Exam I
(Open Book, 50 min.) Name

INSTRUCTIONS: Please read the following before beginning the exam.

- Please show all work for each problem in the space provided. If there is insufficient space provided, use the back of the page. Be sure to indicate in the space provided that additional work is on the back.

- Circle your answers. Be sure to include units!

- A teaching assistant or the instructor will be in the room at all times. Feel free to ask questions.

- The exam consists of many questions, some of which require little or no calculation. First answer those questions which require no calculation. Trial-and-error should not be necessary.

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Code Number for Posting Grades

After the exam is graded, I will hand out a tabulation of all grades. I will use the last four digits of your social security number to code your grades. If you would prefer a different 4-digit code number, please write it below.

Numerical Code: □□□□

Enter a number only if you don’t want me to use the last four digits of your social security number.
5% 1.) What is the inside diameter of a 1-inch, Schedule 40, standard steel pipe?

Reading from the table on p892, the inside diameter is **1.049 inch**.

2.) Steam having an absolute pressure of 103 psia enters a steam chest at a temperature of 400°F.

5% a. Is there any liquid water present in the entering steam? Or is all the water in the vapor phase?

Reading from the steam table on p859, 103 psia steam has a saturation temperature of 330°F. At temperatures higher than this, the steam is supersaturated and **all water exists in the vapor phase**.

5% b. What is the highest temperature at which any removal of heat from 103 psia steam will produce more liquid?

The saturation temperature: **330°F**.

5% c. What is the temperature at which the last bit of water vapor at 103 psia is condensed into liquid?

The saturation temperature: **330°F**. For a single component, **all** condensation takes place at the saturation temperature.

3.) Kerosene is heated by saturated steam at 250°F in a shell-and-tube heater. The kerosene is inside the tubes and the steam is outside. The flow is countercurrent. The average velocity of the kerosene is 8 ft/s. The properties of kerosene at its average temperature are specific gravity 0.805, viscosity 1.5 cP, specific heat 0.583 Btu/lb-°F and thermal conductivity 0.0875 Btu/ft-h-°F. The tubes are low-carbon steel ¾ inch OD by BWG 16.

When the heat exchanger was first installed, 500 lb/min of kerosene could be heated from 70°F to 150°F. This corresponds to an overall heat transfer coefficient (based on inside area) of 136 Btu/ft²-h-°F. After three years of operation, the performance of the exchanger gradually eroded so that only 400 lb/min of kerosene could be heated from 70°F to 150°F using the same 250°F steam.

5% a. What is the most common cause of gradual decrease in heat duty of a heat exchanger? **Accumulation of material on the surface of the tubes, called fouling.**

5% b. Which side of the tubes (inside or outside) is more likely to be affected by this cause in this particular heat exchanger?

Steam is relatively free of components which might deposit on the surface, so the fouling most likely comes from the kerosene, which is **inside** the tubes.

15% c. Regardless of your answers to parts a and b, calculate an apparent fouling factor (based on inside area) which would lead to the observed decrease in heat duty. **Hint:** note that the inlet and outlet temperatures of the hot and cold streams are the same before and after the change; thus the average driving force is the same.
The heat duty of the exchanger is given by the design equation and also equals the increase in enthalpy of the cold fluid (kerosene):

$$q_T = U_iA_i\Delta T_L = m_cC_p,c (T_{c,\text{out}} - T_{c,\text{in}})$$

The areas, temperatures and heat capacity have not changed. Instead, the reduction in heat duty is caused by a reduction in the overall heat transfer coefficient. Dividing the heat duty after fouling by its value before fouling yields:

$$\frac{q_T'}{q_T} = \frac{U'_i}{U_i} = \frac{m'_c}{m_c} = \frac{400}{500} = 0.8 \quad \text{or} \quad U'_i = 0.8U_i = 108.8 \text{ btu ft}^{-2}\text{hr}^{-1}\text{°F}^{-1}$$

The reduction in $U_i$ in turn is caused by a new resistance to heat transfer:

$$\frac{1}{U'_i} = \frac{1}{U_i} + \frac{1}{h_{d,i}}$$

Substituting $U_i = 136$ and $U'_i = 108.8$, we compute

$$h_{d,i} = 544 \text{ btu ft}^{-2}\text{hr}^{-1}\text{°F}^{-1}$$

4.) A single-effect evaporator is concentrating a 10wt% NaOH feed to produce a liquor having 40wt% NaOH. The pressure in the vapor space is 1 atm.

5%  

a. What is the temperature in the vapor space?

This can be read from the Dühring chart on p500. The boiling point of pure water at 1 atm is 212°F. Using this as the abscissa for the chart, we use the 40wt% line to read the ordinate value of 262°F.

5%  

b. The vapor thus produced at 1 atm partially condensed at the same pressure in a second heat exchanger. What is the temperature of the condensate?

The condensate temperature is 212°F. In the condenser, the vapor is in equilibrium with pure water; whereas in the vapor space, the vapor is in equilibrium with 40wt% NaOH solution.

5%  

5.) In a vapor recompression evaporator, we found that compressing the vapor to higher pressures required more power to be supplied to the compressor and more make-up steam was also needed, leading to higher utility costs for the same capacity. What is the economic advantage of more compression (compared to less compression) of the vapor?

By compressing to a higher pressure, we raise the condensation temperature of the vapor. This in turn increases the driving force for heat transfer (to the cooler liquor) and reduces the heat exchanger area required. The economic advantage is the lower capital cost of the heat exchangers.

6.) Below are the xy and Txy diagrams for a mixture of hexane and octane at 1 atm.
15% a. A mixture containing 40mol% hexane and 60mol% octane is flashed at 1atm pressure. One third of the feed is vaporized. Assuming an equilibrium flash, find the composition of the vapor.

First we draw the operating line on the xy-diagram, which passes through (0.4, 0.4) and has a slope of \((f-1)/F\). For \(f=1/3\), this slope equals -2. Where the operating line crosses the equilibrium curve gives us the composition of vapor and liquid products. The ordinate of the intersection point is \(y_p = 0.66\), which means the vapor is \(66\,\text{mol\% hexane}\).

10% b. What is the temperature of the vapor produced by this flash?

Locating the point on the saturated vapor curve of the Txy diagram having an abscissa of 0.66, we find the ordinate is \(377\,\text{°F}\).

5% c. What is the temperature of the liquid produced by this flash?

The liquid has the same temperature: \(377\,\text{°F}\).

5% d. The same mixture of 40mol% hexane and 60mol% octane is charged to a batch still. Find the composition of the first bubble of vapor produced by the still.

The first bubble of vapor will be of that composition which is in equilibrium with a liquid having \(x=0.4\). From the xy-diagram, we read 0.79 as the ordinate of this point. Thus the vapor is \(79\,\text{mol\% hexane}\).

5% e. What is the composition of the last bubble of vapor produced by the still (when virtually no liquid left is in the still)?

This question is a little tricky. Recalling the example worked in the Notes under the topic of “Raleigh equation,” we note that the composition (i.e. mole fraction of the more volatile component) of the remaining liquid in the still decreases monotonically from its initial value to zero as the number of moles remaining decreases. In this case, this implies that the last drop of liquid remaining in the
still and the last bubble of vapor will be pure octane (the less volatile component).