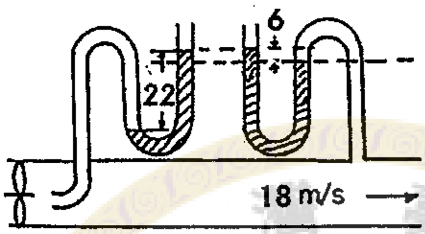
**Problem 1 (6 points)**

An engineer want to know the pressure information of the following flow system using the two manometers indicated in **Figure 1**. What are the static pressure, dynamic pressure and total pressure? (The pressure difference between the two insertion points is negligible.)




(Unit of pressure: $mmH_2O$)

**Figure 1** Measurement of static and dynamic pressures in a wind pipe.

**Problem 2 (14 points)**

In a process for removing $SO_2$ from flue gas, gas at 410°C and 1.2 atm is passed upward through a fluidized bed containing 1.5 mm spherical particles of $Al_2O_3$ impregnated with copper. The particle density is 2,300 kg/m$^3$ and the gas density and viscosity are almost the same as those of the air.

(a). For an initial bed height of 1 m and an initial porosity of 0.45, predict the minimum fluidization velocity. **(7 points)**

(b). If the expanded bed height should be no greater than 2 m, what is the upper limit of the operating superficial velocity? **(7 points)**

[Hint 1]: Pressure drop across particulate bed:

$$\frac{\Delta P}{L}=\frac{150\mu u_s}{\phi_s^2 D_p^2}\frac{(1-\varepsilon)^2}{\varepsilon^3}+\frac{1.75\rho_f u_s^2}{\phi_s D_p}\frac{1-\varepsilon}{\varepsilon^3}$$

**Problem 3 (14 points)**

A $1\frac{1}{4}$ in. steel pipe (schedule 40) is insulated with a 2 inch layer of asbestos covered by a 3 inch layer of 85% magnesia. If the temperature inside the pipe wall is 300 °F and the atmospheric temperature is 80 °F. The thermal conductivities of steel, asbestos and magnesia are 26, 0.087 and 0.034 (Btu/hr/ft/°F), respectively.

(a) What is the heat loss per foot of pipe? **(7 points)**

(b) What is the temperature between the two insulations? **(7 points)**

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**Problem 4 (16 points)**

The following Hagen-Poiseuille equation expresses the mass flow rate $W$ of a fluid flowing through a horizontal capillary circular pipe (radius $R$; length $L$) as a function of the applied pressure $\Delta P$.

$$W = \frac{\pi R^4 \rho}{8 \mu L} \Delta P$$

A fluid (density $\rho$; viscosity $\mu$) is flowing in laminar flow from $A$ to $B$ through a network of tubes, as depicted in **Figures 2**.

(a) Derive Hagen-Poiseuille type expression for the mass flow rate $W$ of the fluid from $A$ to $B$ through the network as a function of the applied pressure $\Delta P$. The derivation of well-known Hagen-Poiseuille equation is not necessary. Neglect the disturbances at the various tube junctions and gravity effect. **(12 points)**

(b) Determine the mass flow rate for the network with a radius of 1.1$R$ under the same applied pressure, *i.e.*, how many percent of the mass flow rate will be increased if the radius of tube is increased from $R$ to 1.1$R$ for the same network under the same applied pressure. **(4 points)**

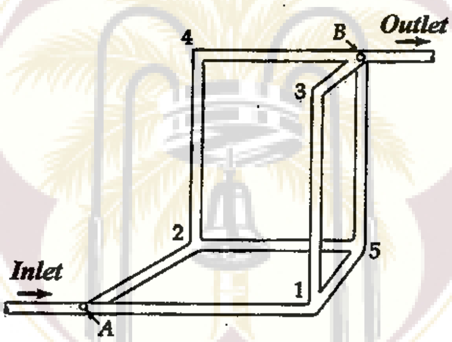


**Figure 2** Flow of a fluid in a network of tubes with branching.

**Problem 5 (25 points)**

A distillation column is to be fed with two streams of **saturated liquid** containing $A$ and $B$. Feed 1, the upper feed, is supplied at 1 kg mol/hr and the mol fraction of $A$ is 0.7. Feed 2, the lower feed, is also fed at 1 kg mol/hr and the mol fraction of $A$ is 0.3. In the bottom product, the mol fraction of $A$ cannot be more than 0.05, and 95% of $A$ fed to the column leaves from the distillate stream. A vapor-liquid phase equilibrium data of the binary system is shown in **Table 1**. Please answer the following questions.

**Table 1**

| $X_A$ | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $Y_A$ | 0 | 0.25 | 0.45 | 0.55 | 0.65 | 0.75 | 0.83 | 0.9 | 0.95 | 0.98 | 1 |

(a) What is the minimum number of equilibrium stages? **(5 points)**

(b) What is the minimum reflux ratio? **(5 points)**

(c) Please describe (or illustrate) how the size of reflux ratio can influence the capital cost and operating cost. **(5 points)**

(d) For a reflux ratio of 2/3, how many equilibrium stages are needed and on what stages should Feed 1 and Feed 2 be introduced to the column? **(10 points)**

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**Problem 6 (12 points)**

Ultrafiltration is a process in which pressure-driven flow of filtrate across a semipermeable membrane. An undesired consequence of the filtration is that the retained macromolecules tend to accumulate near the upstream surface of the membrane, causing membrane fouling, as shown in **Figure 3**. At steady state, the solute concentration in the retentate film $C_R(x)$ is assumed to reach the bulk value $\boldsymbol{C_0}$ at a distance $\boldsymbol{\delta}$ from the membrane. The solute concentration in the membrane is $C_M(x)$. The diffusivities in the retentate film and in the membrane are $\boldsymbol{D_R}$ and $\boldsymbol{D_F}$, respectively. The steady state filtrate velocity is $\boldsymbol{v_F}$, and steady state solute flux is $\boldsymbol{N}$. Due to the interaction of the solute and the membrane, the solute flux inside the membrane region has a form different from a regular form and is expressed as:

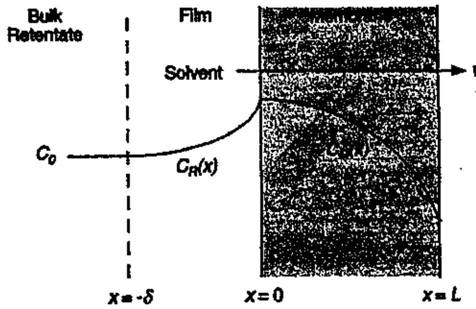

**Figure 3**

$$-D_M \frac{dC_M}{dx} + 0.5\, v_F C_M$$

(a) Derive $C_R(x)$ as a function of the given bold parameters. **(5 points)**

(b) Derive $C_M(x)$ as a function of the given bold parameters. **(7 points)**

**Problem 7 (13 points)**

Two perfectly mixed tanks are separated by a membrane with a thickness of $L$ as shown in **Figure 4(a)**. The volume of each tank is $V$ and the exposed area of the membrane is $A$. The solute concentration and diffusivity within the membrane are $C(x,t)$ and $D$ respectively. The two tanks are originally full of pure water, and have no solute. At $t$=0, the solute concentration in the left tank is suddenly changed to $C_0$. In the very early time period, the solute concentration profile change in the membrane is illustrated in **Figure 4(b)**. In the much larger time scale, the concentration profile is illustrated in **Figure 4(c)**.

(a) What is the criterion of time for us to observe the situation in the very early time period (as shown in **Figure 4(b)**)? **(5 points)**

(b) In the much larger time scale, if assuming pseudo-steady state, please derive how the concentration in the left tank changes with time? **(8 points)**

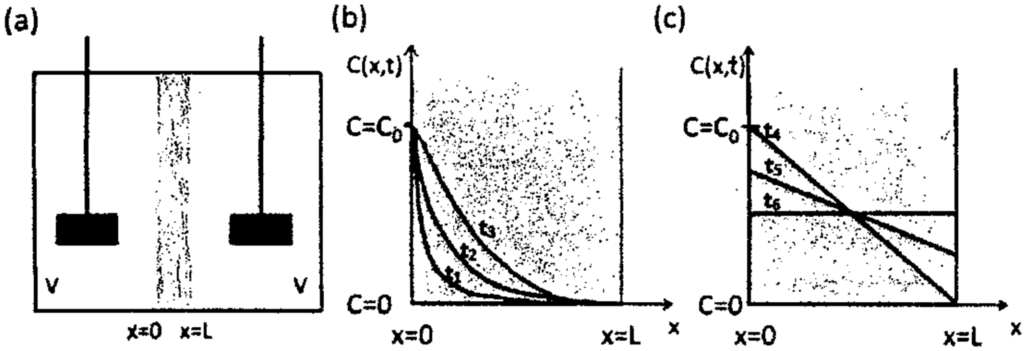

**Figure 4**

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**Table A-1** Dimensions and Capacities of Standard Steel Pipes

| Nominal pipe size, in. | Outside diameter, in. | Schedule no. | Wall thickness, in. | Inside diameter, in. | Cross-sectional area of metal, in.$^2$ | Inside sectional area, ft$^2$ | Circumference, ft or surface, ft$^2$/ft of length | | Capacity at 1 ft/s velocity | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Outside | Inside | U.S. gal/min | Water, lb/h |
| $\frac{1}{8}$ | 0.405 | 40 | 0.068 | 0.269 | 0.072 | 0.00040 | 0.106 | 0.0705 | 0.179 | 89.5 |
| | | 80 | 0.095 | 0.215 | 0.093 | 0.00025 | 0.106 | 0.0563 | 0.113 | 56.5 |
| $\frac{1}{4}$ | 0.540 | 40 | 0.088 | 0.364 | 0.125 | 0.00072 | 0.141 | 0.095 | 0.323 | 161.5 |
| | | 80 | 0.119 | 0.302 | 0.157 | 0.00050 | 0.141 | 0.079 | 0.224 | 112.0 |
| $\frac{3}{8}$ | 0.675 | 40 | 0.091 | 0.493 | 0.167 | 0.00133 | 0.177 | 0.129 | 0.596 | 298.0 |
| | | 80 | 0.126 | 0.423 | 0.217 | 0.00098 | 0.177 | 0.111 | 0.440 | 220.0 |
| $\frac{1}{2}$ | 0.840 | 40 | 0.109 | 0.622 | 0.250 | 0.00211 | 0.220 | 0.163 | 0.945 | 472.0 |
| | | 80 | 0.147 | 0.546 | 0.320 | 0.00163 | 0.220 | 0.143 | 0.730 | 365.0 |
| $\frac{3}{4}$ | 1.050 | 40 | 0.113 | 0.824 | 0.333 | 0.00371 | 0.275 | 0.216 | 1.665 | 832.5 |
| | | 80 | 0.154 | 0.742 | 0.433 | 0.00300 | 0.275 | 0.194 | 1.345 | 672.5 |
| 1 | 1.315 | 40 | 0.133 | 1.049 | 0.494 | 0.00600 | 0.344 | 0.275 | 2.690 | 1,345 |
| | | 80 | 0.179 | 0.957 | 0.639 | 0.00499 | 0.344 | 0.250 | 2.240 | 1,120 |
| $1\frac{1}{4}$ | 1.660 | 40 | 0.140 | 1.380 | 0.668 | 0.01040 | 0.435 | 0.361 | 4.57 | 2,285 |
| | | 80 | 0.191 | 1.278 | 0.881 | 0.00891 | 0.435 | 0.335 | 3.99 | 1,995 |
| $1\frac{1}{2}$ | 1.900 | 40 | 0.145 | 1.610 | 0.800 | 0.01414 | 0.497 | 0.421 | 6.34 | 3,170 |
| | | 80 | 0.200 | 1.500 | 1.069 | 0.01225 | 0.497 | 0.393 | 5.49 | 2,745 |
| 2 | 2.375 | 40 | 0.154 | 2.067 | 1.075 | 0.02330 | 0.622 | 0.541 | 10.45 | 5,225 |
| | | 80 | 0.218 | 1.939 | 1.477 | 0.02050 | 0.622 | 0.508 | 9.20 | 4,600 |
| $2\frac{1}{2}$ | 2.875 | 40 | 0.203 | 2.469 | 1.704 | 0.03322 | 0.753 | 0.647 | 14.92 | 7,460 |
| | | 80 | 0.276 | 2.323 | 2.254 | 0.02942 | 0.753 | 0.608 | 13.20 | 6,600 |
| 3 | 3.500 | 40 | 0.216 | 3.068 | 2.228 | 0.05130 | 0.916 | 0.803 | 23.00 | 11,500 |
| | | 80 | 0.300 | 2.900 | 3.016 | 0.04587 | 0.916 | 0.759 | 20.55 | 10,275 |
| $3\frac{1}{2}$ | 4.000 | 40 | 0.226 | 3.548 | 2.680 | 0.06870 | 1.047 | 0.929 | 30.80 | 15,400 |
| | | 80 | 0.318 | 3.364 | 3.678 | 0.06170 | 1.047 | 0.881 | 27.70 | 13,850 |
| 4 | 4.500 | 40 | 0.237 | 4.026 | 3.17 | 0.08840 | 1.178 | 1.054 | 39.6 | 19,800 |
| | | 80 | 0.337 | 3.826 | 4.41 | 0.07986 | 1.178 | 1.002 | 35.8 | 17,900 |
| 5 | 5.563 | 40 | 0.258 | 5.047 | 4.30 | 0.1390 | 1.456 | 1.321 | 62.3 | 31,150 |
| | | 80 | 0.375 | 4.813 | 6.11 | 0.1263 | 1.456 | 1.260 | 57.7 | 28,850 |
| 6 | 6.625 | 40 | 0.280 | 6.065 | 5.58 | 0.2006 | 1.734 | 1.588 | 90.0 | 45,000 |
| | | 80 | 0.432 | 5.761 | 8.40 | 0.1810 | 1.734 | 1.508 | 81.1 | 40,550 |
| 8 | 8.625 | 40 | 0.322 | 7.981 | 8.396 | 0.3474 | 2.258 | 2.089 | 155.7 | 77,850 |
| | | 80 | 0.500 | 7.625 | 12.76 | 0.3171 | 2.258 | 1.996 | 142.3 | 71,150 |
| 10 | 10.75 | 40 | 0.365 | 10.020 | 11.91 | 0.5475 | 2.814 | 2.620 | 246.0 | 123,000 |
| | | 80 | 0.594 | 9.562 | 18.95 | 0.4987 | 2.814 | 2.503 | 223.4 | 111,700 |
| 12 | 12.75 | 40 | 0.406 | 11.938 | 15.74 | 0.7773 | 3.338 | 3.13 | 349.0 | 174,500 |
| | | 80 | 0.688 | 11.374 | 26.07 | 0.7056 | 3.338 | 2.98 | 316.7 | 158,350 |