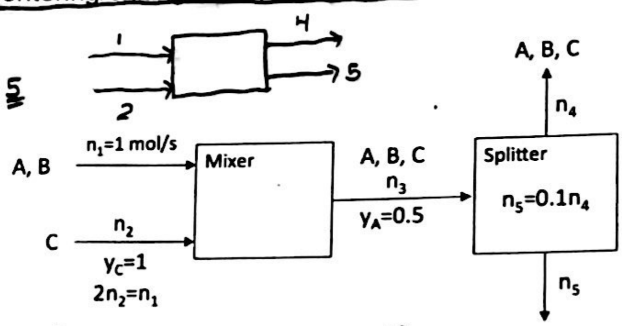
NOT CONFIRMED ANSWER KEY. STUDENT'S WORK

+14/15

1. **Please answer the following T/F questions by circling the correct answer. [6 pts]**
   a. **(True or False)** The Reynolds number, Re, is the ratio of electrostatic forces to viscous forces in a body. [2 pt]
   b. **(True or False)** The rate constant, k, of a reaction typically is a function of temperature, pressure, catalyst, and solvent. [2 pt]
   c. **(True or False)** At time t = 3θ (where θ is the residence time of a transient CST) after a step change in input concentration of a given species, the CST output concentration has achieved roughly 95% of its steady-state concentration of the species . [2 pt]

2. **Please answer the following questions. [9 pts]**
   a. Is the following 2-unit, 3-component system well-defined, under-specified, or over- specified? Explain with a degree of freedom analysis. The species contents of each stream are indicated on the diagram, and the composition of the streams entering/exiting the splitter are the same (only their flowrates differ). [5 pts]

+4/5



overall DoF:

same composition for 5

unknown: $n_4, x_{A,1}, x_{B,1}, x_{B,4}, x_{C,4}$ = 5 unknown

equations: (3 comp × (unit) + ($\Sigma x_i = 1$) = 6 equations

for ① ④ ⑤

DoF: unk − eqn
= 5 − 6 = −1

0.1 $n_4 = n_5$ - not an unknown

y_A: 0.5 = $y_{A,4}$ = $y_{A,5}$
3

Since the number of equations is bigger than the number of unknowns, the system is ~~over~~ specified
under (−1)

b. The Hildebrand number, Hd, for chemical reactions is defined as

$$Hd = (\rho m^3)/(vt^4)$$

Where: **ρ:** density of a fluid reactor (kg/m³); **m:** mass of fluid in the reactor (kg); **v:** velocity of fluid entering the reactor (m/s); **t:** time fluid spent in reactor (s)

+4/4

What are the units and dimensions of the Hd number? [4 pts]

$$Hd = \frac{\rho m^3}{vt^4} = \frac{\frac{kg}{m^3} \times kg^3}{\frac{m}{s} \times s^4} = \frac{\frac{kg^4}{m^3}}{m s^3} = \frac{kg^4}{m^3} \times \frac{1}{m s^3} = \boxed{\frac{kg^4}{m^4 s^3}} \text{ unit}$$

$$\boxed{\text{dimension: } \frac{(\text{mass})^4}{(\text{length})^4 (\text{time})^3}}$$

[redacted] 29/40

3. *Production of rutile from Sorel slag (40 points)*

This problem presents a different method to produce TiO_2 compared to a recent homework problem. **Read this problem statement carefully!** This is a 5-unit, **steady-state** problem (not counting a heat exchanger for cooling) and each unit in the problem statement is underlined for emphasis.

Pure TiO_2 (rutile) is produced from an ore, called Sorel Slag, that has the following composition: 70 wt% TiO_2, 8 wt% Fe, and 22 wt% inerts. This ore is fed to a reactor in one stream, along with concentrated H_2SO_4 (65 wt% H_2SO_4 in H_2O) and pure O_2 in separate streams. The following reactions occur in the reactor:

$$TiO_2 + H_2SO_4 \rightarrow TiOSO_4 + H_2O \quad (1)$$

$$Fe + \tfrac{1}{2}O_2 + H_2SO_4 \rightarrow FeSO_4 + H_2O \quad (2)$$

H_2SO_4 and O_2 are fed in 0% excess (i.e., exactly enough H_2SO_4 is fed to react with all TiO_2 and Fe, and O_2 is fed in a theoretical amount to react with all Fe), and both reactions achieve full conversion. The reactor contents exit in a single stream. A $TiOSO_4$ in H_2O solution is isolated from this stream by cooling the mixture, which causes all inerts and $FeSO_4$ to solidify, allowing their complete removal by a filtration separator. The $FeSO_4$ and inerts leave the separator in a different stream than the $TiOSO_4$ solution. The purified $TiOSO_4$ solution is then sent to an evaporator, where water is evaporated at low pressures from the solution to ultimately create a $TiOSO_4$ in H_2O slurry that is 80 wt% $TiOSO_4$ and 20 wt% H_2O. The $TiOSO_4/H_2O$ slurry is then sent to a dryer, where dry air (which contains no water) is fed to the dryer and passed over the slurry, creating a stream of humidified air and a pure stream of the monohydrate of $TiOSO_4$ (i.e., $TiOSO_4 \cdot H_2O$). Finally, to recover the end product, TiO_2, the $TiOSO_4 \cdot H_2O$ is sent to a kiln, where it is heated and undergoes the following dehydration reaction to full conversion:

$$TiOSO_4 \cdot H_2O \rightarrow TiO_2 + H_2SO_4 \quad (3)$$

Two streams, one of pure TiO_2 and another of pure H_2SO_4, leave the kiln. For any calculations, use a basis of 100 mol/s TiO_2 produced (i.e. TiO_2 kiln output stream is 100 mol/s).

Molecular weights:
Ti: 0.048 kg/mol, **O:** 0.016 kg/mol, **S:** 0.032 kg/mol, **H:** 0.001 kg/mol, **Fe:** 0.0558 kg/mol
TiO_2: 0.080 kg/mol, **$TiOSO_4$:** 0.160 kg/mol, **$TiOSO_4 \cdot H_2O$:** 0.178 kg/mol, **H_2O:** 0.018 kg/mol,
H_2SO_4: 0.098 kg/mol

a) Using the template on the next page, draw a flowsheet of this process, labeling each stream and unit with known and unknown flowrates and compositions. Fill out the diagram with all specified information (conversion, excess, etc.) given in the problem statement. (15 points)
b) What is the mass flowrate (kg/s) of Sorel Slag fed to the process? (10 points)
c) What is the mass fraction of water in the air leaving the dryer if the dry air's flowrate to the dryer is 200 kg per 100 mol of TiO_2 produced? (15 points)

4. Pump malfunction in a continuous stirred tank (45 points + 5 points extra credit)
Consider the continuous stirred cylindrical tank (no reactions) shown below. It has been operating in this configuration for a very long time. The pump providing pure B (stream 2) to the tank malfunctions at $t = 0$ min, thereby increasing the flowrate of the pure B stream to equal the flowrate of the pure A stream (stream 1). The pure A stream pump continues to deliver the same flowrate and the pump on the output (stream 3) continues to remove 100 L/min at all times; only the stream 2 flowrate changes. Pure A and B and mixtures of each all have the same density as given in the figure. Using appropriate mass balances (show all work!), find the following:

a) The volumetric flowrate (L/min) of stream 1. (5 pts) 5|5
b) The concentration of B (kg/L) in the output stream at t=0 min. (5 pts) 5|5
c) The time (minutes) it takes for the tank to overflow. (10 pts) 10|10
d) I am interested in finding the concentration of B in the output stream right when the tank starts to overflow. Set up, but do not solve, a differential equation that describes the change in B concentration (ρ) in the tank as a function of time during the time domain when the tank is filling. Place your final solution in the following form: $\frac{d\rho}{dt} = f(t)r(\rho) + g(t)$ (i.e., your equation should only contain ρ, t, and constants). What is the initial condition for this differential equation? (10 pts)

5|10

e) Instead, if the problem were otherwise the same, but the pure B pump malfunctioned at $t = 0$ min such that stream 2's flowrate linearly decreased to reach no flow 10 min later, how long would it take for the tank to drain? (15 pts) 1/15
f) All or nothing extra credit (no partial credit!): Revisiting part d), find the concentration of B (kg/L) right when the tank overflows. (5 pts) 0