Problem 1 (15 points)

An **artificial kidney** (as shown in **Figure 1(a)**) is a device that removes water and waste metabolites from blood. In one such device, the **hollow fiber hemodialyzer** (as shown in **Figure 1(b)**), blood flows from an artery through the insides of a bundle of hollow cellulose acetate fibers, and dialyzing fluid, which consists of water and various dissolved salts, flows on the outside of the fibers. Water and waste metabolites—principally urea, creatinine, uric acid, and phosphate ions—pass through the fiber walls into the dialyzing fluid, and the purified blood is returned to a vein.

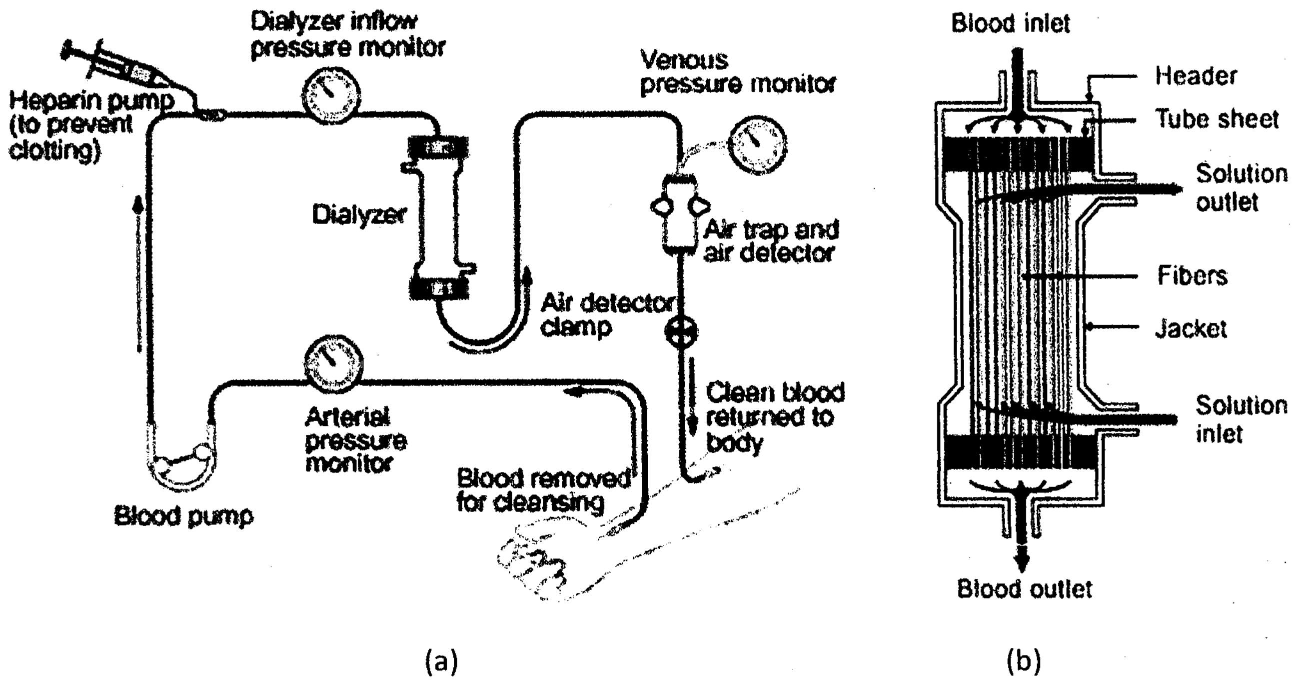

Figure 1 (a) Hemodialysis process and (b) hollow fiber hemodialyzer (Figure 1(a): Courtesy of IEEE GlobalSpce Enginering360; Figure 1(b): Courtesy of BC Renal Agency, Canada)

At some time during a dialysis the arterial and venous blood conditions are as follows:

	Arterial (entering) Blood	Venous (exiting) Blood
Flow Rate	200.0 mL/min	195.0 mL/min
Urea (H_2NCONH_2) Concentration	1.90 mg/mL	1.75 mg/mL

(a) Calculate the rates at which urea and water are being removed from the blood. **(5 points)**

(b) If the dialyzing fluid enters at a rate of 1250 mL/min and the exiting solution (dialysate) leaves at approximately the same rate, calculate the concentration of urea in the dialysate (solution outlet). **(5 points)**

(c) Suppose the total blood volume is 5.0 liters and the average rate of urea removal is that calculated in part (a). If a patient is dialyzed for 3.5 hours with an initial urea level of 2.9 mg/mL, what is the final value of the urea level? (Neglect the loss in total blood volume due to the removal of water in the dialyzer.) **(5 points)**

Problem 2 (20 points)

A schematic diagram of the converging annulus spinneret is shown in **Figure 2** which is used to fabricate hollow fiber membranes for hemodialysis as illustrated in **Figure 1**. In order to understand the rheological behaviors of a polymer solution in the spinneret through theoretical approach and facilitate the mathematical treatment, the annulus was divided into three sections, including a converging section between the first and the third sections. The polymer solution flows in the spinneret is non-Newtonian fluid. For a simple shear flow, the generalized power-law model for the spinning of polymer solutions can be simplified as follows:

$$\tau_{rz} = -m\left|\frac{dV_z}{dr}\right|^{n-1}\left(\frac{dV_z}{dr}\right).$$

If the maximum velocity of the polymer solution occurs at $r = \lambda R$ in Section I. Please derivate the shear stress distribution in the Section I **(10 points)** and the expression of the shear stress at the outer wall **(6 points)**. The assumptions of your derivation should also be defined **(4 points)**.

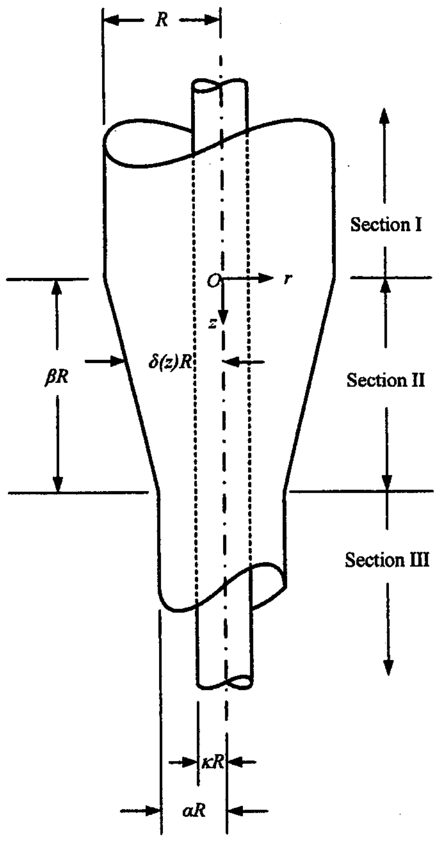

Figure 2 A schematic diagram of the conical annulus spinneret.

$$[\rho D\mathbf{v}/Dt = -\nabla p + \mu\nabla^2\mathbf{v} + \rho\mathbf{g}]$$

Cartesian coordinates (x, y, z):

$$\rho\left(\frac{\partial v_x}{\partial t} + v_x\frac{\partial v_x}{\partial x} + v_y\frac{\partial v_x}{\partial y} + v_z\frac{\partial v_x}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left[\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_x}{\partial y^2} + \frac{\partial^2 v_x}{\partial z^2}\right] + \rho g_x \quad \text{(B.6-1)}$$

$$\rho\left(\frac{\partial v_y}{\partial t} + v_x\frac{\partial v_y}{\partial x} + v_y\frac{\partial v_y}{\partial y} + v_z\frac{\partial v_y}{\partial z}\right) = -\frac{\partial p}{\partial y} + \mu\left[\frac{\partial^2 v_y}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_y}{\partial z^2}\right] + \rho g_y \quad \text{(B.6-2)}$$

$$\rho\left(\frac{\partial v_z}{\partial t} + v_x\frac{\partial v_z}{\partial x} + v_y\frac{\partial v_z}{\partial y} + v_z\frac{\partial v_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left[\frac{\partial^2 v_z}{\partial x^2} + \frac{\partial^2 v_z}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right] + \rho g_z \quad \text{(B.6-3)}$$

接次頁

Cylindrical coordinates (r, θ, z):

$$\rho\left(\frac{\partial v_r}{\partial t} + v_r\frac{\partial v_r}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta} + v_z\frac{\partial v_r}{\partial z} - \frac{v_\theta^2}{r}\right) = -\frac{\partial p}{\partial r} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv_r)\right) + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2} + \frac{\partial^2 v_r}{\partial z^2} - \frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}\right] + \rho g_r \quad \text{(B.6-4)}$$

$$\rho\left(\frac{\partial v_\theta}{\partial t} + v_r\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta} + v_z\frac{\partial v_\theta}{\partial z} + \frac{v_r v_\theta}{r}\right) = -\frac{1}{r}\frac{\partial p}{\partial \theta} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv_\theta)\right) + \frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{\partial^2 v_\theta}{\partial z^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \theta}\right] + \rho g_\theta \quad \text{(B.6-5)}$$

$$\rho\left(\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_z}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta} + v_z\frac{\partial v_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2}\right] + \rho g_z \quad \text{(B.6-6)}$$

Problem 3 (15 points)

During colonial time in Taiwan, Japanese built a dam on Sun Moon Lake for hydro-electric generation as they wanted to develop industry in their colony. Using the Central Mountain Range's Zhuoshui River as its water source and the natural Sun Moon Lake as a water-storage area, which was elevated to about 800 meters, water was sent to Menpai Lake. A 320-meter drop in height was used to generate electricity, creating 100,000 kilowatts of electric power. Now, consider about a similar system: a pump storage facility takes water from a river at night when demand is low and pumps it to a hilltop reservoir 500 ft above the river. The water is returned through turbine in the daytime to help meet peak demand.

(a) For two 30-inch pipes, each 2500 ft long and carrying 20000 gal/min, what pumping power is needed if the pump efficiency is 85 percent? The friction loss is estimated to be 15 ft of water. **(5 points)**

(b) How much power can be generated by the turbines using the same total flow rate? **(5 points)**

(c) What is the overall efficiency of this installation as an energy storage system? **(5 points)**

Problem 4 (20 points)

Please define or explain the terms below:

(a) Thermally fully-developed condition

(b) Reynolds number for the internal flows

(c) Reynolds analogy

(d) Grashof number

Problem 5 (16 points)

Pulverized coal pellets, which can be approximated as carbon spheres of radius r_o (=1 mm), are burned in a pure oxygen atmosphere at 1450 K and 1 atm. Oxygen is transferred to the particle surface by diffusion process, where it is consumed in the reaction:

$C + O_2 \rightarrow CO_2$

The reaction follows the first order kinetics and is of the form:

$N''_{O_2} = -k''_1 C_{O_2}(r_0)$

where $k''_1 = 0.1$ m/s

If the stationary medium and one-dimensional diffusion in *r-direction* are considered, the changes in r_0 is neglected, the properties are constant, the perfect/ideal gas behavior is applied, and the temperature and total concentration (C) are uniform. At 1450 K, the binary diffusion coefficient for O_2 and CO_2 is 1.71 x 10^{-4} m^2/s. The gas constant R is 8.205 x 10^{-2} m^3 atm/kmol·K. (Please refer to **Figure 3**)

(a) Please apply the shell mass balance to derive the differential equation for the relationship between the flux of oxygen (N''_{O_2}) and radius r **(5 points)**

(b) Please show the relationship between the molar flux of oxygen (N''_{O_2}) and the concentration of oxygen **(3 points)**

(c) Determine the steady-state oxygen molar consumption rate in kmol/s using the results in (a) and (b), and the appropriate boundary conditions **(8 points)**.

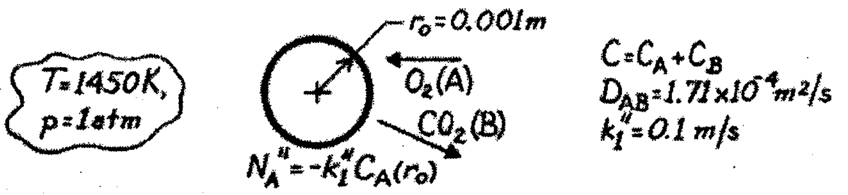

Figure 3. A schematic diagram of the system in Problem 5.

Problem 6 (14 points)

You are given a situation (batch process) for which a chemical X of density ρ = 1,200 kg/m^3 and specific heat c = 2,200 J/kg·K occupies a volume of V_c = 2.25 m^3 in an insulated vessel (see **Figure 4**). The chemical X is to be heated from the room temperature, T_i = 300 K, to a process temperature of T = 450 K by passing saturated steam at T_h = 500 K through a coiled, thin-walled, 20-mm-diameter (D) tube in the vessel. Steam condensation within the tube maintains an interior convection coefficient of h_i = 10,000 W/m^2·K, while the highly agitated liquid in the stirred vessel maintains an outside convection coefficient of h_o = 2,000 W/m^2·K.

Assuming that: (1) Constant properties, (2) Negligible heat loss from vessel to surroundings, (3) Chemical is isothermal, (4) Negligible work due to stirring, (5) Negligible thermal energy generation (or absorption) due to chemical reactions associated with the batch process, (6) Negligible tube wall conduction resistance, (7) Kinetic energy, potential energy, and flow work changes for steam can be neglected.

(a) Applying the law of conservation of energy, please derive the expression for the total heat transfer area of tubing A_s as a function of ρ, V_c, T_h, T_i, T, h_i, h_o, and t **(8 points).**

(b) If the chemical X is to be heated from 300 to 450 K in 60 min, what is the required length L of the submerged tubing? **(6 points)**

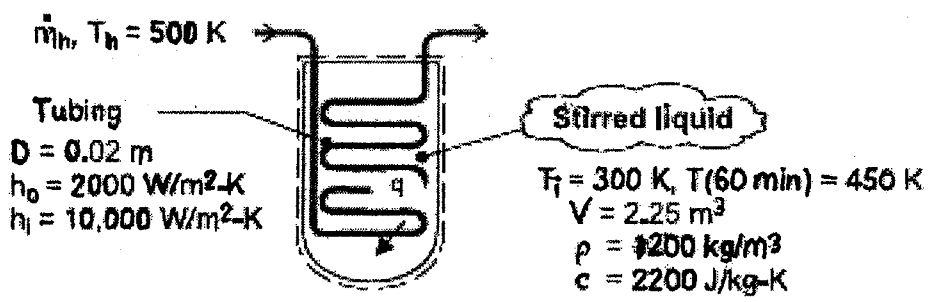

Figure 4. Batch process for heating the chemical X

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