國立清華大學 107 學年度碩士班考試入學試題

系所班組別：化學工程學系碩士班

考試科目（代碼）：輸送現象及單元操作（0901）

　　*請在【答案卡】作答

Problem 1 (40%)

Multiple choice. Pick only one answer for each question. Each question is 2% in score.

1. A Newtonian fluid of constant density and viscosity is bounded between two large parallel plates of a gap of b. Initially the fluid and the plates are at rest. Then at time $t = 0$, the upper plate is set in motion in the positive x direction with velocity U. Give the governing equation for v_x.

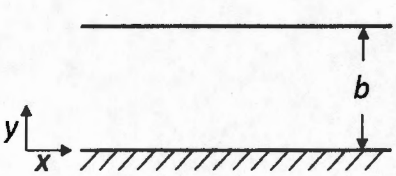
(A) $\dfrac{\partial v_x}{\partial t} = \dfrac{\mu}{\rho}\left(\dfrac{\partial^2 v_x}{\partial y^2} + \dfrac{\partial^2 v_x}{\partial y^2}\right)$

(B) $0 = \dfrac{\mu}{\rho}\dfrac{\partial^2 v_x}{\partial x^2}$

(C) $\dfrac{\partial v_x}{\partial t} = \dfrac{\mu}{\rho}\dfrac{\partial^2 v_x}{\partial x^2}$

(D) $\dfrac{\partial v_x}{\partial t} = \dfrac{\mu}{\rho}\dfrac{\partial^2 v_x}{\partial y^2}$

(E) $\dfrac{\partial v_x}{\partial t} = \dfrac{\mu}{\rho}\dfrac{\partial v_x}{\partial x}$



[Hint]

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z} = 0$$

$$\rho\left(\frac{\partial v_x}{\partial t} + v_x\frac{\partial v_x}{\partial x} + v_y\frac{\partial v_x}{\partial y} + v_z\frac{\partial v_x}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left[\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2}\right] + \rho g_x$$

2. Give the relevant initial condition (IC) and boundary conditions (BCs) for v_x.

(A) IC : $v_x = 0$, at $0 \le y \le b$, when $t = 0$, BC1: $v_x = 0$, at $y = b, t > 0$, BC2: $v_x = U$, at $y = 0, t > 0$

(B) IC : $v_x = U$, at $0 \le y \le b$, when $t = t$, BC1: $v_x = U$, at $y = b, t > 0$, BC2: $v_x = 0$, at $y = 0, t > 0$

(C) IC : $v_x = 0$, at $0 \le y \le b$, when $t = 0$, BC1: $v_x = U$, at $y = b, t > 0$, BC2: $v_x = 0$, at $y = 0, t > 0$

(D) IC : $v_x = U$, at $0 \le y \le b$, when $t = 0$, BC1: $v_x = U$, at $y = b, t > 0$, BC2: $v_x = 0$, at $y = b, t > 0$

(E) IC : $v_x = U$, at $0 \le y \le b$, when $t = 0$, BC1: $v_x = 0$, at $y = b, t > 0$, BC2: $v_x = U$, at $y = 0, t > 0$

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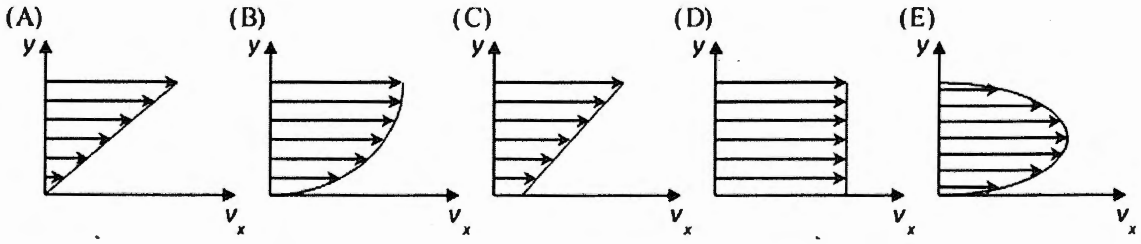
3. At the steady state, if the upper and lower plates are no-slip and we do not consider the gravity and pressure gradient, the velocity profile will become



4. Following the above question, consider the flow of water ($\mu = 1$ cp) with upper plate of surface area equal to 0.5 m^2 and the velocity of the upper plate (U) equal to 2 m/s. If the separation distance between the two plates (b) is equal to 2 mm, calculate the rate of viscous dissipation (J/s).
(A) 0.5　(B) 1　(C) 2　(D) 4　(E) 8

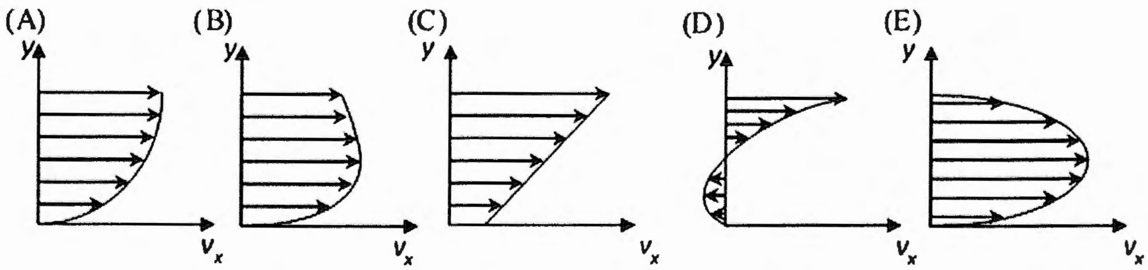
[Hint]

$$\Phi_v = 2\left[\left(\frac{\partial v_x}{\partial x}\right)^2 + \left(\frac{\partial v_y}{\partial y}\right)^2 + \left(\frac{\partial v_z}{\partial z}\right)^2\right] + \left[\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y}\right]^2 + \left[\frac{\partial v_z}{\partial y} + \frac{\partial v_y}{\partial z}\right]^2 + \left[\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right]^2 - \frac{2}{3}\left[\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right]^2$$

$$E_v = \int \mu \Phi_v dV$$

5. The same with the above question. How much force (N) is required to maintained the constant velocity of the upper plate?
(A) 0.1　(B) 0.5　(C) 2　(D) 4　(E) None of above

6. If we consider pressure gradient between two parallel plates this time and the pressure gradient (dp/dx) is greater than zero, the velocity profile will become



7. If the lower plate has slip boundary condition $v_x = k\dfrac{dv_x}{dy}$ at $y = 0$ and without considering pressure gradient and gravity, where k is the slip length, the velocity of the fluid will be

(A) $v_x = \dfrac{y}{b+k}U$

(B) $v_x = \dfrac{y+k}{b}U$

(C) $v_x = \dfrac{y+k/2}{b+k/2}U$

(D) $v_x = \dfrac{y+2k}{b+2k}U$

(E) $v_x = \dfrac{y+k}{b+k}U$

8. Following the above question, consider the velocity of the upper plate (U) equal to 2 m/s, the separation distance between the two plates (b) is equal to 2 mm, and the slip length (k) is equal to 1 mm. Find out the slip velocity (m/s) of the lower plate.
(A) 0.4 (B) 0.5 (C) 0.67 (D) 1 (E) None of above

9. For incompressible non-Newton fluids, the normal stresses usually are nonzero and unequal. If there is a polymeric fluid between the two parallel plates with upper plate moving at a constant speed, the first normal stress difference and second normal stress difference will be positive or negative? And what is their relationship?

(A) $\tau_{xx} - \tau_{yy} > 0, \tau_{yy} - \tau_{zz} > 0, |\tau_{xx} - \tau_{yy}| >> |\tau_{yy} - \tau_{zz}|$

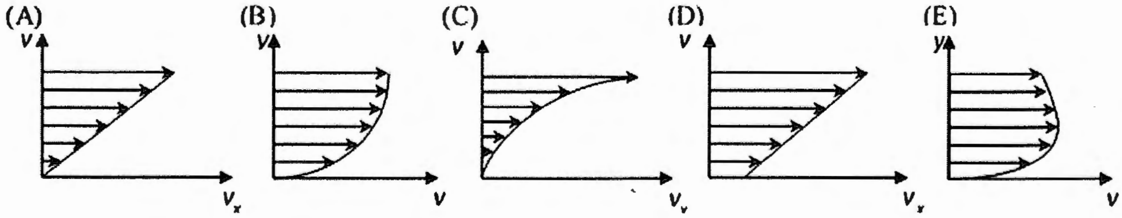
(B) $\tau_{xx} - \tau_{yy} > 0, \tau_{yy} - \tau_{zz} < 0, |\tau_{xx} - \tau_{yy}| << |\tau_{yy} - \tau_{zz}|$

(C) $\tau_{xx} - \tau_{yy} < 0, \tau_{yy} - \tau_{zz} > 0, |\tau_{xx} - \tau_{yy}| << |\tau_{yy} - \tau_{zz}|$

(D) $\tau_{xx} - \tau_{yy} < 0, \tau_{yy} - \tau_{zz} > 0, |\tau_{xx} - \tau_{yy}| = |\tau_{yy} - \tau_{zz}|$

(E) $\tau_{xx} - \tau_{yy} < 0, \tau_{yy} - \tau_{zz} > 0, |\tau_{xx} - \tau_{yy}| >> |\tau_{yy} - \tau_{zz}|$

10. Following the above question, the velocity profile of the polymeric fluid will become



11. There exist mathematical and physical similarities between momentum and energy transfers. What is the physical quantity in momentum transfer that is corresponding to heat flux in energy transfer?
(A) viscosity,
(B) shear stress,
(C) velocity gradient,
(D) momentum density gradient.

12. What is the SI unit of thermal diffusivity?
(A) W/(m K), (B) W/(m^2 K), (C) W/(cm^2 K), (D) m^2/s.

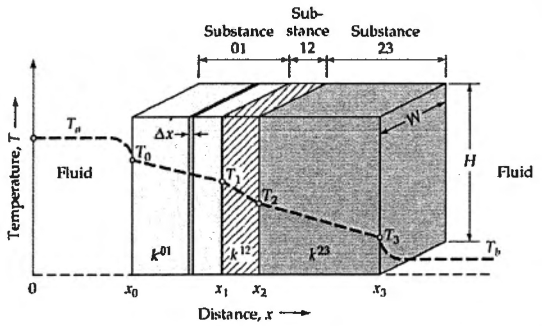
13. For the following materials, (a) H_2 at 1 atm and 273 K, (b) brick at 273 K, (c) H_2O at 20 °C, and (d) H_2 at 0.1 atm and 273 K, place them in the order of increasing thermal conductivity.
(A) (d)(a)(c)(b), (B) (b)(a)(c)(d), (C) (a)(b)(d)(c), (D) (a)(b)(c)(d).

14. What is the order of magnitude of the Prandtl number of ethylene glycol 300 K?
(A) $\ll 1$, (B) $\gg 1$, (C) ~ 1, and (D) ~ -1.

15. Consider an electric wire of radius R. The electric current generates heat at a rate per unit volume of Se. The surface of the wire is coated with an insulating material of thickness d and thermal conductivity k. The surface of the wire is maintained at temperature T_0. At steady state, what is the relationship between the heat flow rate at the surface of the insulating material (a) and the heat generation rate by the electric current (b)?
(A) a=b, (B) a>b, (C) a<b, (D) cannot be determined.

16. Consider a Newtonian fluid of constant density and viscosity, flowing between two large plates separated by a distance b. The fluid flow is driven by the motion of the upper plate at a constant velocity V. The temperature of the lower plate (located at x=0) is maintained at T_0 and that of the upper plate at T_b (located at x=b). Let Br be the Brinkman number of the fluid flow. Under what conditions will the temperature distribution be linear?
(A) Br=0, (B) Br<0, (C) Br>0, (D) any Br.

17. Consider the following steady state temperature profile in a laminated system (Fig. 10.6-1 of "Transport Phenomena" by R.B. Bird, W.E. Stewart, E.N. Lightfoot, 2nd ed., Wiley, 2002). Which of the following statements is true?



(A) $k^{01}>k^{12}>k^{23}$, (B) $k^{12}>k^{01}>k^{23}$, (C) $k^{01}>k^{23}>k^{12}$, (D) $k^{12}>k^{23}>k^{01}$.

18. The equation of change for temperature in terms of the heat flux vector, $\underline{q}$, with negligible viscous heating, is given as the following.

$$\rho\hat{C}_p\frac{DT}{Dt}=-\underline{\nabla}\cdot\underline{q}-\left(\frac{\partial\ln\rho}{\partial\ln T}\right)_p\frac{Dp}{Dt},$$

where D/Dt is the substantial time derivative operator, ρ the density, $\hat{C}_p$ the heat capacity per unit mass, T the temperature, $\underline{v}$ the velocity vector, and p the pressure of the fluid. The symbol t is for time. All physical properties are considered constant. If Fourier's law of heat conduction applies, what form will the above equation be reduced to for heat transfer in an ideal gas? (k is the thermal conductivity of the gas.)

(A) $\rho\hat{C}_p\frac{\partial T}{\partial t}=k\nabla^2T+\frac{Dp}{Dt}$, (B) $\rho\hat{C}_p\frac{DT}{Dt}=k\nabla^2T$, (C) $\rho\hat{C}_p\frac{DT}{Dt}=k\nabla^2T+\frac{Dp}{Dt}$,

(D) $\rho\hat{C}_p\frac{\partial T}{\partial t}=k\nabla^2T$

19. A solid material occupying the space from y=0 to $y=\infty$ is initially at temperature T_0. At time t=0, the surface at y=0 is suddenly raised to temperature T_1 and maintained at that temperature for t>0. (α and k are the thermal diffusivity and thermal conductivity of the material, respectively.) Which of the following statements is ***wrong***?

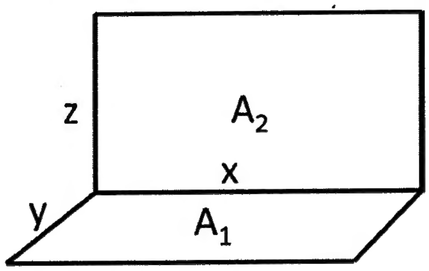
(A) The temperature profile reaches a steady state after a long time.

(B) The normal heat flux at y=0 decreases with increasing time.

(C) The thermal boundary layer thickness increases with increasing time.

(D) The temperature will be raised faster if the material possesses a larger thermal diffusivity.

20. Consider the view factor of the following direct radiation between adjacent rectangles in perpendicular planes.



(A) F_{22} increases with increasing y/x;
(B) F_{11} decreases with increasing z/x;
(C) F_{12} decreases with increasing z/x;
(D) F_{11} is irrelevant to both z/x and y/x.

Problem 2 (8%)

Answer the following questions regarding mass transport:

(a) How is the binary mass diffusivity defined ? Give the SI unit of mass diffusivity. Give the typical orders of magnitude of the diffusivities for gases, liquids and solids. *(4%)*

(b) Define “equimolar counter-diffusion”. Give one example where the condition of “equimolar counter-diffusion” applies. *(4%)*

Problem 3 (12%)

Under suitable circumstances the rate of oxygen metabolism by bacterial cells is very nearly zero order with respect to oxygen concentration. We examine such a case here and focus our attention on a spherical aggregate of cells, which has a radius R. We wish to determine the total rate of oxygen uptake by the aggregate as a function of aggregate size, oxygen mass concentration ρ_0 at the aggregate surface, the metabolic activity of the cells, and the diffusional behavior of oxygen. For simplicity we consider the aggregate to be homogeneous. We then approximate the metabolic rate by an effective volumetric reaction rate $r_{O2}=-k_0$ and the diffusional behavior by Fick’s law, with the effective pseudobinary diffusivity D_{AB}. Because the solubility of oxygen is very low in this system, both convective oxygen transport and transient effect may be neglected.

(a) Show by means of a shell mass balance that the quasi-steady-state oxygen concentration profile is described by the differential equation *(5%)*

$$\frac{1}{\varepsilon^2}\frac{d}{d\varepsilon}\left(\varepsilon^2\frac{dX}{d\varepsilon}\right)=N \qquad (3.1)$$

where $X=\rho_{O2}/\rho_0$, $\varepsilon=r/R$, and $N=k_0R^2/(\rho_0 D_{AB})$.

(b) There may be an oxygen-free core in the aggregate, if N is sufficiently large, such that $X=0$ for $\varepsilon<\varepsilon_0$. Write sufficient boundary conditions to integrate Eq. (3.1) for this situation. To do this, it must be recognized that both X and $dX/d\varepsilon$ are zero at $\varepsilon=\varepsilon_0$. *(3%)*

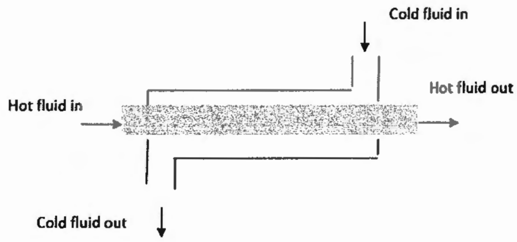
(c) Perform the integration of Eq. (3.1) and show how ε_0 may be determined. *(4%)*

Problem 4 (10%)

A coaxial-tube counter-flow heat exchanger (see the figure below) is used to cool 0.04 kg/s of benzene from 370 K to 320 K with water at 290 K. If the inner tube outside diameter is 0.02 m, and the overall heat transfer coefficient based on outside area is 650 W/m^2 K, the specific heats of benzene and water can be taken as 1880 and 4175 J/kg K, respectively:

(a) Determine the minimum water flow rate (expressed in kg/s) to this task. *(5%)*

(b) If the water flow rate is 0.03 kg/s, determine the tube length (expressed in m) required. *(5%)*



Problem 5 (10%)

A fuel rod in a nuclear reactor has an averaged power generation rate per volume (Q_v) of 152 W/cm^3. The diameter of the rod is 0.825 cm. The thermal conductivity of the rod is 2.5 W/m^2 K and the outer surface temperature of the rod is at 1640 K. Calculate the temperature at the centerline of the rod.

Problem 6 (10%)

Emission of CO_2, a greenhouse gas, has been a concern to the development of traditional chemical engineering. On the other hand, this challenge of the control of CO_2 emission becomes an opportunity for the chemical engineer: to explore new methods for reducing the impact to environment.

(a) In a fossil fuel-based power plant, the engineers plan to employ a new unit to reduce the amount of CO_2 emitted to the atmosphere via flue gas of the plant. The concept is to use an amine-based aqueous solution continuously flowing though a column to trap the CO_2 from the flue gas to the solution phase. The flue gas flows from the bottom to the top of the column, and the amine-based aqueous solution flows from the top to the bottom of the column. Based on the mechanism of mass transfer, what is the name of this unit operation? *(2%)*
(Hint: solid or liquid extraction, membrane separation, distillation, gas absorption or stripping, and adsorption etc)

(b) Following on (a): The flue gas with a flow rate of 1 kgmol/min is composed of 5 % of CO_2 and 95% of air (i.e., in molar ratio). For simplifying the calculation, we assume that the amount of air taken by the aqueous solution is negligible (i.e., the solubility of CO_2 in the solution is not affected by the presence of air). The solubility of CO_2 (i.e., in terms of molar ratio) in the amine-based solution is equal to the concentration ratio of CO_2 in the flue gas (i.e., as an equilibrium correlation). The target concentration of CO_2 in the flue gas is 1%. Please find the minimum flow rate of the amine-based solution (*3%*), and estimate the number of ideal stages required if the flow rate of amine-based solution is 2 kgmol/min (*2%*). Details of derivation to the results are required.
(Hint: the mass flow rates of solution and flue gas are assumed to be constant)

(c) Following on (b): We aim to use a spray tower to increase the solubility of CO_2 in the amine-based solution by the increase of mass transfer area. The results show that creating a number of bubbles increases the solubility of CO_2 (i.e., in terms of molar concentration) in the amine-based solution to be the 4 times of the molar concentration of CO_2 in the flue gas. Please estimate the number of ideal stages required in order to lower the concentration of CO_2 in the flue gas to be 1%. The flow rate of flue gas is constant at 1 kgmol/min, and the flow rate of amine-based solution is 2 kgmol/min. (Details of derivation to the results are required.) *(3%)*

Problem 7 (10%)

(a) Electrostatic precipitation has shown to be very useful for the removal of fine particles in the flue gas. Here, we use this method as a separation technique to improve the quality of aerosol-based products.
In the aerosol-based product, a mixture of spherical Au nanoparticles (specific gravity of 10, 20 nm in diameter), and spherical polystyrene latex particle (specific density of 1.1, 40 nm in diameter), is to be separated in the gas phase by a customized electrostatic classifier. A direct-circuit electric field of E is supplied to the classifier. The external force exerting on a particle can be expressed as $F_e = n \times e \times E$. Through an uniform charging process, all particles contain a net charge of +1 (i.e., $n = +1$). In order to reach the targeted position of the classifier (i.e., 0.05 m from the starting point) in a residence time of 5 seconds, what is the electric field required for the two types of particles (*4%*)? If we change the residence time to be 50 seconds, what is the new electric field required for 20-nm Au nanoparticles (*1 %*)? Note that usually the gravity force of nanoparticle usually can be negligible in this case. [e is 1.6×10^{-19} coulombs; the viscosity of air is 1.81×10^{-5} kg/(m. s)]

(b) Leaching, or solid extraction, has been commonly used for the manufacture of herbal medicine product. Here the target solute is Ingredient A. Here a solid raw material containing 20 wt% of Ingredient A is to be extracted by a countercurrent unit operation. Our objective is to recover Ingredient A from the raw material by 90 % (i.e., only 10 % in total remains in the raw material).
The fresh solvent (de-ionized water) is used for performing the extraction. Based on the design, the target is to have an extract solution containing 50 wt% of Ingredient A. If 5 kg/hr of solution is removed into the underflow in association with every 4 kg/hr of exhausted raw material, how many ideal stages are required *(2%)*, and how much solvent is required in term of mass flow rate ? *(3%)*