 298 K and atmospheric pressure, respectively. The relative elution concentration (C/C_0) is zero when elution time are $\leqq$ 2 hours. When the elution time equals to 3, 4, 5 hours, C/C_0 equals to 0.5%, 50% and 99.5%, respectively. The operation stopped at 10 hours with $C/C_0 = 1$； to simply the calculation, we assume $C/C_0 = 0$ when $C/C_0 \leqq 0.005$, and $C/C_0 = 1$ when $C/C_0 \geq 99.5$ %.

- Please estimate the saturation capacity of the MOF particle (in terms of g of solute/g of MOF). **Details of the calculations are required. (4%)**
- Do you expect to see a change of the breakthrough curve by increasing the operating pressure to 20 bar? Please provide your justification. **(1%)**

Problem 8 (12%)

A biogas stream containing 70 mol% CH_4 and 30 mol% CO_2 is processed using cryogenic distillation to upgrade the calorific value of biomethane. Impurities such as H_2S and water have already been removed in the pretreatment step. A CH_4-rich stream is obtained as the biomethane product. The distillation column contains a total condenser and a reboiler.

The design specifications are as follows:

- 98 mol% of CH_4 purity in CH_4-rich stream
- 90% of the methane in the feed is recovered in the CH_4-rich stream
- The feed enters the column as saturated vapor with a flow rate of 100 kmol/h.
- The column is operated at 30 bar
- A total condenser is operated at the bubble point assumed at -85°C

The physical properties are as follows:

- Pure-component boiling point at 30 bar: CH_4: -88°C; CO_2: -4°C
- Latent heat of vaporization at 30 bar: CH_4: 7 kJ/mol; CO_2: 12 kJ/mol, assumed independent of mixture composition and temperature.
- The average equilibrium K-value is 0.5 for CH_4 and 0.09 for CO_2

Please answer the following questions:

(a) What are the distillate and bottoms flow rates (kmol/h) and their mole fractions? **(4%)**

(b) Assuming reflux ratio is 2 mol reflux/mol distillate, estimate the cooling duty (kJ/h) in the condenser, assuming the enthalpy of superheating and subcooling are negligible. **(3%)**

(c) Calculate the minimum number of stages (N_{min}) required for the separation using the Fenske equation $N_{min} = \dfrac{\ln\left[\left(\frac{x_D}{1-x_D}\right)/\left(\frac{x_B}{1-x_B}\right)\right]}{\ln \alpha_{avg}}$ where x_D and x_B are mole fraction of methane in distillate and bottom, respectively. α_{avg} is the average relative volatility. **(3%)**

(d) Estimate the number of stages required for this column, assuming an overall plate efficiency of 50%. **(2%)**