Problem 1 (5%)

When fluid flow is characterized as fully turbulent, which of the following is a true statement?

(a) Friction factor will increase with increase of Reynolds Number.
(b) Friction factor will decrease with increase of Reynolds Number.
(c) Friction factor is independent of Reynolds Number.
(d) Friction factor is independent of relative roughness.

Problem 2 (5%)

Consider the flow of air and water in pipes of the same diameter, at the same temperature and at the same mean velocity. Which flow is more likely to be turbulent? Why?

Problem 3 (20%)

The simplest patient infusion system is that of gravity flow from an intravenous (IV) bag. A 500 ml IV bag containing an aqueous solution is connected to a vein in the forearm of a patient. Venous pressure in the forearm is 0 mm Hg (gauge pressure). The IV bag is placed on a stand such that the entrance to the tube leaving the IV bag is exactly one meter above the vein into which the IV fluid enters. The length of the IV bag is 30cm. The IV is fed through an 18 gauge tube (internal diameter = 0.953 mm) and the total length of the tube is 2 meters. (Please state all the assumptions.)

(a) Calculate the flowrate of the IV fluid. (10%)
(b) Estimate the time needed to empty the bag. (10%)

Problem 4 (20%)

Chickens with an average mass of 2.2 kg and average specific heat of 3.54 kJ/kg · °C are to be cooled by chilled water that enters a continuous-flow-type immersion chiller at 0.5°C. Chickens are dropped into the chiller at a uniform temperature of 15°C at a rate of 500 chickens per hour and are cooled to an average temperature of 3°C before they are taken out. The chiller gains heat from the surroundings at a rate of 200 kJ/h. Determine

(a) the rate of heat removal from the chickens in kW. (10%)
(b) the mass flow rate of water in kg/s, if the temperature rise of water is not to exceed 2°C. (10%)

Problem 5 (30%)

A thermal biosensor for analyte S (diffusion coefficient = D) is based on an ideal planar heat absorber (mass = m; specific heat = σ) having a surface modified with an enzyme, which instantly catalyzes a reaction S → P (standard enthalpy of reaction = ΔH_0). For a sensing process at room temperature (T_0), an analyte solution with a bulk concentration (far from the biosensor) of C_0 is in contact with the biosensor (pre-equilibrated at T_0) under quiescent conditions, and S is instantaneously run out (becoming zero concentration) at the biosensor's surface. Then the enzymatic reaction heat is completely transferred to the thermal biosensor, and the increase of the biosensor's temperature can be used to quantify C_0 accordingly.

(a) Show that the concentration profile of S in the sensing process can be expressed as follows. (x is the

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distance away from the biosensor's surface, and t is the sensing time.) (12%)

$$C(x,t) = C_0 erf\left[\frac{x}{2(Dt)^{1/2}}\right], \text{ where } erf(u) \equiv \frac{2}{\pi^{1/2}}\int_0^u e^{-y^2}dy.$$

(b) Show that the temperature of the biosensor (T) can be expressed as a function of time as follows. (10%)

$$T = T_0 + \frac{2A}{m\sigma}C_0\left(\frac{D}{\pi}\right)^{1/2}t^{1/2}$$, where A is the area of the thermal biosensor.

(c) Briefly describe how the temperature-time correlation for the thermal biosensor will be different from (b) when the analyte solution is convective stirring. (8%)

(Note: provide reasonable assumptions during mathematical derivation, and you may correct the expressions if you don't agree with them.)

Problem 6 (20%)

(a) Draw a typical McCabe-Thiele diagram and illustrate how to use the diagram to determine the number of theoretical plates (N) of distillation columns for binary mixtures. (10%)

(b) In capillary electrophoresis, the separation efficiency is also expressed in terms of the theoretical plate number, N, which is defined as L/H. L is the length of the capillary tube, and H is the plate height, which is given by $H = \sigma^2/L$ (σ^2 is the spatial variance of a electrophoretic band). The migration velocity of a DNA segment is given by $v = \mu V/L$, where v is the velocity, μ is the electrophoretic mobility for DNA, and V is the total applied voltage. If molecular diffusion alone is responsible for electrophoretic band broadening, the spatial variance σ^2 can be regarded as the square of DNA's diffusion length. Show that the N value for DNA capillary electrophoresis is proportional to $\mu V/2D$ and is independent of the length of the capillary tube (D is the diffusion coefficient of DNA). (10%)

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