10.213 Chemical Engineering Thermodynamics
Spring 2002

Problem Set B
Due Wednesday, February 20, 2002

Problem 5
Methanol is synthesized from carbon monoxide and hydrogen in a catalytic reactor by the reaction:

$$CO + 2H_2 \rightarrow CH_3OH$$

The fresh feed to the process contains 32.0 mol % CO, 64.0 mol % H_2, and 4.0 mol % N_2. This stream is mixed with a recycle stream in a ratio 5 mol recycle/ 1 mole fresh feed to the reactor, which contains 13.0 mol % N_2. A low single-pass conversion is attained to the reactor. The reactor effluent goes to a condenser from which two streams emerge: a liquid product stream containing essentially all the methanol formed in the reactor, and a gas stream containing all the CO, H_2, and N_2 leaving the reactor. The gas stream is split into two fractions: one is removed from the process as a purge stream, and the other is the recycle stream that combines with the fresh feed to the reactor. Calculate:

a) the production rate of methanol (mol/h),
b) the molar flow rate and composition of the purge gas, and
c) the overall and single-pass conversions.

Problem 6
Chemical leavening agents rely on the reaction between acidic and basic compounds to form bubbles of carbon dioxide. The alkaline compound of choice is almost always sodium bicarbonate $NaHCO_3$, commonly called baking soda, because it is nontoxic, tasteless, cheap, and easily purified. The baking soda forms many small gas cells of carbon dioxide in the batter. These expand in size during cooking to form a baked product of light final texture as the cooking process sets the material around the bubbles to prevent coalescence and collapse of the baked food upon cooling.

The baking soda reacts with acidic materials in the batter by the following reaction

$$NaHCO_3 + H^+ = Na^+ + H_2O + CO_2(g)$$

In the absence of any baking soda the batter expands 11 % during the cooking process.

1) Estimate the amount of baking soda, in grams, needed to increase an initial volume of 500 mL of a cake batter fourfold during the baking process. Assume the bubbles contain only carbon dioxide at atmospheric pressure.
2) Estimate the amount of baking soda required if the bubbles contain 40 mol% water vapor and 60 mol% carbon dioxide at atmospheric pressure.

Assume that the reaction of sodium bicarbonate to carbon dioxide goes to completion, no carbon dioxiode is lost during baking, and all of the carbon dioxide goes into the bubbles.The batter is initially at room temperature of 25° C and the cake reaches the temperature of the oven 350° F. You may assume that carbon dioxide and water vapor behave as perfect gases.
The atomic weights of several elements are: C 12, H 1, O 16.01, Na 23.00

Problem 7

A process consists of two steps:

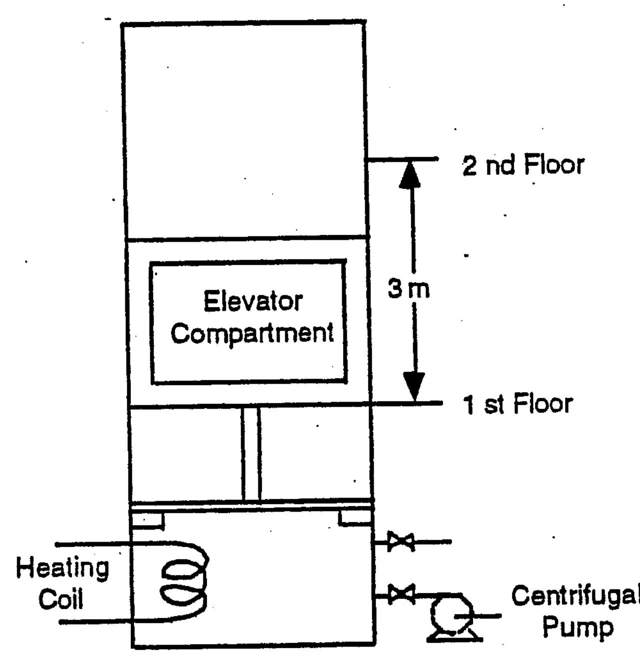
1) One mole of air at T = 800 K and P = 4 bar is cooled at constant volume to T = 350 K.
2) The air is then heated at constant pressure until its temperature reaches 800 K.

If this two-step process is replaced with a single isothermal expansion of air from 800 K and 4 bar to some final pressure P, what is the value of P that makes the work of the two processes the same? Assume mechanical reversibility and treat air as an ideal gas with $C_p = 3.5$ R and $C_v = 2.5$ R.

Problem 8

A clever(?) chemical engineer has devised the thermally operated elevator shown below. The elevator compartment is made to rise by electrically heating the air contained in the piston and cylinder drive mechanism, and the elevator is lowered by opening a valve at the side of the cylinder, allowing the air to escape slowly. Once the elevator compartment returns to the lower level, a small compressor removes the remaining air in the cylinder and replaces it with air at 20 °C and a pressure sufficient to support the elevator compartment. The cycle can then be repeated. There is no heat transfer between the piston, cylinder, and the gas; the weight of the piston, elevator, and elevator contents is 4000 kg; the piston has an area of 2.5 m^2; and the volume in the cylinder when the elevator is at its lowest level is 25 m^3. There is no friction between the piston and the cylinder, and the air in the cylinder is assumed to be an ideal gas with C_p = 30 J/mol K.

a) What is the pressure in the cylinder throughout the process?
b) How much heat must be added to the air during the process of raising the elevator 3 m, and what is the final temperature of the gas?
c) What fraction of the heat added is used in doing work? What fraction is used in raising the temperature of the gas?
d) How many moles of air must escape in order for the elevator to return to the first floor?
e) What do you think of this engineer's ideas? Justify your opinion.



Additional Practice Problems (not to be handed in)

Problem P3

In Problem 3, you considered the synthesis of ammonia starting from hydrogen and air. We assumed that all reactions went to completion and that air contained only nitrogen and oxygen (i.e., we ignored that air contains 0.94 mol% argon). For the real process, the combustion reaction can be made to go to completion; however, the reaction to form ammonia from hydrogen and nitrogen does not go to completion, thereby requiring the addition of a separator and recycle stream to the flow sheet generated in Problem 3. The inclusion of the recycle stream sets up an interesting problem as the separator unit generates a stream of ammonia and a stream of lighter gases (hydrogen, nitrogen, argon) that get recycles to the reactor. For this flow chart where the entering stream of air into the combustor contains 78 mol% N_2, 21.06 mol% O_2, and 0.94 mol% Ar, the argon lacks an exit from the process. As a result, the argon builds up in concentration in the recycle stream until it contains no nitrogen or hydrogen for ammonia production. A purge is used to solve this problem.

To examine this problem, consider the operation of your ammonia plant where an excess of hydrogen is burned with air so that the generated gas contains nitrogen and hydrogen in a 1:3 molar ratio and no oxygen or water. Argon is present in this gas since it accounts for 0.94 mol% of the air used in the combustion. This gas is fed to a reactor where there is a 20% conversion of the N_2-H_2 mixture to ammonia. The ammonia is separated by condensation, and the unconverted gases are recycled to the reactor. To prevent accumulation of argon in the system, some of the unconverted gases are vented to the atmosphere before being recycled to the reactor. The upper limit of argon in the reactor is to be 5% of the entering gases.

a) What percentage of the recycle stream is vented?
b) What percentage of the original hydrogen that enters the process is converted into ammonia? Compare this latter answer with your result from Problem 3.
c) For a common flow rate of materials into this process, how much greater is the flow rate into the reactor in Problem P3 than in Problem 3?

Practice Problem P4

A mixture containing 50 wt% methanol and 50 wt% ethanol undergoes a process involving two unit operations and is separated into two product streams that each contain 90 wt% of one of the components (referred to as the "methanol-rich" and "ethanol-rich" products) and a third waste stream of unknown composition. In the first unit, the mixture is separated into the above methanol-rich phase that is collected and another stream that has twice the mass flow rate of the methanol-rich phase. This second stream enters a second separation unit that produces the ethanol-rich product and another stream of unknown composition with twice the mass flow rate of the ethanol-rich stream.

a) Determine the relative mass flow rates of the methanol-rich product, the ethanol-rich product, the waste product stream, and the stream flowing between the two separation units.
b) Determine the compositions of the waste stream and the stream flowing between the two separation units.