FINAL EXAMINATION, PART I - Dec. 14th, 2020
Chemical Engineering 140
50 Points (3 multi-part problems)*
Fall 2020

INSTRUCTIONS
You have 105 minutes to complete this exam and submit your answers to Gradescope once downloaded from bCourses (90 minute exam time, 15 minute upload time). If you have trouble uploading to Gradescope, send a pdf file of your solutions to Prof. McCloskey (bmcclosk@berkeley.edu). Please keep track of your time.

Time Penalty: 3 pts. per minute late (e.g., turning in your exam 110 minutes after completing the bCourse quiz will result in a 15 point deduction).

Open notes and book. Equation solvers (Matlab, Wolfram, Excel, etc.) are allowed.

If you use Matlab or other software to solve a problem, clearly identify the equation, boundary conditions, or other parameters you input into the software and indicate that you used the software to calculate a final answer. No need to submit code with your response.

No internet searches allowed.

Completion on a tablet or on paper is allowable. Please upload your solution in proper order (solution to problem 1 first, problem 2 second, etc.). And on Gradescope, indicate ALL pages that contain ANY part of a solution for each problem.

Show all of your work, walk us through your thought process, keep it legible. BOX ALL ANSWERS if numerical solution or equation is requested.

Read each problem statement carefully, particularly the long ones.

*Extra 5% (5 pts) will be added for those who filled out the course survey and submitted the course survey quiz.

Ideal gas constant:
R= 8.314 J mol^{-1} K^{-1}; 8.205×10^{-5} m^3 atm mol^{-1} K^{-1}; 8.314×10^{-2} L bar mol^{-1} K^{-1}

Steam tables are located at the end of the exam

Integral Table

$$\int \frac{1}{(x+a)^2}dx = -\frac{1}{x+a}$$

$$\int \frac{1}{a^2+x^2}dx = \frac{1}{a}\tan^{-1}\frac{x}{a}$$

$$\int \frac{x}{a^2+x^2}dx = \frac{1}{2}\ln|a^2+x^2|$$

$$\int \frac{1}{a/x+bx}dx = \frac{1}{2b}ln(a+bx^2)$$

$$\int x^n dx = \frac{1}{n+1}x^{n+1}$$

$$\int \frac{1}{x}dx = \ln|x|$$

$$\int u dv = uv - \int v du$$

$$\int \frac{1}{ax+b}dx = \frac{1}{a}\ln|ax+b|$$

$$\int e^{ax^2}\,\mathrm{d}x = -\frac{i\sqrt{\pi}}{2\sqrt{a}}\mathrm{erf}\left(ix\sqrt{a}\right)$$

$$\int e^{-ax^2}\,\mathrm{d}x = \frac{\sqrt{\pi}}{2\sqrt{a}}\mathrm{erf}\left(x\sqrt{a}\right)$$

$$\int xe^{-ax^2}\,\mathrm{dx} = -\frac{1}{2a}e^{-ax^2}$$

$$\int \ln ax dx = x\ln ax - x$$

$$\int \frac{\ln ax}{x}dx = \frac{1}{2}(\ln ax)^2$$

$$\int \ln(ax+b)dx = \left(x+\frac{b}{a}\right)\ln(ax+b) - x, a \neq 0$$

$$\int \frac{x}{a+bx^2}dx = \frac{1}{2b}ln(a+bx^2)$$

$$\int e^{ax}dx = \frac{1}{a}e^{ax}$$

$$\int \sqrt{x}e^{ax}dx = \frac{1}{a}\sqrt{x}e^{ax} + \frac{i\sqrt{\pi}}{2a^{3/2}}\mathrm{erf}\left(i\sqrt{ax}\right),$$

$$\text{where } \mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$$

$$\int xe^x dx = (x-1)e^x$$

$$\int xe^{ax}dx = \left(\frac{x}{a} - \frac{1}{a^2}\right)e^{ax}$$

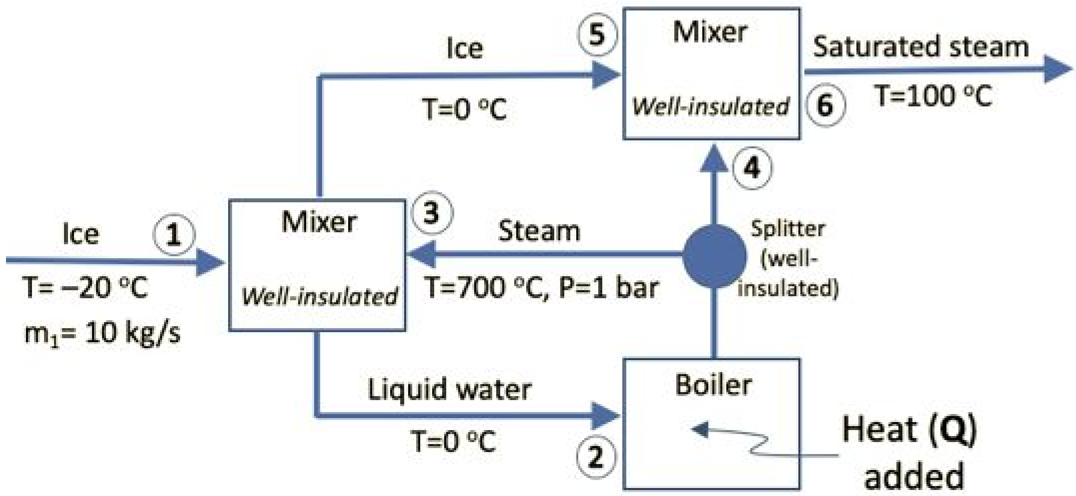
$$\int x^2e^x dx = \left(x^2-2x+2\right)e^x$$

1. Ice-to-Steam [15 points]

I want to generate steam from ice, and I have designed the process in the diagram below to do so. The following properties for ice will be useful:

$\hat{C}_{p,\,ice} =$ 2.11 kJ kg^{-1} K^{-1} (treat as constant with temperature)
$\Delta H_m = 333.9$ kJ/kg (heat of melting of ice at its melting point, 0 °C)

For liquid water and steam, please use the steam tables to evaluate relevant properties (steam tables are located on the last few pages of this part of the exam, or Table B.5-7 in your textbook).



Assume that all piping and the mixers are well-insulated, such that heat is only transferred to/from the system through the boiler. Using appropriate mass and energy balances (please clearly state them throughout the problem!), calculate:

a. [10 pts] Q, the heat added to the boiler, in kJ/s.
b. [5 pts] Stream 2 (the boiler inlet stream) flow rate in kg/s.

2. A leak in a single component tank [18 points]

Ideal gas constant: R = 8.205 x 10^{-5} m^3 atm K^{-1} mol^{-1}
1 atm = 760 mm Hg

3000 mols (MW=30 g/mol) of pure species A is being stored in a 10 m^3 tank, initially at 25 °C. Species A is condensable and exists in the tank as both a liquid and gas. At all temperatures relevant to this problem, species A vapor pressure at vapor-liquid equilibrium is described by Antoine's equation with the following form:

$$log(P^*) = 10.5 - \frac{1000}{120+T}$$

Where P* is in mm Hg, and T is in °C. The ideal gas law can be assumed for gas-phase behavior. The liquid has a specific gravity of 1 (1000 kg/m^3) and can be safely assumed to not be a function of temperature.

a. [2 pts] What is the pressure of the tank at these conditions?
b. [4 pts] How many mols of species A exist as gas and liquid at these conditions? You can safely assume that the liquid volume in the tank is negligible compared to the gas volume (i.e., the gas volume is 10 m^3).

At t = 0 min, a leak develops near the top of the tank (only gas leaks from the tank), which is proportional to the pressure difference between the tank and atmospheric pressure (1 atm), i.e., $\dot{n}_{leak} = -\alpha(P_{tank} - 1\ atm)$, where $\alpha = 0.2$ mol s^{-1} atm^{-1} and P_{tank} is in atm. Note that P_{tank} is related to the moles of gas present in the tank.

c. [12 pts] Using appropriate transient mass balances (clearly state balances, as well as initial/final conditions), how long will it take, from t = 0 min, for all of the liquid to fully evaporate? To solve this problem, there are two important time domains you will have to consider as described below, including assumptions that can be used to simplify the problem:
   i. Initially, the gas leaks from the tank isothermally at 25 °C, but negligible liquid evaporates, such that the pressure of the tank decreases. Assume the pressure continues to change until it hits the expected vapor-liquid equilibrium pressure of species A at T=23 °C. Continue to treat the volume of the liquid as negligible, such that the gas volume is 10 m^3.
   ii. Once the T=23 °C VLE pressure is achieved, assume that the liquid evaporates at a rate that maintains vapor liquid equilibrium at T=23 °C (the tank's temperature has dropped because evaporation is an endothermic process). VLE occurs at T=23 °C until all of the liquid evaporates.

3. CSTR and Recycle [17 points]

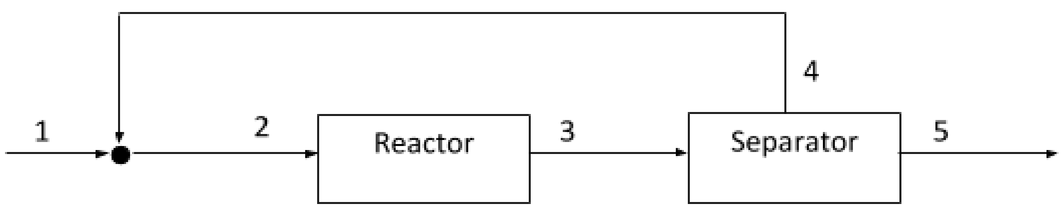
Species A is dissolved in a solvent and is reacting in a CSTR to produce species B and C.

$$A \rightarrow B + C$$

The reaction is irreversible and second order with respect to species A. The rate constant, k, is 1.00 L/(mol s). The CSTR operates at steady state. For all parts in this problem, you can assume that A, B, and C are all present at sufficiently small concentrations that allow the dilute approximation to be used for all streams.

a. [7 pts] 100 mol/s of A enter the reactor in a solvent with C_A= 1 mol/L. The reactor has a volume of 50 L. Solve for the outlet molar flow rate of species A, B, and C, as well as the fractional conversion for this reactor.

To increase the overall conversion, you incorporate a recycle stream and a separator into the process as shown in the diagram below. Assume the separator operates such that stream 4 has a volumetric flow rate of 40 L/s, and only contains solvent and A. The concentration of A in stream 4 is three times higher than in stream 3. Stream 1 still has a molar flow rate of 100 mol/s A and C_A= 1 mol/L.



b. [10 pts] Calculate the reactor's single pass conversion AND the overall conversion of species A for the process.

Table B.5 Properties of Saturated Steam: Temperature Table[a]

		$\widehat{V}$ (m³/kg)		$\widehat{U}$ (kJ/kg)		$\widehat{H}$ (kJ/kg)		
T(°C)	**P(bar)**	**Water**	**Steam**	**Water**	**Steam**	**Water**	**Evaporation**	**Steam**
0.01	0.00611	0.001000	206.2	zero	2375.6	+0.0	2501.6	2501.6
2	0.00705	0.001000	179.9	8.4	2378.3	8.4	2496.8	2505.2
4	0.00813	0.001000	157.3	16.8	2381.1	16.8	2492.1	2508.9
6	0.00935	0.001000	137.8	25.2	2383.8	25.2	2487.4	2512.6
8	0.01072	0.001000	121.0	33.6	2386.6	33.6	2482.6	2516.2
10	0.01227	0.001000	106.4	42.0	2389.3	42.0	2477.9	2519.9
12	0.01401	0.001000	93.8	50.4	2392.1	50.4	2473.2	2523.6
14	0.01597	0.001001	82.9	58.8	2394.8	58.8	2468.5	2527.2
16	0.01817	0.001001	73.4	67.1	2397.6	67.1	2463.8	2530.9
18	0.02062	0.001001	65.1	75.5	2400.3	75.5	2459.0	2534.5
20	0.0234	0.001002	57.8	83.9	2403.0	83.9	2454.3	2538.2
22	0.0264	0.001002	51.5	92.2	2405.8	92.2	2449.6	2541.8
24	0.0298	0.001003	45.9	100.6	2408.5	100.6	2444.9	2545.5
25	0.0317	0.001003	43.4	104.8	2409.9	104.8	2442.5	2547.3
26	0.0336	0.001003	41.0	108.9	2411.2	108.9	2440.2	2549.1
28	0.0378	0.001004	36.7	117.3	2414.0	117.3	2435.4	2552.7
30	0.0424	0.001004	32.9	125.7	2416.7	125.7	2430.7	2556.4
32	0.0475	0.001005	29.6	134.0	2419.4	134.0	2425.9	2560.0
34	0.0532	0.001006	26.6	142.4	2422.1	142.4	2421.2	2563.6
36	0.0594	0.001006	24.0	150.7	2424.8	150.7	2416.4	2567.2
38	0.0662	0.001007	21.6	159.1	2427.5	159.1	2411.7	2570.8
40	0.0738	0.001008	19.55	167.4	2430.2	167.5	2406.9	2574.4
42	0.0820	0.001009	17.69	175.8	2432.9	175.8	2402.1	2577.9
44	0.0910	0.001009	16.04	184.2	2435.6	184.2	2397.3	2581.5
46	0.1009	0.001010	14.56	192.5	2438.3	192.5	2392.5	2585.1
48	0.1116	0.001011	13.23	200.9	2440.9	200.9	2387.7	2588.6
50	0.1234	0.001012	12.05	209.2	2443.6	209.3	2382.9	2592.2
52	0.1361	0.001013	10.98	217.7	2446	217.7	2377	2595
54	0.1500	0.001014	10.02	226.0	2449	226.0	2373	2599
56	0.1651	0.001015	9.158	234.4	2451	234.4	2368	2602
58	0.1815	0.001016	8.380	242.8	2454	242.8	2363	2606
60	0.1992	0.001017	7.678	251.1	2456	251.1	2358	2609
62	0.2184	0.001018	7.043	259.5	2459	259.5	2353	2613
64	0.2391	0.001019	6.468	267.9	2461	267.9	2348	2616
66	0.2615	0.001020	5.947	276.2	2464	276.2	2343	2619
68	0.2856	0.001022	5.475	284.6	2467	284.6	2338	2623
70	0.3117	0.001023	5.045	293.0	2469	293.0	2333	2626
72	0.3396	0.001024	4.655	301.4	2472	301.4	2329	2630
74	0.3696	0.001025	4.299	309.8	2474	309.8	2323	2633
76	0.4019	0.001026	3.975	318.2	2476	318.2	2318	2636
78	0.4365	0.001028	3.679	326.4	2479	326.4	2313	2639
80	0.4736	0.001029	3.408	334.8	2482	334.9	2308	2643
82	0.5133	0.001030	3.161	343.2	2484	343.3	2303	2646
84	0.5558	0.001032	2.934	351.6	2487	351.7	2298	2650
86	0.6011	0.001033	2.727	360.0	2489	360.1	2293	2653
88	0.6495	0.001034	2.536	368.4	2491	368.5	2288	2656
90	0.7011	0.001036	2.361	376.9	2493	377.0	2282	2659
92	0.7560	0.001037	2.200	385.3	2496	385.4	2277	2662
94	0.8145	0.001039	2.052	393.7	2499	393.8	2272	2666
96	0.8767	0.001040	1.915	402.1	2501	402.2	2267	2669
98	0.9429	0.001042	1.789	410.6	2504	410.7	2262	2673
100	1.0131	0.001044	1.673	419.0	2507	419.1	2257	2676
102	1.0876	0.001045	1.566	427.1	2509	427.5	2251	2679

Table B.7 Properties of Superheated Steam[a]

$\hat{H}$ and $\hat{U}$ values in kJ/kg, $\hat{V}$ in m^3/kg

P(bar) ($T_{sat.}$°C)		Sat'd Water	Sat'd Steam	Temperature (°C)→ 50	75	100	150	200	250	300	350
0.0	$\hat{H}$	—	—	2595	2642	2689	2784	2880	2978	3077	3177
(—)	$\hat{U}$	—	—	2446	2481	2517	2589	2662	2736	2812	2890
	$\hat{V}$	—	—	—	—	—	—	—	—	—	—
0.1	$\hat{H}$	191.8	2584.8	2593	2640	2688	2783	2880	2977	3077	3177
(45.8)	$\hat{U}$	191.8	2438.0	2444	2480	2516	2588	2661	2736	2812	2890
	$\hat{V}$	0.00101	14.7	14.8	16.0	17.2	19.5	21.8	24.2	26.5	28.7
0.5	$\hat{H}$	340.6	2646.0	209.3	313.9	2683	2780	2878	2979	3076	3177
(81.3)	$\hat{U}$	340.6	2484.0	209.2	313.9	2512	2586	2660	2735	2811	2889
	$\hat{V}$	0.00103	3.24	0.00101	0.00103	3.41	3.89	4.35	4.83	5.29	5.75
1.0	$\hat{H}$	417.5	2675.4	209.3	314.0	2676	2776	2875	2975	3074	3176
(99.6)	$\hat{U}$	417.5	2506.1	209.2	313.9	2507	2583	2658	2734	2811	2889
	$\hat{V}$	0.00104	1.69	0.00101	0.00103	1.69	1.94	2.17	2.40	2.64	2.87
5.0	$\hat{H}$	640.1	2747.5	209.7	314.3	419.4	632.2	2855	2961	3065	3168
(151.8)	$\hat{U}$	639.6	2560.2	209.2	313.8	418.8	631.6	2643	2724	2803	2883
	$\hat{V}$	0.00109	0.375	0.00101	0.00103	0.00104	0.00109	0.425	0.474	0.522	0.571
10	$\hat{H}$	762.6	2776.2	210.1	314.7	419.7	632.5	2827	2943	3052	3159
(179.9)	$\hat{U}$	761.5	2582	209.1	313.7	418.7	631.4	2621	2710	2794	2876
	$\hat{V}$	0.00113	0.194	0.00101	0.00103	0.00104	0.00109	0.206	0.233	0.258	0.282
20	$\hat{H}$	908.6	2797.2	211.0	315.5	420.5	633.1	852.6	2902	3025	3139
(212.4)	$\hat{U}$	906.2	2598.2	209.0	313.5	418.4	603.9	850.2	2679	2774	2862
	$\hat{V}$	0.00118	0.09950	0.00101	0.00102	0.00104	0.00109	0.00116	0.111	0.125	0.139
40	$\hat{H}$	1087.4	2800.3	212.7	317.1	422.0	634.3	853.4	1085.8	2962	3095
(250.3)	$\hat{U}$	1082.4	2601.3	208.6	313.0	417.8	630.0	848.8	1080.8	2727	2829
	$\hat{V}$	0.00125	0.04975	0.00101	0.00102	0.00104	0.00109	0.00115	0.00125	0.0588	0.0665
60	$\hat{H}$	1213.7	2785.0	214.4	318.7	423.5	635.6	854.2	1085.8	2885	3046
(275.6)	$\hat{U}$	1205.8	2590.4	208.3	312.6	417.3	629.1	847.3	1078.3	2668	2792
	$\hat{V}$	0.00132	0.0325	0.00101	0.00103	0.00104	0.00109	0.00115	0.00125	0.0361	0.0422
80	$\hat{H}$	1317.1	2759.9	216.1	320.3	425.0	636.8	855.1	1085.8	2787	2990
(295.0)	$\hat{U}$	1306.0	2571.7	208.1	312.3	416.7	628.2	845.9	1075.8	2593	2750
	$\hat{V}$	0.00139	0.0235	0.00101	0.00102	0.00104	0.00109	0.00115	0.00124	0.0243	0.0299
100	$\hat{H}$	1408.0	2727.7	217.8	322.9	426.5	638.1	855.9	1085.8	1343.4	2926
(311.0)	$\hat{U}$	1393.5	2547.3	207.8	311.7	416.1	627.3	844.4	1073.4	1329.4	2702
	$\hat{V}$	0.00145	0.0181	0.00101	0.00102	0.00104	0.00109	0.00115	0.00124	0.00140	0.0224
150	$\hat{H}$	1611.0	2615.0	222.1	326.0	430.3	641.3	858.1	1086.2	1338.2	2695
(342.1)	$\hat{U}$	1586.1	2459.9	207.0	310.7	414.7	625.0	841.0	1067.7	1317.6	2523
	$\hat{V}$	0.00166	0.0103	0.00101	0.00102	0.00104	0.00108	0.00114	0.00123	0.00138	0.0115
200	$\hat{H}$	1826.5	2418.4	226.4	330.0	434.0	644.5	860.4	1086.7	1334.3	1647.1
(365.7)	$\hat{U}$	1785.7	2300.8	206.3	309.7	413.2	622.9	837.7	1062.2	1307.1	1613.7
	$\hat{V}$	0.00204	0.005875	0.00100	0.00102	0.00103	0.00108	0.00114	0.00122	0.00136	0.00167
221.2(P_c)	$\hat{H}$	2108	2108	228.2	331.7	435.7	645.8	861.4	1087.0	1332.8	1635.5
(374.15)(T_c)	$\hat{U}$	2037.8	2037.8	206.0	309.2	412.8	622.0	836.3	1060.0	1302.9	1600.3
	$\hat{V}$	0.00317	0.00317	0.00100	0.00102	0.00103	0.00108	0.00114	0.00122	0.00135	0.00163

Superheated Steam table (Con't)
$\widehat{H}$ and $\widehat{U}$ values in kJ/kg, $\widehat{V}$ in m^3/kg

***P*(bar)**		**Temperature (°C)→**							
($T_{sat.}$°C)		**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
0.0	$\widehat{H}$	3280	3384	3497	3597	3706	3816	3929	4043
(—)	$\widehat{U}$	2969	3050	3132	3217	3303	3390	3480	3591
	$\widehat{V}$	—	—	—	—	—	—	—	—
0.1	$\widehat{H}$	3280	3384	3489	3596	3706	3816	3929	4043
(45.8)	$\widehat{U}$	2969	3050	3132	3217	3303	3390	3480	3571
	$\widehat{V}$	21.1	33.3	35.7	38.0	40.3	42.6	44.8	47.2
0.5	$\widehat{H}$	3279	3383	3489	3596	3705	3816	3929	4043
(81.3)	$\widehat{U}$	2969	3049	3132	3216	3302	3390	3480	3571
	$\widehat{V}$	6.21	6.67	7.14	7.58	8.06	8.55	9.01	9.43
1.0	$\widehat{H}$	3278	3382	3488	3596	3705	3816	3928	4042
(99.6)	$\widehat{U}$	2968	3049	3132	3216	3302	3390	3479	3570
	$\widehat{V}$	3.11	3.33	3.57	3.80	4.03	4.26	4.48	4.72
5.0	$\widehat{H}$	3272	3379	3484	3592	3702	3813	3926	4040
(151.8)	$\widehat{U}$	2964	3045	3128	3213	3300	3388	3477	3569
	$\widehat{V}$	0.617	0.664	0.711	0.758	0.804	0.850	0.897	0.943
10	$\widehat{H}$	3264	3371	3478	3587	3697	3809	3923	4038
(179.9)	$\widehat{U}$	2958	3041	3124	3210	3296	3385	3475	3567
	$\widehat{V}$	0.307	0.330	0.353	0.377	0.402	0.424	0.448	0.472
20	$\widehat{H}$	3249	3358	3467	3578	3689	3802	3916	4032
(212.4)	$\widehat{U}$	2946	3031	3115	3202	3290	3379	3470	3562
	$\widehat{V}$	0.151	0.163	0.175	0.188	0.200	0.211	0.223	0.235

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Chemical Engineering 140
50 Points (2 multi-part problems)
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Ideal gas constant:

R= 8.314 J mol^{-1} K^{-1}; 8.205x10^{-5} m^3 atm mol^{-1} K^{-1}; 8.314 x 10^{-2} L bar mol^{-1} K^{-1}

Integral Table

$$\int \frac{1}{(x+a)^2}dx = -\frac{1}{x+a}$$

$$\int \frac{1}{a^2+x^2}dx = \frac{1}{a}\tan^{-1}\frac{x}{a}$$

$$\int \frac{x}{a^2+x^2}dx = \frac{1}{2}\ln|a^2+x^2|$$

$$\int \frac{1}{a/x+bx}dx = \frac{1}{2b}ln(a+bx^2)$$

$$\int x^n dx = \frac{1}{n+1}x^{n+1}$$

$$\int \frac{1}{x}dx = \ln|x|$$

$$\int u dv = uv - \int v du$$

$$\int \frac{1}{ax+b}dx = \frac{1}{a}\ln|ax+b|$$

$$\int e^{ax^2}\,\mathrm{d}x = -\frac{i\sqrt{\pi}}{2\sqrt{a}}\mathrm{erf}\left(ix\sqrt{a}\right)$$

$$\int e^{-ax^2}\,\mathrm{d}x = \frac{\sqrt{\pi}}{2\sqrt{a}}\mathrm{erf}\left(x\sqrt{a}\right)$$

$$\int xe^{-ax^2}\,\mathrm{dx} = -\frac{1}{2a}e^{-ax^2}$$

$$\int \ln ax dx = x\ln ax - x$$

$$\int \frac{\ln ax}{x}dx = \frac{1}{2}(\ln ax)^2$$

$$\int \ln(ax+b)dx = \left(x+\frac{b}{a}\right)\ln(ax+b) - x, a \neq 0$$

$$\int \frac{x}{a+bx^2}dx = \frac{1}{2b}ln(a+bx^2)$$

$$\int e^{ax}dx = \frac{1}{a}e^{ax}$$

$$\int \sqrt{x}e^{ax}dx = \frac{1}{a}\sqrt{x}e^{ax} + \frac{i\sqrt{\pi}}{2a^{3/2}}\mathrm{erf}\left(i\sqrt{ax}\right),$$

$$\text{where } \mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt$$

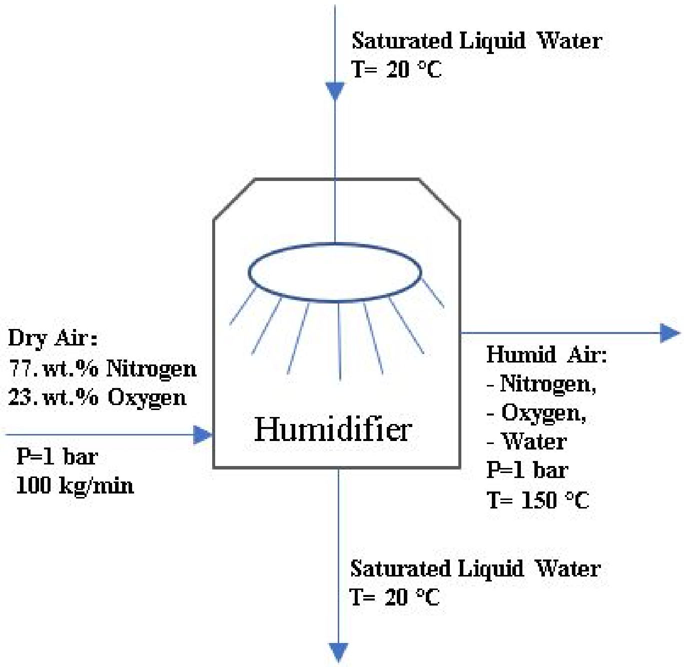
$$\int xe^x dx = (x-1)e^x$$

$$\int xe^{ax}dx = \left(\frac{x}{a} - \frac{1}{a^2}\right)e^{ax}$$

$$\int x^2e^x dx = (x^2 - 2x + 2)\,e^x$$

1. Hot air humidifier [18 pts]

A well-insulated humidifying unit is designed to lower the temperature of hot, dry air by bringing it into direct contact with a stream of liquid water as shown in the diagram below.



The high temperature from the dry air stream evaporates some of the liquid water, resulting in a humid stream of air leaving the unit. The inlet water flow rate is very large such that liquid water exiting the humidifier can be assumed to leave the humidifier at the same temperature (20 °C). Note that given the temperature differences, vapor-liquid equilibrium between liquid and vapor water in the outlet streams is not established. For energy properties of water, please use the steam tables in B.5 of the textbook, or if needed, relevant portions of the steam tables are included in subsequent pages. You can treat the air as an ideal gas.

	Molar Mass	Heat capacity (Cp)
Air (77 wt% N_2, 23 wt% O_2)	28.8 kg/kmol	29 kJ/(kmol * °C)
Water	18 Kg/kmol	---

a. [12 pts] Assume the inlet temperature of dry air is at 300 °C. Calculate the weight fraction of water in the humid air stream using appropriate mass and energy balances.

b. [6 pts] For downstream applications, humid air leaving the unit can only hold a maximum of 2.00 wt% water. Using this information, calculate the maximum temperature in the dry air stream (which still enters the humidifier at 100 kg/min) that can be cooled to 150 °C upon leaving the humidifier.

2. Energy flows in an engine [32 points]

A process is powered by an engine, where energy released by a reversible chemical reaction is converted to usable (i.e., shaft) work by the engine. Not all energy released by the reaction is converted to usable work, such that heat losses to the engine surroundings can also occur. The chemical reaction occurs entirely in the gas phase and is:

$$A + B \leftrightarrow C \qquad [1]$$

The table below provides standard enthalpies of formation and heat capacities for all species in this problem. The following conditions/assumptions are relevant to this problem:

1. Ambient temperature is 35 °C, and the reactants, A and B, enter the engine in separate streams at this temperature. (Note: the engine temperature and exhaust gas temperatures will be hotter than this due to the energy released by the reaction).
2. The engine needs to deliver 30 kW of shaft work to power the process.
3. 1.00 mol/s of pure A is fed to the engine in stream 1.
4. 100% excess B is fed to the engine in stream 2, and B is supplied to the engine in a 50:50 mol:mol mixture of B and an inert species, D. Only A, B, and D are fed to the engine.
5. Assume kinetic and potential energy changes of all species entering and exiting the engine can be neglected, as can any heat generation due to friction of moving parts in the engine.
6. The engine's inlet and exhaust (outlet) stream's pressures can be assumed to be atmospheric pressure (1 bar).
7. A single exhaust stream exits the engine and contains all 4 species: A, B, C, D.

You may find an excel spreadsheet to be useful in completing calculations in a timely fashion. Please state all species, definitions, and energy balances clearly when necessary.

a. [4 points] Draw a diagram of the engine and label all known and unknown species flow rates and temperatures.
b. [8 points] This is a reversible process, and at the engine's operating temperature, the equilibrium constant of reaction 1 is K= 10. If the reaction proceeds to equilibrium, such that the species in the engine exhaust stream are at equilibrium, what is the overall conversion of species A in the engine?
c. [4 points] Calculate the flow rate (in mol/s) of all species entering and exiting the engine.
d. [3 points] Calculate the standard enthalpy of reaction per mol of A for reaction 1.
e. [10 points] The exhaust gas from the engine cannot have a temperature above 150 °C due to corrosion concerns. As a result, engineers design the engine to be largely encased by a cooling jacket, where anti-freeze is pumped into and out of the jacket and circulated through a radiator. Assuming that heat can be transferred from the engine to the anti-freeze flowing through the jacket, how much heat has to be removed (in kW) from the engine to keep the exhaust gas temperature at 150 °C? If you were unable to solve for conversion in part b., assume the conversion of A is 80% (f_A=0.8). Don't forget the shaft work!
f. [3 points] Similarly, corrosion of anti-freeze piping becomes a concern if the anti-freeze reaches a temperature of 80 °C. What is the minimum flowrate of anti-freeze (in kg/s) through the jacket necessary to ensure it never reaches 80 °C if its inlet temperature to the jacket is 35 °C (ambient)?

Compound (phase)	$\hat{H}_f^o$ * [kJ mol^{-1}]	$\hat{C}_p$ *** [kJ mol^{-1} K^{-1}]
A	-250	0.025
B	0	0.025
C	-400	0.3
D	0	0.025
Anti-Freeze	N/A	3.5**

*Values at 1 bar and 25 °C

** in units of kJ kg^{-1} K^{-1}

***Heat capacities are constant with temperature

Table B.5 Properties of Saturated Steam: Temperature Table[a]

		$\widehat{V}(m^3/kg)$		$\widehat{U}(kJ/kg)$		$\widehat{H}(kJ/kg)$		
$T(^\circ C)$	P(bar)	Water	Steam	Water	Steam	Water	Evaporation	Steam
0.01	0.00611	0.001000	206.2	zero	2375.6	+0.0	2501.6	2501.6
2	0.00705	0.001000	179.9	8.4	2378.3	8.4	2496.8	2505.2
4	0.00813	0.001000	157.3	16.8	2381.1	16.8	2492.1	2508.9
6	0.00935	0.001000	137.8	25.2	2383.8	25.2	2487.4	2512.6
8	0.01072	0.001000	121.0	33.6	2386.6	33.6	2482.6	2516.2
10	0.01227	0.001000	106.4	42.0	2389.3	42.0	2477.9	2519.9
12	0.01401	0.001000	93.8	50.4	2392.1	50.4	2473.2	2523.6
14	0.01597	0.001001	82.9	58.8	2394.8	58.8	2468.5	2527.2
16	0.01817	0.001001	73.4	67.1	2397.6	67.1	2463.8	2530.9
18	0.02062	0.001001	65.1	75.5	2400.3	75.5	2459.0	2534.5
20	0.0234	0.001002	57.8	83.9	2403.0	83.9	2454.3	2538.2
22	0.0264	0.001002	51.5	92.2	2405.8	92.2	2449.6	2541.8
24	0.0298	0.001003	45.9	100.6	2408.5	100.6	2444.9	2545.5
25	0.0317	0.001003	43.4	104.8	2409.9	104.8	2442.5	2547.3
26	0.0336	0.001003	41.0	108.9	2411.2	108.9	2440.2	2549.1
28	0.0378	0.001004	36.7	117.3	2414.0	117.3	2435.4	2552.7
30	0.0424	0.001004	32.9	125.7	2416.7	125.7	2430.7	2556.4
32	0.0475	0.001005	29.6	134.0	2419.4	134.0	2425.9	2560.0
34	0.0532	0.001006	26.6	142.4	2422.1	142.4	2421.2	2563.6
36	0.0594	0.001006	24.0	150.7	2424.8	150.7	2416.4	2567.2
38	0.0662	0.001007	21.6	159.1	2427.5	159.1	2411.7	2570.8
40	0.0738	0.001008	19.55	167.4	2430.2	167.5	2406.9	2574.4
42	0.0820	0.001009	17.69	175.8	2432.9	175.8	2402.1	2577.9
44	0.0910	0.001009	16.04	184.2	2435.6	184.2	2397.3	2581.5
46	0.1009	0.001010	14.56	192.5	2438.3	192.5	2392.5	2585.1
48	0.1116	0.001011	13.23	200.9	2440.9	200.9	2387.7	2588.6
50	0.1234	0.001012	12.05	209.2	2443.6	209.3	2382.9	2592.2
52	0.1361	0.001013	10.98	217.7	2446	217.7	2377	2595
54	0.1500	0.001014	10.02	226.0	2449	226.0	2373	2599
56	0.1651	0.001015	9.158	234.4	2451	234.4	2368	2602
58	0.1815	0.001016	8.380	242.8	2454	242.8	2363	2606
60	0.1992	0.001017	7.678	251.1	2456	251.1	2358	2609
62	0.2184	0.001018	7.043	259.5	2459	259.5	2353	2613
64	0.2391	0.001019	6.468	267.9	2461	267.9	2348	2616
66	0.2615	0.001020	5.947	276.2	2464	276.2	2343	2619
68	0.2856	0.001022	5.475	284.6	2467	284.6	2338	2623
70	0.3117	0.001023	5.045	293.0	2469	293.0	2333	2626
72	0.3396	0.001024	4.655	301.4	2472	301.4	2329	2630
74	0.3696	0.001025	4.299	309.8	2474	309.8	2323	2633
76	0.4019	0.001026	3.975	318.2	2476	318.2	2318	2636
78	0.4365	0.001028	3.679	326.4	2479	326.4	2313	2639
80	0.4736	0.001029	3.408	334.8	2482	334.9	2308	2643
82	0.5133	0.001030	3.161	343.2	2484	343.3	2303	2646
84	0.5558	0.001032	2.934	351.6	2487	351.7	2298	2650
86	0.6011	0.001033	2.727	360.0	2489	360.1	2293	2653
88	0.6495	0.001034	2.536	368.4	2491	368.5	2288	2656
90	0.7011	0.001036	2.361	376.9	2493	377.0	2282	2659
92	0.7560	0.001037	2.200	385.3	2496	385.4	2277	2662
94	0.8145	0.001039	2.052	393.7	2499	393.8	2272	2666
96	0.8767	0.001040	1.915	402.1	2501	402.2	2267	2669
98	0.9429	0.001042	1.789	410.6	2504	410.7	2262	2673
100	1.0131	0.001044	1.673	419.0	2507	419.1	2257	2676
102	1.0876	0.001045	1.566	427.1	2509	427.5	2251	2679

$\hat{H}$ and $\hat{U}$ values in kJ/kg, $\hat{V}$ in m^3/kg

Table B.7 Properties of Superheated Steam[a]

P(bar)		**Sat'd**	**Sat'd**	**Temperature (°C)→**							
($T_{sat.}$°C)		**Water**	**Steam**	**50**	**75**	**100**	**150**	**200**	**250**	**300**	**350**
0.0	$\hat{H}$	—	—	2595	2642	2689	2784	2880	2978	3077	3177
(—)	$\hat{U}$	—	—	2446	2481	2517	2589	2662	2736	2812	2890
	$\hat{V}$	—	—	—	—	—	—	—	—	—	—
0.1	$\hat{H}$	191.8	2584.8	2593	2640	2688	2783	2880	2977	3077	3177
(45.8)	$\hat{U}$	191.8	2438.0	2444	2480	2516	2588	2661	2736	2812	2890
	$\hat{V}$	0.00101	14.7	14.8	16.0	17.2	19.5	21.8	24.2	26.5	28.7
0.5	$\hat{H}$	340.6	2646.0	209.3	313.9	2683	2780	2878	2979	3076	3177
(81.3)	$\hat{U}$	340.6	2484.0	209.2	313.9	2512	2586	2660	2735	2811	2889
	$\hat{V}$	0.00103	3.24	0.00101	0.00103	3.41	3.89	4.35	4.83	5.29	5.75
1.0	$\hat{H}$	417.5	2675.4	209.3	314.0	2676	2776	2875	2975	3074	3176
(99.6)	$\hat{U}$	417.5	2506.1	209.2	313.9	2507	2583	2658	2734	2811	2889
	$\hat{V}$	0.00104	1.69	0.00101	0.00103	1.69	1.94	2.17	2.40	2.64	2.87
5.0	$\hat{H}$	640.1	2747.5	209.7	314.3	419.4	632.2	2855	2961	3065	3168
(151.8)	$\hat{U}$	639.6	2560.2	209.2	313.8	418.8	631.6	2643	2724	2803	2883
	$\hat{V}$	0.00109	0.375	0.00101	0.00103	0.00104	0.00109	0.425	0.474	0.522	0.571
10	$\hat{H}$	762.6	2776.2	210.1	314.7	419.7	632.5	2827	2943	3052	3159
(179.9)	$\hat{U}$	761.5	2582	209.1	313.7	418.7	631.4	2621	2710	2794	2876
	$\hat{V}$	0.00113	0.194	0.00101	0.00103	0.00104	0.00109	0.206	0.233	0.258	0.282
20	$\hat{H}$	908.6	2797.2	211.0	315.5	420.5	633.1	852.6	2902	3025	3139
(212.4)	$\hat{U}$	906.2	2598.2	209.0	313.5	418.4	603.9	850.2	2679	2774	2862
	$\hat{V}$	0.00118	0.09950	0.00101	0.00102	0.00104	0.00109	0.00116	0.111	0.125	0.139
40	$\hat{H}$	1087.4	2800.3	212.7	317.1	422.0	634.3	853.4	1085.8	2962	3095
(250.3)	$\hat{U}$	1082.4	2601.3	208.6	313.0	417.8	630.0	848.8	1080.8	2727	2829
	$\hat{V}$	0.00125	0.04975	0.00101	0.00102	0.00104	0.00109	0.00115	0.00125	0.0588	0.0665
60	$\hat{H}$	1213.7	2785.0	214.4	318.7	423.5	635.6	854.2	1085.8	2885	3046
(275.6)	$\hat{U}$	1205.8	2590.4	208.3	312.6	417.3	629.1	847.3	1078.3	2668	2792
	$\hat{V}$	0.00132	0.0325	0.00101	0.00103	0.00104	0.00109	0.00115	0.00125	0.0361	0.0422
80	$\hat{H}$	1317.1	2759.9	216.1	320.3	425.0	636.8	855.1	1085.8	2787	2990
(295.0)	$\hat{U}$	1306.0	2571.7	208.1	312.3	416.7	628.2	845.9	1075.8	2593	2750
	$\hat{V}$	0.00139	0.0235	0.00101	0.00102	0.00104	0.00109	0.00115	0.00124	0.0243	0.0299
100	$\hat{H}$	1408.0	2727.7	217.8	322.9	426.5	638.1	855.9	1085.8	1343.4	2926
(311.0)	$\hat{U}$	1393.5	2547.3	207.8	311.7	416.1	627.3	844.4	1073.4	1329.4	2702
	$\hat{V}$	0.00145	0.0181	0.00101	0.00102	0.00104	0.00109	0.00115	0.00124	0.00140	0.0224
150	$\hat{H}$	1611.0	2615.0	222.1	326.0	430.3	641.3	858.1	1086.2	1338.2	2695
(342.1)	$\hat{U}$	1586.1	2459.9	207.0	310.7	414.7	625.0	841.0	1067.7	1317.6	2523
	$\hat{V}$	0.00166	0.0103	0.00101	0.00102	0.00104	0.00108	0.00114	0.00123	0.00138	0.0115
200	$\hat{H}$	1826.5	2418.4	226.4	330.0	434.0	644.5	860.4	1086.7	1334.3	1647.1
(365.7)	$\hat{U}$	1785.7	2300.8	206.3	309.7	413.2	622.9	837.7	1062.2	1307.1	1613.7
	$\hat{V}$	0.00204	0.005875	0.00100	0.00102	0.00103	0.00108	0.00114	0.00122	0.00136	0.00167
221.2(P_c)	$\hat{H}$	2108	2108	228.2	331.7	435.7	645.8	861.4	1087.0	1332.8	1635.5
(374.15)(T_c)	$\hat{U}$	2037.8	2037.8	206.0	309.2	412.8	622.0	836.3	1060.0	1302.9	1600.3
	$\hat{V}$	0.00317	0.00317	0.00100	0.00102	0.00103	0.00108	0.00114	0.00122	0.00135	0.00163

Superheated Steam table (Con't)
$\widehat{H}$ and $\widehat{U}$ values in kJ/kg, $\widehat{V}$ in m^3/kg

P(bar)		**Temperature (°C)→**							
($T_{sat.}$°C)		**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
0.0	$\widehat{H}$	3280	3384	3497	3597	3706	3816	3929	4043
(—)	$\widehat{U}$	2969	3050	3132	3217	3303	3390	3480	3591
	$\widehat{V}$	—	—	—	—	—	—	—	—
0.1	$\widehat{H}$	3280	3384	3489	3596	3706	3816	3929	4043
(45.8)	$\widehat{U}$	2969	3050	3132	3217	3303	3390	3480	3571
	$\widehat{V}$	21.1	33.3	35.7	38.0	40.3	42.6	44.8	47.2
0.5	$\widehat{H}$	3279	3383	3489	3596	3705	3816	3929	4043
(81.3)	$\widehat{U}$	2969	3049	3132	3216	3302	3390	3480	3571
	$\widehat{V}$	6.21	6.67	7.14	7.58	8.06	8.55	9.01	9.43
1.0	$\widehat{H}$	3278	3382	3488	3596	3705	3816	3928	4042
(99.6)	$\widehat{U}$	2968	3049	3132	3216	3302	3390	3479	3570
	$\widehat{V}$	3.11	3.33	3.57	3.80	4.03	4.26	4.48	4.72
5.0	$\widehat{H}$	3272	3379	3484	3592	3702	3813	3926	4040
(151.8)	$\widehat{U}$	2964	3045	3128	3213	3300	3388	3477	3569
	$\widehat{V}$	0.617	0.664	0.711	0.758	0.804	0.850	0.897	0.943
10	$\widehat{H}$	3264	3371	3478	3587	3697	3809	3923	4038
(179.9)	$\widehat{U}$	2958	3041	3124	3210	3296	3385	3475	3567
	$\widehat{V}$	0.307	0.330	0.353	0.377	0.402	0.424	0.448	0.472
20	$\widehat{H}$	3249	3358	3467	3578	3689	3802	3916	4032
(212.4)	$\widehat{U}$	2946	3031	3115	3202	3290	3379	3470	3562
	$\widehat{V}$	0.151	0.163	0.175	0.188	0.200	0.211	0.223	0.235