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國立清華大學 115 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。
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Problem 1 (10%)

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

A Newtonian liquid is pumped through the annular gap between a solid cylindrical core and a surrounding protective tube, a configuration commonly encountered in cable cooling and coaxial conduit systems. The outer tube has radius R, while the inner solid core has radius κR, where $0 < \kappa < 1$. The flow is driven by a constant axial pressure gradient $\Delta P/L$and has reached steady, fully developed laminar conditions. Gravitational effects are neglected.

1. Reynolds number is defined as $Re = \rho v D/\mu$. For the flow is the annular gap, which of the following is an appropriate D?

   (A) $2R$　　(B) $2R(1-\kappa)$　　(C) $R(1-\kappa)$

   (D) $2R\sqrt{1-\kappa^2}$　　(E) $2R\sqrt{1-\kappa}$

2. From a shell momentum balance, the shear stress distribution $\tau_{rz}(r)$ in the annular flow must take which of the following mathematical forms? (A and B are non-zero constants.)

   (A) $\tau_{rz} = Ar + B$　　(B) $\tau_{rz} = Ar^2 + Br$　　(C) $\tau_{rz} = Ar^2 + B$

   (D) $\tau_{rz} = Ar + Br^{-1}$　　(E) $\tau_{rz} = Ar^{-1} + Br^{-2}$

3. If the axial velocity $\underline{v}_z(r)$ reaches its maximum at $r = \lambda R$, determine the expression of λ. [Boundary conditions: $v_z(\kappa R) = 0$; $v_z(R) = 0$]

   (A) $\sqrt{\frac{1+\kappa}{2}}$　(B) $\sqrt{\frac{1+\kappa}{2(1-\kappa)}}$　(C) $\frac{1-\kappa^2}{2(1-\kappa)}$　(D) $\frac{\ln(1/\kappa)}{1-\kappa}$　(E) $\sqrt{\frac{1-\kappa^2}{2\ln\left(\frac{1}{\kappa}\right)}}$

4. Let $\langle \underline{v}_z \rangle$ and $v_{z,\max}$ be the cross-sectional average velocity and the maximum velocity, respectively. Determine the ratio $\langle \underline{v}_z \rangle / v_{z,\max}$ as $\kappa \to 1$?

   (A) 1/3　(B) 1/2　(C) 2/3　(D) 1　(E) ln 2

5. Let F_{out} be the total axial force exerted by the fluid on the inner wall of the outer pipe ($r = R$); and let F_{in} be the total axial force exerted by the fluid on the outer wall of the inner pipe ($r = \kappa R$). If $\kappa = 0.5$, determine the ratio F_{out}/F_{in}.

   (A) 1.58　(B) 1.75　(C) 2.05　(D) 2.60　(E) 2.72

Problem 2 (10%)

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

A nurse administers a drug using a syringe connected to a long, slender needle of radius R and length L, where $L \gg R$. The injected fluid is incompressible and Newtonian, and the flow inside the needle is steady, laminar, and fully developed.

Assume:

- Gravitational effects are negligible
- Kinetic energy changes are negligible
- Mechanical compliance of the syringe is negligible
- The syringe barrel cross-sectional area is constant

6. To sustain flow through the needle, the nurse must apply a force to overcome a pressure drop ΔP along the needle. For this system, which physical mechanism is the primary contributor to the pressure drop?

   (A) Conversion of kinetic energy due to flow acceleration at the needle entrance
   (B) Distributed viscous dissipation arising from momentum transport between fluid layers
   (C) Coulomb-type friction between the fluid and the needle wall
   (D) Local energy loss due to flow separation and vena contracta formation at the entrance
   (E) Pressure work required to maintain volumetric flow against internal shear stresses

7. The nurse uses an automated syringe pump operating in constant volumetric flow rate mode (Q fixed) to inject the Newtonian fluid. The needle is replaced with another needle of half the original radius ($R_{new} = 0.5R$), while the needle length remains unchanged. By what factor must the force applied by the pump increase in order to maintain the same flow rate Q?

   (A) 2　(B) 4　(C) 8　(D) 16　(E) 32

Now consider two different drug formulations flowing through the same needle:

- Fluid N (Newtonian): viscosity $\mu = \mu_0$
- Fluid S (Shear-thinning): power-law fluid with consistency index $m = \mu_0$ and flow behavior index $n = 0.5$

Unless otherwise stated, flow remains steady, laminar, and fully developed.

8. Both fluids are delivered at the same fixed volumetric flow rate Q using an automated syringe pump. Which statement correctly describes the radial profiles of axial velocity $v_z(r)$ and shear stress $\tau_{rz}(r)$ for Fluid S?

   (A) Velocity is flatter than parabolic (plug-like); shear stress remains linear

   (B) Velocity is flatter than parabolic (plug-like); shear stress becomes nonlinear

   (C) Velocity approaches a uniform (plug) profile while shear stress is nearly zero throughout the needle

   (D) Velocity is parabolic; shear stress is linear

   (E) Velocity is parabolic; shear stress is nonlinear

9. Under the same condition of fixed volumetric flow rate Q, which fluid experiences a higher maximum shear rate $\dot{\gamma}_{max}$ at the needle wall?

   (A) They are identical because Q and R are the same

   (B) Fluid N has a higher $\dot{\gamma}_{max}$ because its viscosity is constant

   (C) Fluid S has a higher $\dot{\gamma}_{max}$ because velocity gradients are concentrated near the wall

   (D) Fluid S has a lower $\dot{\gamma}_{max}$ because shear-thinning reduces wall stress

   (E) Fluid S and Fluid N have the same $\dot{\gamma}_{max}$, but differ only in wall shear stress, not shear rate

10. The nurse switches to manual injection, applying a constant force to the plunger. Assume this results in a constant pressure drop ΔP across the needle. Comparing the two fluids, which statement is correct?

    (A) Both fluids exit the needle at the same flow rate

    (B) Fluid S flows more slowly because its overall flow resistance is higher

    (C) The wall shear stress τ_w differs between the two fluids

    (D) Fluid S and Fluid N have the same average velocity, but Fluid S has a different velocity profile shape

    (E) Fluid S flows faster because its local apparent viscosity near the wall is lower than μ_0

Problem 3 (20%)

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

As endurance sports such as marathon running have gained popularity worldwide, understanding the physiological and transport processes that govern athletic performance has become increasingly important. During a marathon, the human body is subjected to prolonged physical stress, requiring efficient management of nutrient delivery, mass exchange, and thermal regulation. These challenges are closely linked to fundamental principles of mass transfer, which play a critical role in sustaining performance and preventing fatigue, dehydration, or heat-related injury.

11. To maintain energy supply during long-distance running, athletes often ingest carbohydrate–electrolyte drinks or energy gels. After ingestion, nutrients must be transported from the gastrointestinal tract into the bloodstream. This transport process may be idealized as mass transfer across an intestinal membrane under isothermal and steady conditions. Which of the following best represents the primary driving force for nutrient absorption into the bloodstream?

    (A) The concentration difference of nutrients across the intestinal membrane

    (B) The pressure difference generated by peristaltic motion in the intestine

    (C) The temperature difference between ingested fluids and body tissue

    (D) Convective transport induced by bulk fluid motion in the intestine

    (E) The combined effect of shear stress and viscous dissipation at the membrane surface

12. After ingestion, nutrient absorption across the intestinal wall can be modeled as steady-state diffusion through a thin membrane. Assume one-dimensional mass transfer normal to the membrane and neglect any convective resistance. The nutrient concentration on the intestinal side is C_1 = 6.0 mol/m^3, and that in the bloodstream is C_2 = 2.0 mol/m^3. The effective membrane thickness is δ = 0.50 mm, and the effective diffusion coefficient of the nutrient in the membrane is D = 1.0×10^{-9} m^2/s. Assuming steady-state diffusion, what is the magnitude of the molar flux of the nutrient across the membrane?

    (A) 4.0×10^{-3} mol/m$^2\cdot$s　(B) 8.0×10^{-3} mol/m$^2\cdot$s　(C) 1.6×10^{-5} mol/m$^2\cdot$s

    (D) 4.0×10^{-6} mol/m$^2\cdot$s　(E) 8.0×10^{-6} mol/m$^2\cdot$s

13. The absorption of A from the intestinal lumen into the bloodstream is modeled as steady-state, one-dimensional mass transfer with three resistances in series: (1) Lumen-side film: $k_L = 2.0\times10^{-5}$ m/s; (2) Intestinal membrane: thickness = 200 μm, diffusivity = 1.0×10^{-10} m^2/s; (3) Blood-side film: $k_B = 5.0\times10^{-5}$ m/s. The bulk concentrations are: $C_{L,\infty} = 20$ mM, $C_{B,\infty} = 2$ mM. The effective absorption area is $A = 0.25$ m^2. Estimate and choose the closest molar absorption rate.

(A) 3.0×10^{-6} mol/s (B) 1.0×10^{-5} mol/s (C) 3.0×10^{-5} mol/s

(D) 1.0×10^{-4} mol/s (E) 3.0×10^{-4} mol/s

14. Following the above question, nutrient A is transported from the intestinal lumen to the intestinal wall. Assume that the rate-limiting step is convective mass transfer in the lumen, and the intestine can be approximated as a cylindrical tube. Assume diameter $D = 2$ cm, length $L = 0.5$ m, average velocity $v = 0.02$ m/s, density $\rho = 1000$ kg/m^3, viscosity $\mu = 1.0\times10^{-3}$ Pa·s, diffusivity $D_{AB} = 6.0\times10^{-10}$ m^2/s. Assume laminar, fully developed flow and constant wall concentration.

(A) Re = 40, Sc = 1.7×10^3 (B) Re = 400, Sc = 1.7×10^3 (C) Re = 40, Sc = 1.7×10^6

(D) Re = 400, Sc = 1.7×10^6 (E) Re = 400, Sc = 1.7×10^5

15. Following the above question, use the correlation: $Sh = 1.62\left(\frac{ReScD}{L}\right)^{1/3}$ to estimate the closest mass transfer coefficient k.

(A) 3.0×10^{-7} m/s (B) 8.0×10^{-7} m/s (C) 1.5×10^{-6} m/s

(D) 4.0×10^{-6} m/s (E) 1.2×10^{-5} m/s

16. During marathon running, sweat evaporates from the skin surface into the surrounding air. Which of the following changes would most directly increase the sweat evaporation rate during a marathon?

(A) Increasing ambient air humidity

(B) Decreasing air velocity near the skin

(C) Thickening the concentration boundary layer

(D) Increasing air velocity around the runner

(E) Increasing the density of sweat on the skin surface

17. Which statement best explains why increasing running speed enhances the evaporation rate?

(A) Increased pressure reduces the saturation concentration of water vapor

(B) Higher air velocity reduces the thickness of the concentration boundary layer

(C) Faster motion increases molecular diffusivity of water vapor in air

(D) Evaporation becomes limited by internal diffusion within sweat glands

(E) The vapor–liquid equilibrium shifts due to mechanical motion

18. Sweat evaporation from a runner's skin is modeled as laminar forced convection over a flat plate. The mass transfer resistance is dominated by the concentration boundary layer of water vapor in air. For laminar flow over a flat plate, the local concentration boundary-layer thickness may be approximated as: $\delta_c(x) \sim \frac{5x}{\sqrt{\mathrm{Re}_x}\mathrm{Sc}^{1/3}}$, where air velocity $v_\infty = 4$ m/s, distance from leading edge $x =$ 0.4 m, air density = 1.2 kg/m^3, air viscosity = 1.9×10^{-5} Pa·s, $D_{AB} = 2.5\times10^{-5}$ m^2/s. Which of the following is the best estimate of the local concentration boundary-layer thickness δ_c?

(A) 3.5 mm　(B) 4.5 mm　(C) 5.5 mm　(D) 6.5 mm　(E) 7.5 mm

19. Assume that the mass flux of water vapor from the skin surface is controlled by diffusion across the concentration boundary layer: $N_A \sim \frac{D_{AB}(C_s - C_\infty)}{\delta_c}$, where C_s-C_∞ is constant. If the runner increase speed, which of the following best describes the resulting change in local evaporation mass flux N_A?

(A) Increases by a factor of $\sqrt{2}$　(B) Increases by a factor of 1.2

(C) Increases by a factor of 2　(D) Increases by a factor of $2^{2/3}$

(E) Increases by a factor of 4

20. Following the above question, estimate the total sweat–vapor mass loss rate m_{total} (kg/s) from the skin surface. You may use the following correlation for average mass transfer over a flat plate: $\mathrm{Sh}_L = 0.664\mathrm{Re}_L^{1/2}\mathrm{Sc}^{1/3}$, $k_L = \frac{\mathrm{Sh}_L D_{AB}}{L}$, where plate length (flow direction) L = 0.4 m, plate width W = 0.12 m, water vapor concentration at the skin surface C_s = 0.03 kg/m^3, water vapor concentration in the ambient air C_∞ = 0.012 kg/m^3.

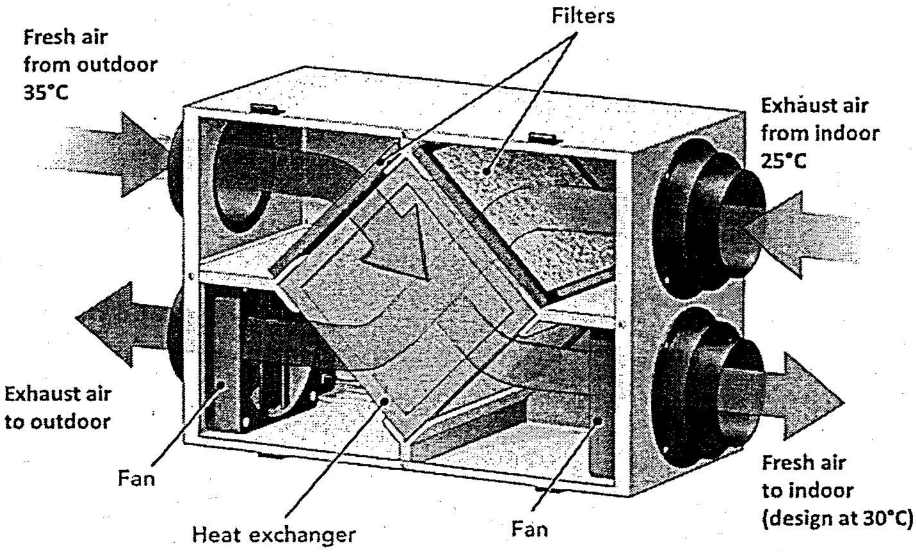
(A) 1.0×10^{-7} kg/s　(B) 5.0×10^{-7} kg/s　(C) 1.0×10^{-6} kg/s

(D) 5.0×10^{-6} kg/s　(E) 1.0×10^{-5} kg/s

Problem 4 (20%)

Multiple choice: (Pick only one answer for each problem.)

In summer, an office operates air conditioning with windows closed. To enable outdoor fresh-air intake and indoor exhaust-air discharge while minimizing the cooling load of air conditioner, a countercurrent plate-type energy recovery ventilator (ERV) is installed to recover cooling from the indoor exhaust air and pre-cool the incoming outdoor fresh air. The schematic of ERV is shown below.



Assumptions:

- Equal indoor exhaust air and outdoor fresh air flow rates: 2 m^3/s
- Indoor exhaust air temperature: 25°C
- Outdoor fresh air temperature: 35°C
- Fresh air design temperature at the ERV outlet: 30°C
- The ERV is treated as a sensible heat exchanger assuming no phase change
- Fresh air and exhaust air have identical physical properties (independent of temperature)
- Air properties
    - Heat capacity: 1.0 $\frac{kJ}{kg \cdot K}$
    - Density: 1.2 $\frac{kg}{m^3}$
    - Dynamic viscosity: 1.9 x10^{-5} $Pa \cdot s$
    - Thermal conductivity: 0.026 $\frac{W}{m \cdot K}$

- Hydraulic diameter of air channel: 0.01 m
- Air flow cross-sectional area per side: 0.5 m^2

21. Calculate the heat duty exchanged by the ERV. (2%)

(A) 12 kW (B) 18 kW (C) 24 kW (D) 32 kW (E) 48 kW

22. Calculate the exhaust air temperature at the ERV outlet. (2%)

(A) 26°C (B) 28°C (C) 30°C (D) 32°C (E) 35°C

23. Estimate the overall heat transfer coefficient using the convective heat transfer correlation $Nu = 0.023Re^{0.8}Pr^{0.4}$ (Assume identical heat transfer coefficients on both sides and negligible wall resistance). (4%)

(A) 5 $\frac{W}{m^2 \cdot K}$ (B) 14 $\frac{W}{m^2 \cdot K}$ (C) 20 $\frac{W}{m^2 \cdot K}$ (D) 28 $\frac{W}{m^2 \cdot K}$ (E) 34 $\frac{W}{m^2 \cdot K}$

24. Calculate the log-mean temperature approach. (2%)

(A) 2 K (B) 5 K (C) 8 K (D) 10 K (E) Indeterminate

25. (4 pts) Calculate the heat transfer area needed. (4%)

(A) 35 m^2 (B) 85 m^2 (C) 120 m^2 (D) 150 m^2 (E) 170 m^2

26. If the coefficient of performance (COP, defined as $\frac{Cooling\ duty\ (kW)}{Electrical\ power\ input\ (kW)}$) of the air-conditioning system is 3.2 and the office operates 200 h/month, what is the monthly cost saving if electricity price is $4/kWh? (4%)

(A) $3000 (B) $4500 (C) $6000 (D) $7500 (E) $9000

27. If the air filters on both the fresh-air and exhaust-air sides are not properly cleaned and become clogged, which consequence is least likely? (2%)

(A) The pressure drop across the ERV increases

(B) The air flow rate through the ERV decreases

(C) The convective heat transfer coefficient decreases

(D) The ERV exchanged heat duty increases

(E) None of above

Problem 5 (10%)

Indicate whether each of the following statements is correct or incorrect. If a statement is incorrect, provide the corrected version.

(a) For steady-state radial heat conduction in a hollow cylinder without heat generation, the temperature varies linearly with radius. **(2%)**

(b) Adding insulation to a cylindrical pipe can increase heat loss if the radius of insulation is less than the critical radius. **(2%)**

(c) For steady heat conduction in a rod with varying cross-sectional area, the heat flux is generally constant but the heat transfer rate may vary with position. **(2%)**

(d) A small Biot modulus implies significant temperature gradient within the solid. **(2%)**

(e) In forced convection over a flat plate, increasing the Reynolds number generally increases the thermal boundary layer thickness. **(2%)**

Problem 6 (10%)

A thin slab of thickness $2L$ occupies the region $-L \leq x \leq L$. The slab has constant thermal conductivity k and undergoes steady, one-dimensional heat conduction with the position-dependent volumetric heat generation given by

$$Q(x) = Q_0[1 - (x/L)^2]$$

where Q_0 is a constant (W/m^3). The surface of the slab at $x = -L$ is insulated (adiabatic) and the other surface is exposed to a surrounding fluid at temperature T_∞ and exchanges heat by convection with a uniform heat transfer coefficient h.

(a) Determine the temperature distribution $T(x)$. **(6%)**

(b) Where and what is the maximum temperature in this slab. **(4%)**

Problem 7 (10%)

1. A dual pressure swing adsorption system is used for the CO_2 capture via the mechanism of gas adsorption. During the operation, one column is used for the CO_2 adsorption, while the other column is operated under the desorption mode for the regeneration of adsorbent. Each column contained a fixed bed of 500 g of zeolite used as CO_2 adsorbent.

During the adsorption stage, the overall gas flow rate of the feed is 0.2 L/min, and the volume fraction of CO_2 in the gas flow is constant at 10%. The moles of CO_2 in the feed are calculated by assuming constant pressure (1 atm) and constant temperature (298 K). The gas constant is 0.082 L·atm/(K·mol).

In the system, a downstream infrared-based CO_2 detector is used to measure the concentration of CO_2 eluting from the column in the range of 0.002 to 0.2 (in term of volume fraction of CO_2 in the gas flow). During the operation, it is found that volume fraction of CO_2 in the gas flow was not immeasurable at the eluting time (t) of 0 hour, 1 hour, and 2 hour, suggesting that relative concentration of CO_2 in the gas flow is assumed to be zero. At the 5th hour, the volume fraction of CO_2 in the gas flow was found to be 0.002, the lowest concentration that can be detected by the infrared-based CO_2 detector. A linear increase of the volume fraction of CO_2 in the gas flow from 0.002 to 0.098 was observed from $t = 5$ h to $t = 10$ h. When $t = 15$ h, we identified that volume fraction of CO_2 in the gas flow was the same as the original value (i.e., without using the CO_2 capture system).

Based on the information shown above, please determine:

(1) the saturation capacity of the zeolite used as adsorbent (unit: mol of CO_2/g of zeolite). (4%)

(2) the fraction of the adsorbent bed being used when the detected volume fraction of CO_2 in the gas flow was 0.005. (4%)

<u>Details of calculation with a breakthrough curve are required</u>.

2. Following the above question, after a complete regeneration process, the amount of zeolite in each column is increased by two times for the next run. What is the amount of CO_2 capture (unit: mole) when the operating time is 2 h in the next run? <u>A brief justification to the answer is required</u>. (2%)

Problem 8 (10%)

1. Molecular sieve, silica gel, polystyrene bean and aluminum oxide nanopowder: Which one has the highest binding affinity to water molecule? Which one has the highest adsorption capacity to the water molecule evaporated from the tank of de-ionized water? A brief justification to the answer of each question is required. (2%)

2. Metal-organic framework A (MOF-A), in the form of powder with ultrafine nanopore, is used for the adsorption of water. The weight of the batch of dry MOF-A powder is 100 g and specific surface area of the MOF-A is 2000 m^2/g. After the operation of the Day 1, the free moisture content of the MOF-A is 0.27 kg H_2O/kg dry solid. For the regeneration of these MOF-A powder, we use continuous-mode hot air blower for the drying. The starting drying rate is 2.0 kg $H_2O/(m^2 \cdot h)$.

Based on the data reported in the literature, the critical moisture content of the MOF-A is 0.25 kg H_2O/kg dry solid. To simplify the calculation, we assume the rate of drying is constant when the free moisture content of the MOF-A is between 0.25 kg H_2O/kg dry solid and 0.60 kg H_2O/kg dry solid. Besides, the rate of drying is linearly proportional to the free moisture content of MOF-A when the free moisture content of the MOF-A is below 0.25 kg H_2O/kg dry solid.

(a) What is the time for drying required if the target free moisture content of MOF-A is 0.02 kg H_2O/kg dry solid? (2%)

(b) Continued on <2a>: What is the time for drying required if the target free moisture content of MOF-A further decreases to 0.001 kg H_2O/kg dry solid? (2%)

(c) Continued on <2b>: We add the infrared light radiation for speeding up the drying rate. The starting drying rate is expected to be increased by 100%. Calculate the time for drying required, when the target free moisture content of MOF-A is 0.001 kg H_2O/kg dry solid. Assuming the critical point is unchanged. (2%)

(d) Continued on <2c>: Due to the significant increase in environmental humidity, the free moisture content of the MOF-A becomes 0.50 kg H_2O/kg dry solid after the operation of the Day 2. Calculate the time for drying required for the Day 2 operation, when the target free moisture content of MOF-A is 0.001 kg H_2O/kg dry solid. Note that we continue to use hot air blowing plus infrared light radiation for the drying. (2%)

Details of the derivations for the equations used for calculating the time of drying are required in the answers of the above questions.