MIDTERM #2 PART I EXAMINATION – November 10th, 2020
Upload to Gradescope 75 minutes after you submit the bCourses quiz that contains the link to this document (keep track of your own time!).
Chemical Engineering 140
Fall 2020
50 Points

1. Natural gas storage tank (25 pts)

Natural gas, or methane (CH_4), has become increasingly prevalent as an energy source in recent decades. You're an engineer working at a natural gas production plant, and you've been tasked with designing a storage system for methane. For this problem, assume that any gas phase can be treated as ideal unless otherwise stated.

Methane data

Compound	$T_{critical}$	$P_{critical}$	$T_{triple\ point}$	$P_{triple\ point}$	Density (liquid)
Methane	196 K	45.4 atm	90.67 K	0.115 atm	450 kg/m³=28100mol/m³

Antoine Equation Constants

Compound	A	B	C
Methane	6.34159	342.22	260.221

Antoine's equation parameters for methane where P* is in mm Hg, T is in °C:

$$\log_{10}(P^*) = A - B/(T + C)$$

a. [4 pts] Using the critical point and triple point data, draw an ***approximate*** vaporization line on a P-T diagram for methane, making sure to label the critical point and triple point, as well as the expected liquid and vapor phase regions on the plot. What is methane's phase at ambient conditions (i.e., room temperature (25 °C) and atmospheric pressure)?

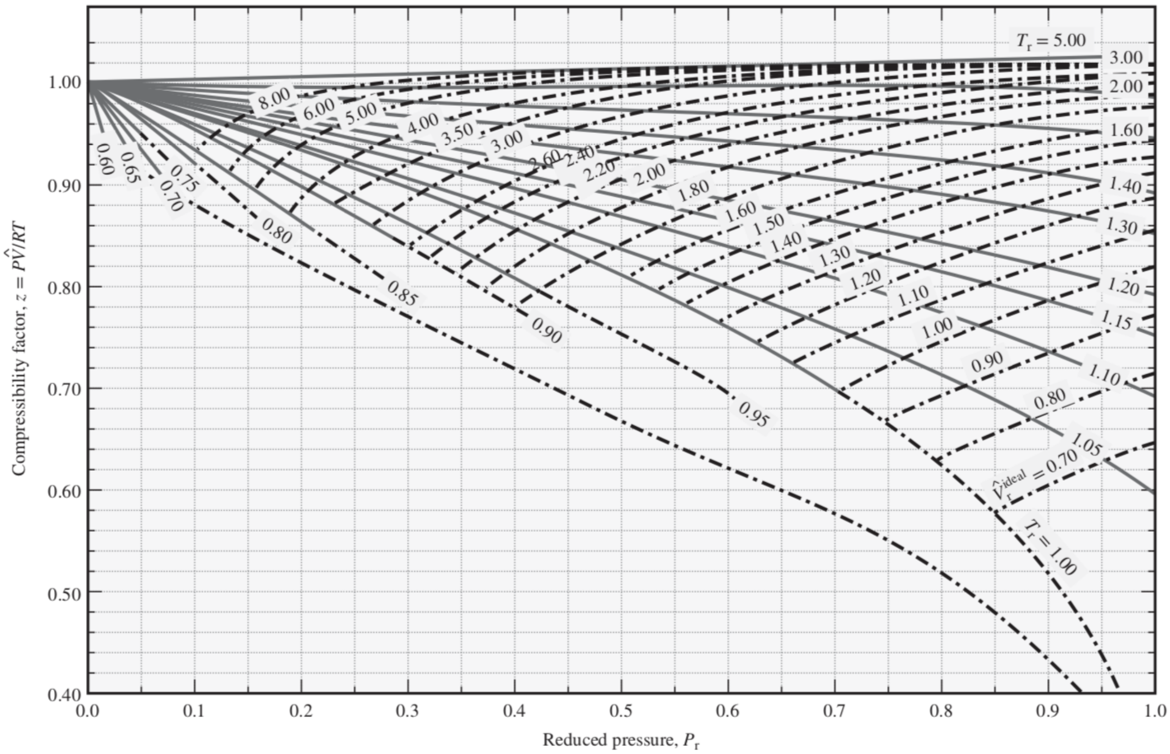
b. [5 pts] Suppose you need to store 10,000 kg of methane (623 kmol). There's an older, but still working, storage container that used to store ethane that you may be able to reuse. The volume of this container is 500 m³ and has a pressure limit of 10 atm. At ambient conditions, determine if you would be able to reuse this storage container.

c. You find another old container, still in excellent condition, that was designed for cryogenic applications. This container is designed to operate at -140 °C. The tank volume and pressure limits are the same as in part b.

   i. [5 pts] Considering the tank's pressure limit (10 atm), using calculations and physical arguments, determine if it is possible to store 10,000 kg of methane in this container?

   ii. [8 pts] Using appropriate calculations, how much (in kmoles) of the 623 kmole of methane exists in the liquid and vapor phases (note: liquid methane density provided above)?

   iii. [3 pts] Is using the ideal gas law valid for methane at these conditions? Justify your response using law of corresponding states and the following compressibility chart.



PROBLEM 2 IS ON THE NEXT PAGE

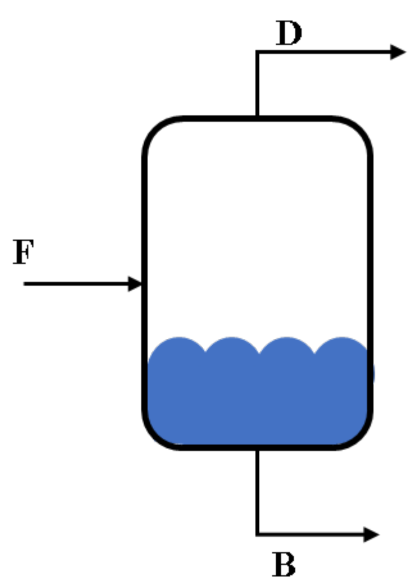
2. Flash separation (25 pts)

You are a well-trained chemical engineer recently hired by a chemical plant. The first task assigned to you is to distill an alkane mixture coming from the upstream processes. The liquid feed (F) stream contains a mixture of n-heptane, n-pentane, and n-octane with respective mole fractions $Z_H = 0.20$, $Z_P = 0.35$ and $Z_O = 0.45$. You send the feed stream into a flash drum (as shown in the diagram below) and determine the degree of separation. Stream D is pure vapor while stream B is pure liquid, both of which are in equilibrium. Stream F has a molar flowrate of 1000 kmole/h. Clearly state the final equations you are solving to obtain the answer in each part below.

$$\log_{10}(P^*) = A - B/(T + C)$$

Antoine's equation parameters for each species where P* is in mm Hg, T is in °C:

Antoine Equation Constants			
Compound	**A**	**B**	**C**
n-heptane	6.90253	1267.828	216.823
n-pentane	6.84471	1060.793	231.541
n-octane	6.91874	1351.756	209.100



a) [10 pts] The flash drum will operate at a constant pressure of 2 atm. Calculate the bubble point and dew point temperatures of the mixture.

b) [15 pts] After your calculation in part a), you decide to use 120°C and 2 atm as the operating condition. Calculate the flowrates of B and D, as well as each stream's composition.

MIDTERM #2 PART II EXAMINATION – November 10th, 2020
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1. Design of a plug flow reactor with recycle (50 pts.)

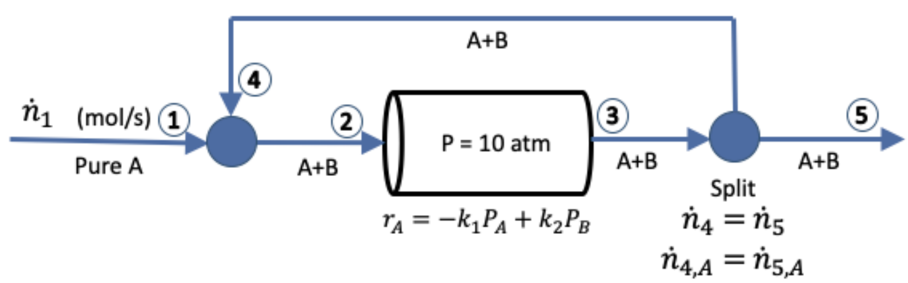
I am interested in converting gaseous species A into gaseous species B via the following reversible reaction:

$$A \leftrightarrow B \qquad r_A = -kP_A + kP_B$$

I feed pure species A at a molar flowrate of $\dot{n}_1$ mol/s to a steady-state packed bed reactor, where the above reaction is catalyzed with the rate expression given. r_A is the rate of reaction of species A in units of mol/(s atm), and the forward and reverse reaction rate constants (*k*) are equal to each other at the operation temperature of the reactor. The total pressure, *P*, of the PBR is kept constant, although the partial pressures of each gas ($P_i = y_i P$) change down the reactor.

a) [5 pts] What is the highest conversion of species A (f_A) I can achieve for this reaction?
b) [3 pts] Rewrite the rate expression only in terms of *k*, *P*, and y_A.
c) [8 pts] Starting from the PBR design equation, derive an algebraic expression (via integration of the design equation) that relates reactor volume, *V*, to the conversion of A, f_A, using only the known quantities above ($\dot{n}_1$, *P*, and *k*).
d) [4 pts] If my total reactor volume is 500 L and the inlet molar flowrate is $\dot{n}_1$ = 100 mol/s, *P*= 10 atm, and *k*=0.01 mol/(s atm), what is the outlet conversion of species A?

To increase overall process conversion, I decide to add a recycle stream to my reactor. The recycle splits the effluent (outlet) of the reactor into two streams (4 and 5 shown in the schematic below) of equivalent molar flowrates. Here, f_A is defined as the single pass conversion of the reactor: moles of A reacted in the reactor divided by moles A fed to the reactor (i.e., $\frac{(\dot{n}_{A,2}-\dot{n}_{A,3})}{\dot{n}_{A,2}}$).



e) [5 pts] Using appropriate total mole balances, calculate $\dot{n}_2$ and $\dot{n}_3$, the total molar flowrates of stream 2 and 3, respectively, as a function only of $\dot{n}_1$ (i.e., your answer should contain no other parameters other than constants and $\dot{n}_1$). Hint: no *total* moles are generated or consumed in the reactor.
f) [5 pts] Similarly, now using appropriate species A mole balances and the definition f_A, find an expression for species A molar flowrate in stream 2 as a function only of $\dot{n}_1$ and f_A.
g) [5 pts] Find an expression for the mole fraction of A in stream 3, $y_{A,3}$, only as a function of f_A.
h) [10 pts] Noting that the conversion and $y_{A,3}$ will vary with reactor volume, start with the PFR design equation and derive an algebraic expression (via integration of the design equation) that relates reactor volume, *V*, to the single pass conversion of A, f_A, using only the known constants above ($\dot{n}_1$, *P*, and *k*).
i) [5 pts] Finally, what is the overall conversion of the process (i.e., $\frac{(\dot{n}_1-\dot{n}_{A,5})}{\dot{n}_1}$) in terms of the single pass conversion, f_A?