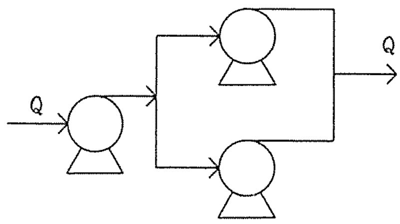
Problem 1 (20 points)

(a) Navier-Stokes equation is a mathematical statement of a physical principle. What is the principle? (3 points)

(b) The "operating line" used in the calculations of many separation processes is a graphical presentation of a physical principle. What is the principle? (3 points)

(c) Three identical centrifugal pumps are connected as shown in the figure. The head increase across a single such pump varies with the flow rate Q as: $\Delta h = a + bQ^2$. Here a and b are constants. Calculate the head increase in the arrangement shown in the right figure in terms of a, b and Q. (4 points)



(d) Please define the "effectiveness, ε" used in the heat exchanger design and calculations. (3 points)

(e) Please define the Biot number (Bi) and Nussult number (Nu), and comment on the differnece between them. (4 points)

(f) Please describe the difference between the "free convection" and "forced convection" (3 points)

Problem 2 (25 points)

We consider a Newtonian liquid with uniform velocity v_∞ past a spherical **bubble** of radius R filled with air at creeping flow condition. The velocity and pressure field around the bubble has been solved as follows:

$$v_r = v_\infty\left[1-\left(\frac{R}{r}\right)\right]cos\theta, \qquad v_\theta = -v_\infty\left[1-\frac{1}{2}\left(\frac{R}{r}\right)\right]sin\theta, \qquad v_\phi = 0$$

$$p = p_0 - \rho g r cos\theta - \left(\frac{\mu v_\infty}{R}\right)\left(\frac{R}{r}\right)^2 cos\theta$$

Here p_0 is the pressure very far from the bubble.

(a) We want to derive the equation of drag force acting on the bubble. Please indicate which stress components (Ex:$\tau_{\phi r}$) are relevant to this derivation and obtain their formula using the velocity field. (6 points)

(b) Determine the drag force exerted on the bubble? Remember to include the pressure contribution. (10 points)

(c) Determine the drag coefficient C_D of the bubble at this condition. (4 points)

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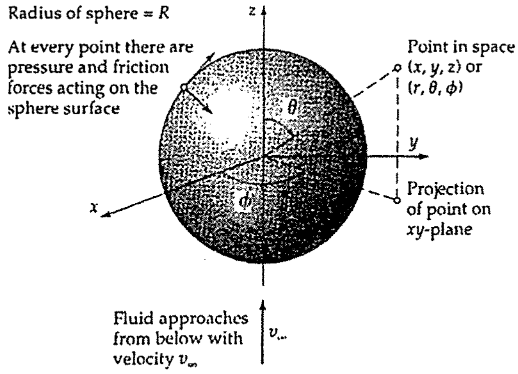


(d) The result in (c) is somewhat different from Stokes' law. What causes this difference? If you do not have the answer for (c), make a guess and explain your reason. (5 points)

Newton's law of viscosity for incompressible fluid in spherical coordinates:

$$\tau_{rr} = -\mu[2\frac{\partial v_r}{\partial r}]$$

$$\tau_{\theta\theta} = -\mu\left[2\left(\frac{1}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{v_r}{r}\right)\right]$$

$$\tau_{\phi\phi} = -\mu\left[2\left(\frac{1}{r\sin\theta}\frac{\partial v_\phi}{\partial \phi} + \frac{v_r + v_\theta\cot\theta}{r}\right)\right]$$

$$\tau_{r\theta} = \tau_{\theta r} = -\mu\left[r\frac{\partial}{\partial r}\left(\frac{v_\theta}{r}\right) + \frac{1}{r}\frac{\partial v_r}{\partial \theta}\right]$$

$$\tau_{\theta\phi} = \tau_{\phi\theta} = -\mu\left[\frac{\sin\theta}{r}\frac{\partial}{\partial \theta}\left(\frac{v_\phi}{\sin\theta}\right) + \frac{1}{r\sin\theta}\frac{\partial v_\theta}{\partial \phi}\right]$$

$$\tau_{\phi r} = \tau_{r\phi} = -\mu\left[\frac{1}{r\sin\theta}\frac{\partial v_r}{\partial \phi} + r\frac{\partial}{\partial r}(\frac{v_\phi}{r})\right]$$

<u>Problem 3 (15 points)</u>

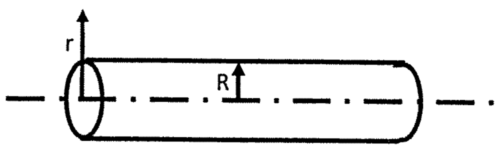
It is desired to separate a binary mixture by simple distillation. If the feed mixture has a composition of 0.5 mole fraction, and the distillate has a composition of 0.75 mole fraction, calculate the fraction which it is necessary to vaporize. The equilibrium curve is given by: y = 1.2x + 0.2.

(a) Use a flash distillation process. (5 points)

(b) Use a differential distillation process. (10 points)

Problem 4 (25 points)

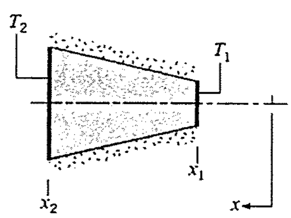
Gas A diffuses through a stagnant gas film to the surface of a nonporous cylindrical catalyst, where it undergoes the chemical reaction: 2A → B (the reaction rate constant = k). Gas B then diffuses from the surface of the catalyst and is swept away. If the diffusion and reaction on the ends of the particle are neglected and the temperature, diffusion coefficient D_{AB}, and total concentration C remain constant. Consider this a steady-state operation and one-dimensional (r-direction) mass transfer (see the figure below), please answer the following questions:



(a) What is the unit of the "reaction rate constant k" ? (3 points)
(b) What is the unit of the "molar flux of A" ? (3 points)
(c) Please show your results after performing the "shell mass balance" on both species A and B. (6 points)
(d) N_{Ar} = □ N_{Br} at r = R (the catalyst surface), what is □ ? Please also give the reason why this stoichiometry relationship stays true at any r. (5 points)
(e) If the chemical reaction at the surface is very fast, and $y_A = y_{A\delta}$ at $r = \delta R$, please derive an equation for the molar flux of A. (8 points)

Problem 5 (15 points)

The figure shown below is a conical section fabricated from pyroceram. It is of circular cross section with the diameter D = ax, where a = 0.25. The small end is at x_1 = 5 cm and the large end at x_2 = 25 cm; the end temperatures are T_1 = 400 K and T_2 = 600 K. If the lateral surface is well insulated, no heat generation is involved, steady-state condition is considered, and all properties are assumed constant. Please answer the folllowing questions:



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(a) Starting from the "equation of conservation of energy" or "energy balance equation", please explain the reason why the heat transfer rate q_x is independent of x. (4 points)

(b) Derive an expression for the temperature distribution T(x) in symbolic form, assuming one-dimensional conditions. Sketch the temperature distribution. (7 points)

(c) Determine the heat transfer rate, q_x, through the cone. (4 points)

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