Chemical Engineering 140 **December 13, 2010**

Final Examination

(100) 1. Production of Acetaldehyde from Ethanol

To produce acetaldehyde (CH_3CHO), ethanol is reacted with air as shown

$$C_2H_5OH + 0.5O_2 \rightarrow CH_3CHO + H_2O \tag{1}$$

Unfortunately, acetic acid (CH_3COOH) is produced as an unwanted byproduct

$$2CH_3CHO + O_2 \rightarrow 2CH_3COOH \tag{2}$$

We desire a reactor to produce 1200 kmol of acetaldehyde (CH_3CHO) per hour Laboratory data indicate that if we use a new catalyst and adjust the feed ratio to 5.7 moles ethanol per mole oxygen, we can achieve 25% conversion of ethanol in the reactor with a selectivity for acetaldehyde of 1.5. Pure ethanol vapor and air (79 mol% N_2, 21 mol% O_2) are fed to the reactor at 300°C and 1.0 atm. Reactor effluent is also at 1.0 atm and all vapor. To maintain a constant reactor temperature of 300°C, how much heat needs to be added or removed? Approximate constant heat capacities are given in Table 1. Appendix F of the text lists the necessary standard heats of formation.

Table 1 Molar Heat Capacities.

Substance	$\tilde{C}_p$ (J/gmol°C) approx.
O_2 (g)	29.3
C_2H_5OH (g)	65.5
CH_3CHO (g)	54.7
CH_3COOH (g)	66.5
H_2O (g)	33.6

(100) 2. Cooling of a Fermentation Broth

A 10,000 L batch of fermentation broth is sterilized by holding it under pressure at 121 °C for 26 min. Before use, it must cool to 37 °C. Cooling is accomplished by placing the 10,000 L vessel in a large room where the temperature is 35 °C. The rate of cooling is given by Newton's law with $\underline{U}A$ = 3760 kJ/ min °C). Mass density of the broth is 1.05 kg/L and its constant-pressure heat capacity is 4 kJ/(kg °C).

(15) a. Write Newton's-law expression for the rate of cooling, $\underline{\dot{Q}}$.

(25) b. What is the expression for the total amount of heat that must be removed?

(40) c. Find the an expression for the temperature of the broth as a function of time

(10) c. Plot the temperature of the broth as a function of time

(10) d. How long will it take to cool the broth?

(100) 3.Comparison of the Direct and Indirect Methods for Continuous Hot Water Supply

Recently, Sutter and Heaters touted the advantages of direct steam injection (DSI) for providing a continuous (steady) supply of hot water (P. Sutter, P Heaters, "Producing Hot Water by Direct Steam Injection," Chemical Engineering Progress, 48-51, May 2010). The alternative is to heat water by indirect steam heating as in a cladded vessel. Figures 2A (indirect heating) and 2B (direct heating) illustrate the two methods. A fixed, steady supply of hot water at mass flow rate $\dot{m}_w$ and temperature T_∞ is desired. With indirect heating in Figure 2A, steam heats the water externally by condensing in the steam chest. Conversely, with direct heating in Figure 2B, inlet steam is mixed directly into the heated water. Assume in both Figures 2A and 2B that steam is completely condensed and that the water heat capacity, $\hat{C}_{pw}$ is constant. Assume also that the cost of producing steam is the gauge of efficiency. Label the inlet water temperature as T_O and the steam condensation temperature as T_S. In both cases, inlet steam is fully saturated vapor. Denote the mass enthalpy of vaporization of water as $\Delta\hat{H}_{vap}$

(20) a. Explain physically why direct hot water heating is more efficient than indirect heating (no equations!).

(25) b. Perform mass and energy balances for the indirect heating method to find an expression for the mass steam rate $\dot{m}_S$.

(25) c. Perform mass and energy balances for the direct heating method to find an expression for the mass steam rate $\dot{m}_S$.

(20) d. Use the results in parts b and c to obtain an expression for the ratio of efficiencies for the two processes. Is the direct method actually more efficient?

(10) e. List disadvantages of the direct method as pictured in Figure 2B.

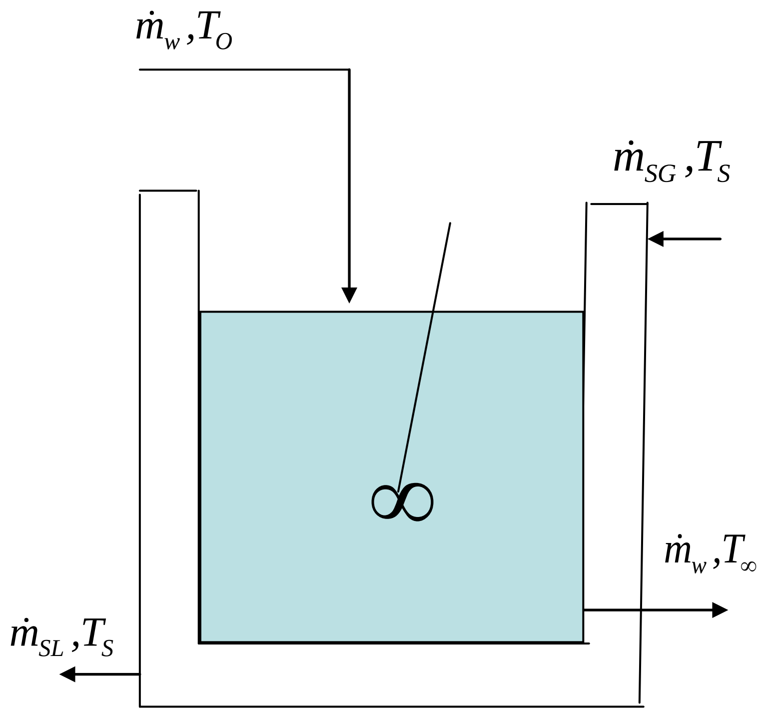

Figure 2A Steady Indirect Heating of Water (steam cladding).All steam condenses in the cladding chest.

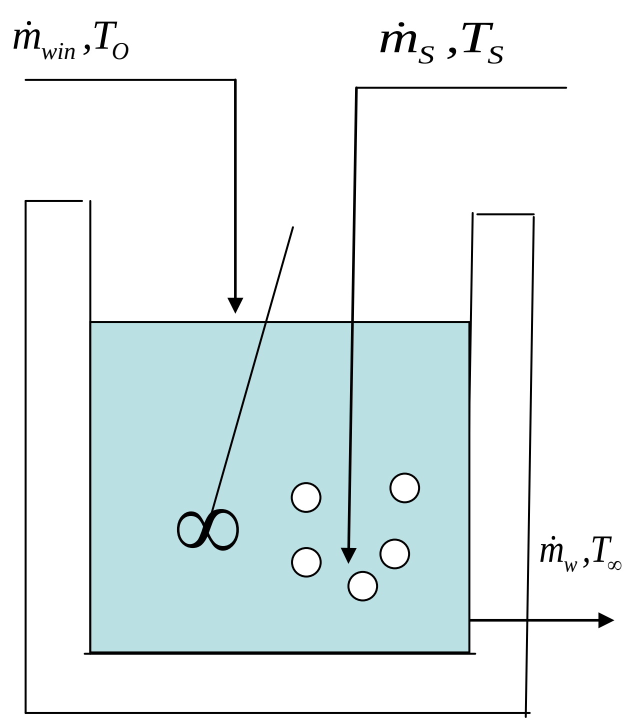

Figure 2B. Steady Direct Heating of Water (DSI). Vapor bubbles completely condense and the cladding chest is not used.

(135) 4. Short Answer Questions

(25) a Below is a qualitative $P-\tilde{V}$ diagram for water. Qualitatively sketch the corresponding P-T diagram for water. Label the phases and label points A-F from the P-V diagram onto the P-T diagram.

From the P-V diagram, which point(s), if any, correspond to:

(10) i. saturated water at the bubble point?

(10) ii. saturated water at the dew point?

(10) iii. the critical point?

(10) iv the triple point?

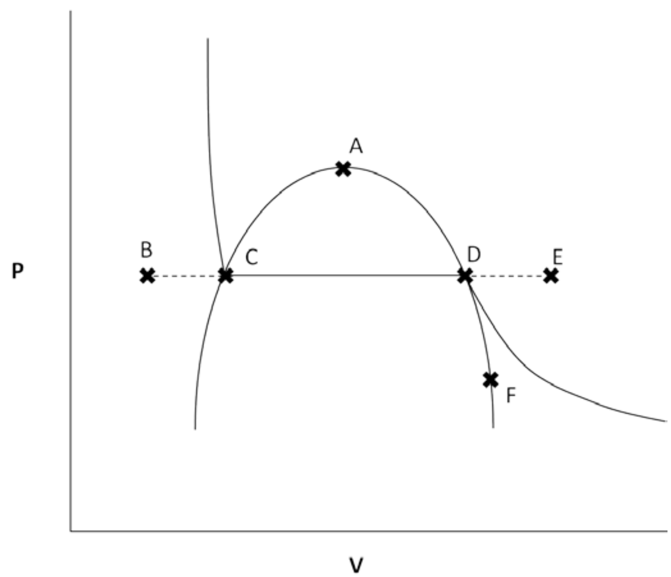

Figure 4a Qualitative Sketch of the $P-\tilde{V}$ Diagram for Water

(20) b. Find the temperature of saturated water at 600 kPa. Prove why knowing the pressure is not enough information to find the temperature for subcooled water.

(25) c. A counter-current heat exchanger has N tubes with length of 2 m and diameter of 10.5 cm. The rate of heat transfer can be determined by the design equation: $Q = UA\Delta T_{lm}$

where the subscript *lm* standards for logarithmic mean. The overall heat transfer coefficient, $\underline{U}$, is 10 kJ/(°C m^2 s) and $\underline{\dot{Q}}$ = 30,000 kJ/s. What is the required number of tubes in the heat exchanger?

(25) d. Find an expression for the isothermal internal energy change from molar volume $\tilde{V}_1$ to molar volume $\tilde{V}_2$ for a gas that obeys Amagat's equation of state: $P(\tilde{V} - b) = RT$ where $\tilde{V}$ is the molar volume, T is temperature, and b is a known constant that corrects for molecular finite size. Explain the physical reason underlying your answer.