

國立成功大學

115學年度碩士班招生考試試題

編 號： 51

系 所： 化學工程學系

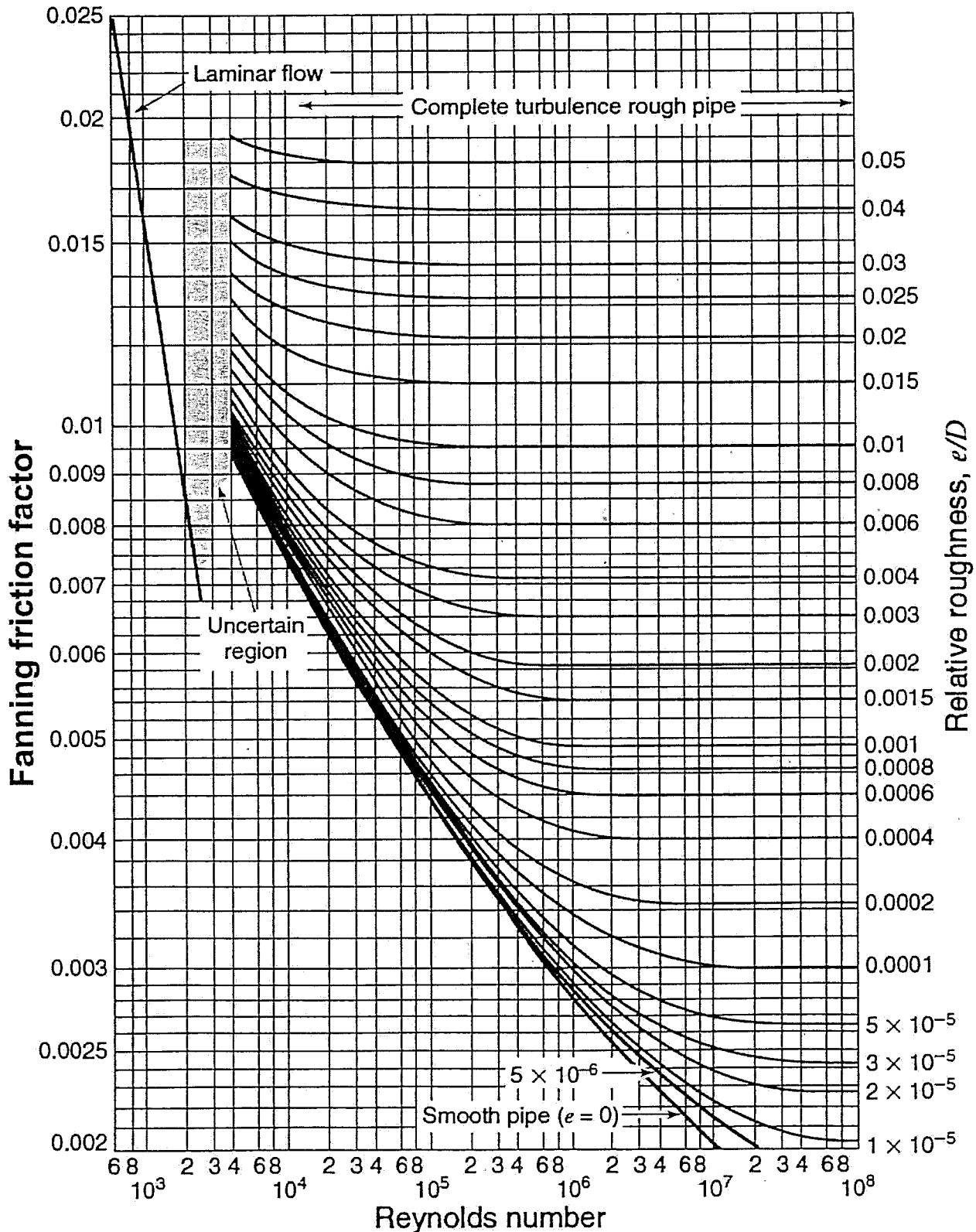
科 目： 單元操作與輸送現象

日 期： 0203

節 次： 第 1 節

注 意： 1. 可使用計算機
2. 請於答案卷(卡)作答，於
試題上作答，不予計分。

1. Dimethyl sulfoxide in a storage tank is transported to a reactor through a cast-iron pipe ($e = 0.00006 \text{ m}$) with a constant flow rate of 11.8 kg/s . The absolute pressure at the entrance of the pipe at the storage tank is 159080 Pa , and the pressure at the end of the pipe at the reactor is 101300 Pa . The location of the storage tank is 5.0 m above the reactor, and the length of the pipe is 120 m . The density and viscosity of dimethyl sulfoxide are 1100 kg/m^3 and $0.002 \text{ Pa}\cdot\text{s}$, respectively. According to the chart below, what are the Fanning friction factor (8%) and the required diameter of the pipe (8%) for this application, respectively?



2. Boundary-layer theory is usually used to estimate the shear force between the surface and the fluid flowing on it. For turbulent boundary layer, since no analytical solution can be found, the von Kármán approximation shown below should be used to estimate the shear force.

$$\frac{\tau_0}{\rho} = \left(\frac{d}{dx} v_\infty \right) \int_0^\delta (v_\infty - v_x) dy + \frac{d}{dx} \int_0^\delta v_x (v_\infty - v_x) dy$$

In addition, for turbulent boundary layer, the following Blasius's correlation is usually used to express the surface shear stress.

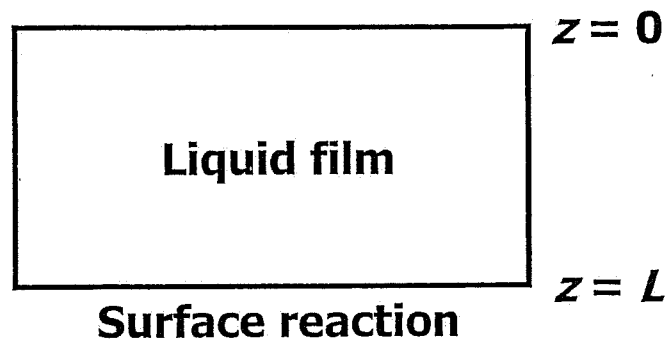
$$\tau_0 = 0.0225 \rho v_\infty^2 \left(\frac{v}{v_\infty \delta} \right)^{1/4}$$

For a fluid flowing on the x direction with a constant speed of v_∞ , the boundary layer is formed when it flows through a flat plate. The front edge of the flat plate is defined as the leading edge, and the entire boundary layer is assumed as turbulent boundary layer.

- (a) Express the velocity profile (v_x) in the boundary layer by using the power-law velocity profile with $n=10$ (4%).
- (b) With the velocity profile from (a), derive the **expression of δ** as the function of x , μ , ρ and v_∞ (10%).

3. Consider the liquid film as illustrated in the following figure. At the position of $z = 0$, the concentration of species A is C_{A0} . A surface reaction occurs at $z = L$. The surface reaction is assumed to be first-order in species A with a surface reaction rate constant, k . You may assume that the transport of products of the reaction is ignored.

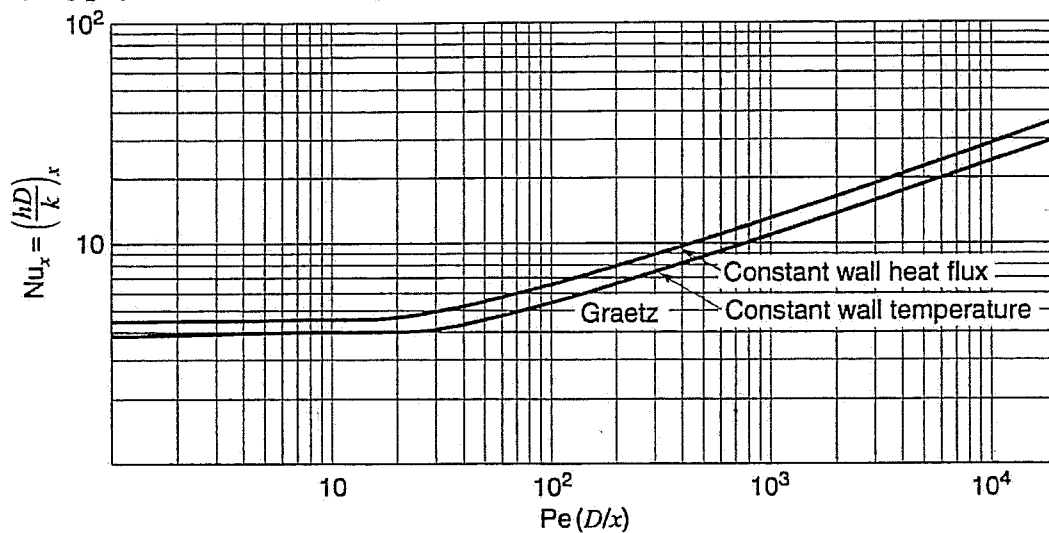
- (a) What is the concentration of A at $z = L$? State all reasonable assumptions as necessary (11%).
- (b) What is the molar flux of A at $z = L$ (3%)?
- (c) If consumption of A by the reaction is considerably faster than diffusion of A through the liquid film, nondimensionalize the concentration of A at $z = L$ (Hint: the concentration of A at $z = L$ is not zero.) (3%).
- (d) If the reaction is considerably slower than diffusion of A , simplify the concentration of A at $z = L$ (3%).



25% 4. A shell-and-tube heat exchanger with one shell pass and two tube passes (1-2 configuration) is used to heat a cold process stream (Stream C) by a hot utility stream (Stream H). The cold stream flows through the tubes, while the hot stream flows on the shell side. The heat transfer process involves a series of thermal resistances: internal convection, wall conduction, and external convection.

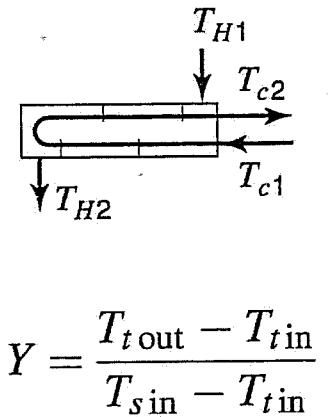
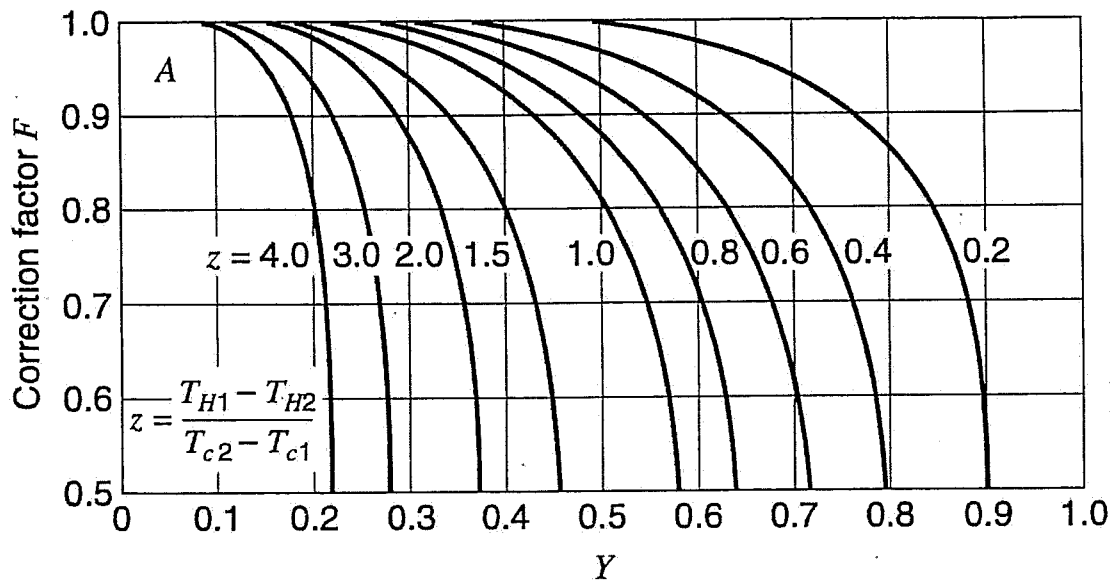
(Multiple-selection questions. Full credit requires selecting all and only the correct options. Half credit is given for at most one incorrect or missing option; two or more errors receive zero credit.)

(a) To characterize the heat transfer efficiency, we examine the tube-side local Nusselt number (Nu_x). The figure below illustrates the variation of Nu_x as a function of the Graetz number, defined as $Gz = Pe \cdot (D/x)$, for laminar flow. Specifically, the figure compares cases of constant wall temperature and constant wall heat flux. Regarding the trend shown in the figure where Nu_x generally increases with $Pe(D/x)$ and reaches a constant value at lower $Pe(D/x)$, which of the following statements correctly describe the underlying physical mechanisms (12%)?



- A. The increase in Nu_x at large $Pe(D/x)$ is primarily because the average fluid velocity is higher in the region where $Pe(D/x)$ is large.
- B. The decrease of Nu_x in the region of lower $Pe(D/x)$ is primarily due to the enhancement of the fluid's thermal conductivity (k) along the axial direction.
- C. The variation of Nu_x is fundamentally governed by the development and thickness of the thermal boundary layer.
- D. At very small values of $Pe(D/x)$, Nu_x reaches a constant value because the dimensionless temperature profile becomes invariant with respect to the axial position.
- E. The sharp increase in Nu_x at high $Pe(D/x)$ indicates a transition from laminar flow to turbulent flow.
- F. For fluids with a very high Prandtl number ($Pr = \nu/\alpha \gg 1$), the thermal entry length is significantly shorter than the hydrodynamic entry length, causing Nu_x to reach its constant value more rapidly.
- G. Under the constant wall temperature condition, the wall-to-bulk temperature difference decreases along the flow direction as the fluid temperature approaches the wall temperature, resulting in a reduced local wall temperature gradient despite the continued growth of the thermal boundary layer.
- H. The Nusselt number is higher for a constant heat flux wall because the imposed uniform heat flux maintains a smaller wall-to-bulk temperature difference, and according to $q'' = h(T_w - T_b)$, this necessarily leads to a larger heat transfer coefficient.

(b) For heat exchangers that deviate from ideal counterflow, the logarithmic-mean temperature difference (LMTD) must be corrected using a correction factor F . The figure below shows the LMTD correction factor F for a 1–2 shell-and-tube heat exchanger, plotted as a function of Y and z , where subscripts t and s denote tube-side and shell-side streams, respectively. Which of the following statements correctly describe the physical meaning and trends of the correction factor shown in the figure (13%)?



- A. At a constant z value, increasing Y leads to a reduction in the actual heat transfer rate because a lower correction factor implies a smaller overall heat-transfer driving force between the hot and cold streams.
- B. A higher z value indicates that the temperature change of the hot stream is larger than that of the cold stream from inlet to outlet, implying that more heat is transferred to the hot stream than the cold stream receives.
- C. At a fixed Y value, the correction factor decreases with increasing z because transferring more heat to the hot stream enhances shell-side induced vortices, making the heat-transfer process less ideal.
- D. When Y increases, the correction factor decreases more dramatically at higher z values than at lower z values because a smaller heat-capacity coefficient ($\dot{m}C_p$) of the hot stream causes a smaller change in Y for a given increase in heat-transfer rate.
- E. For this 1–2 shell-and-tube heat exchanger, the correction factor is always less than unity because this configuration inherently contains regions of both counterflow and parallel flow within the exchanger.
- F. For the same correction factor value, a smaller Y implies that the hot-stream temperature can be changed more easily.
- G. The decrease in the correction factor is a direct consequence of a larger fraction of the maximum possible heat being transferred within the exchanger.
- H. Increasing the inlet temperature of the hot stream reduces the value of Y , thereby increasing the correction factor.

5. Consider a counterflow cooling tower. Air at temperature T_{yb} and enthalpy H_{yb} enters the bottom of the tower and leaves at the top with temperature T_{ya} and enthalpy H_{ya} . Water enters the top at temperature T_{xa} and leaves at the bottom at temperature T_{xb} . The mass velocity of the air is G'_y (the mass of vapor-free air per hour per unit cross-section of the tower). The mass velocities of water at the inlet and outlet are, respectively, G_{xa} and G_{xb} . At a distance Z from the bottom of the contact zone, the air and water temperatures are T_y and T_x , and the air enthalpy is H_y .

(a) Derive the operating line for the tower, on a plot of air enthalpy versus water temperature. Please indicate the slope of the operating line. You may assume G_x to be constant (i.e., $G_{xb} = G_{xa}$) with a constant specific heat of water (c_L) (5%).

(b) The tower operates with $T_{xa} = 95^\circ\text{F}$ and $T_{xb} = 75^\circ\text{F}$ when the air has dry-bulb and wet-bulb temperatures, respectively, of 70 and 60°F. The enthalpy of air at the bottom (H_b) is estimated at 18.7 Btu/lb. The tower has 4 ft of stacked plastic fill, and the flow rates are $G'_y = 2,000 \text{ lb/h} \cdot \text{ft}^2$ and $G_x = 2,200 \text{ lb/h} \cdot \text{ft}^2$. Determine the number of transfer units (N_{Oy}), the height of a transfer unit based on the overall gas-phase driving force (H_{Oy}), and the temperature approach. For $75^\circ\text{F} \leq T_x \leq 95^\circ\text{F}$, c_L is taken to be 1 Btu/lb·°F, and the equilibrium line is approximated by: $H_y^* = 1.2T_x - 59$ (10%).

6. For mass transfer in fixed-bed adsorption, a solute material balance for a section dL of the bed is written as:

$$\varepsilon \frac{\partial c}{\partial t} + (1 - \varepsilon) \rho_p \frac{\partial W}{\partial t} = -u_0 \frac{\partial c}{\partial L}$$

where ε is the external void fraction of the bed; c is the solute concentration; ρ_p is the density of the particle; W is the adsorbate loading; u_0 is the superficial velocity of the fluid; L is the distance through the bed. The rate of accumulation in the fluid and in the solid is the difference between input and output flows. For adsorption from a gas or a dilute solution, the accumulation in the fluid is usually negligible compared to the accumulation on the solid. The transfer process is approximated using an overall volumetric coefficient ($K_c a$) and an overall driving force:

$$\rho_p (1 - \varepsilon) \frac{\partial W}{\partial t} = K_c a (c - c^*)$$

where c^* is the concentration in equilibrium with the average concentration W in the solid.

(a) Consider irreversible adsorption with a constant mass-transfer coefficient, in which case the rate of mass transfer is just proportional to the fluid concentration. Derive the concentration at the end of the bed, assuming that the first portion of the bed has not been saturated (3%).

(b) After the first portion of the bed is saturated, the concentration profile moves steadily down the bed, keeping the same shape. The concentration profile can be expressed using dimensionless terms:

$$\ln \frac{c}{c_0} = N(\tau - 1) - 1$$

where N represents the overall number of transfer units; τ is the ratio of the time (t) to the ideal time t^* ($\tau = t/t^*$). Determine N for a 20-cm bed with 60% utilization at the break point (when $c/c_0 = 0.05$) (4%).

(c) Predict N when the bed length is increased to 40 cm (3%).