



NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY

FACULTY OF ENGINEERING

DEPARTMENT OF CHEMICAL ENGINEERING

CHEMICAL ENGINEERING THERMODYNAMICS 1A

ECE/TCE 2104

Final Examination Paper

December 2024

This examination paper consists of 7 pages

Time Allowed: 3 hours

Total Marks: 100

Special Requirements: Chemical Engineering Thermodynamics Tables

INSTRUCTIONS

1. Answer ALL QUESTIONS in Section A and ANY TWO (2) questions in Section B
2. Each question carries 25 marks
3. Use of calculators is permissible

MARK ALLOCATION

QUESTION	MARKS
A1.	25
A2.	25
B1.	25
B2.	25
B3.	25
TOTAL ATTAINABLE MARKS	100

SECTION A

Answer all questions

QUESTION A1

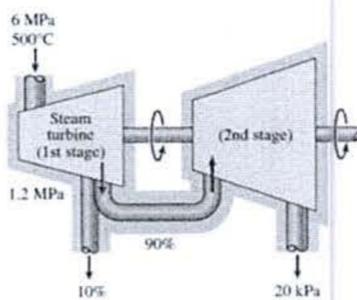
a. A tank containing 20 kg of water at 293.15 K (20°C) is fitted with a stirrer that delivers work to the water at the rate of 0.25 kW. How long does it take for the temperature of the water to rise to 303.15 K (30°C) if no heat is lost from the water? For water, $C_p = 4.18 \text{ kJ kg}^{-1}\text{°C}^{-1}$. [3]

b. Propane gas at 1 bar and 308.15 K (35°C) is compressed to a final state of 135 bar and 468.15 K (195°C). Estimate the molar volume of the propane in the final state and the enthalpy and entropy changes for the process. In its initial state, propane may be assumed an ideal gas. [10]

$$\int_{T_0}^T \frac{C_p}{R} dT = \left[A + \frac{B}{2} T_0(\tau + 1) + \frac{C}{3} T_0^2(\tau^2 + \tau + 1) + \frac{D}{\tau T_0^2} \right] (T - T_0)$$

$$\frac{\Delta S}{R} = \int_{T_0}^T \frac{C_p^{ig}}{R} \frac{dT}{T} = \left[A + \left[B T_0 + \left(C T_0^2 + \frac{D}{\tau^2 T_0^2} \right) \left(\frac{\tau + 1}{2} \right) \right] \left(\frac{\tau - 1}{\ln \tau} \right) \right] \ln \tau$$

c. Steam at 6 MPa and 500°C enters a two-stage adiabatic turbine at a rate of 15 kg/s. 10 percent of the steam is extracted at the end of the first stage at a pressure of 1.2 MPa for other use. The remainder of the steam is further expanded in the second stage and leaves the turbine at 20 kPa. Determine the power output of the turbine, assuming (i) the process is reversible and (ii) the turbine has an isentropic efficiency of 85%. [10]



d. A heat engine that pumps water out of an underground mine accepts 700 kJ of heat and produces 250 kJ of work. How much heat does it reject, in kJ? [2]

QUESTION A2

ai. What are the characteristics of all heat engines? [2]

ii. What is the Kelvin–Planck expression of the second law of thermodynamics? [2]

- iii. Is it possible for a heat engine to operate without rejecting any waste heat to a low-temperature reservoir? Explain. [2]
- iv. What is the difference between a refrigerator and a heat pump? [2]
- v. What is the difference between a refrigerator and an air conditioner? [2]
- b. Determine the COP of a refrigerator that removes heat from the food compartment at a rate of 5040 kJ/h for each kW of power it consumes. Also, determine the rate of heat rejection to the outside air. [5]
- c. A gas-turbine engine with a compression ratio of $P_B/P_A = 6$ operates with air entering the compressor at 298.15 K. if the maximum permissible temperature in the turbine is 1033.15 K, determine:
- i. The efficiency, η of the ideal air cycle for the conditions if $\gamma = 1.14$. [2]
- ii. The thermal efficiency of an air cycle for the given conditions if the compressor and turbine operate adiabatically but irreversibly with efficiencies $\eta_c = 0.83$ and $\eta_t = 0.86$ [8]

$$\eta = 1 - \frac{T_D - T_A}{T_C - T_B} = 1 - \left(\frac{P_A}{P_B}\right)^{(\gamma-1)/\gamma}$$

SECTION B

Answer any 2 questions

QUESTION B1

- a. A 40 kg steel casting of $C_p = 0.5$ kJ/kg at a temperature of 450°C is quenched in 150 kg of oil of $C_p = 2.5$ kJ/kg at 25°C. If there are no heat losses, what is the change in entropy of;
- (i) the casting, (ii) the oil, and (iii) both condensed together? [7]
- b.i. What is throttling? Define the Joule-Thomson Coefficient. [3]
- ii. Given that $\mu = 1.11$ K atm⁻¹ for carbon dioxide, calculate the value of its isothermal Joule-Thomson coefficient. Calculate the energy that must be supplied as heat to maintain constant

temperature when 12 mol of CO_2 flows through a throttle in an isothermal Joule-Thomson experiment and the pressure drop is 55 atm. [5]

c. Steam enters an adiabatic nozzle at 2 MPa and 350°C with a velocity of 55 m/s and exits at 0.8 MPa and 390 m/s. If the nozzle has an inlet area of 7.5 cm^2 , determine

i. the exit temperature and (ii) the rate of entropy generation for this process. [10]

QUESTION B2

a. Steam generated in a power plant at a pressure of 8 600 kPa and a temperature of 773.15 K is fed to a turbine of rated capacity 56 400 kW. Exhaust from the turbine enters a condenser at 10 kPa, where it is condensed to a saturated liquid, which is then pumped into a boiler.

i. What is the thermal efficiency of a Rankine cycle operating at these conditions? [6]

ii. What is the thermal efficiency of a practical cycle operating at these conditions if the turbine efficiency and pump efficiency are both 0.75? [5]

iii. If the rating of the power cycle is 80 000 KW, what is the steam rate, and what are the heat transfer rates in the boiler and condenser? [6]

b. A 1.5 m^3 tank contains 500 kg of liquid water in equilibrium with pure water vapour which fills the remainder of the tank. The temperature and pressure are 373.15 K and 101.33 kPa. From a water line at a constant temperature of 342.15 K and a constant pressure somewhat above 101.33 kPa, 750 kg of liquid is bled into the tank. If the temperature and pressure in the tank are not to change as a result of the process, how much energy as heat must be transferred to the tank? [8]

QUESTION B3

a. Water at 301.15 K flows in a straight horizontal pipe in which there is no exchange of either heat or work with the surroundings. Its velocity is 14 m s^{-1} in a pipe with an internal diameter of 2.5 cm until it flows into a section where the pipe diameter abruptly increases.

i. What is the temperature change of the water if the downstream diameter is 3.8 cm? [5]

ii. If it is 7.5 cm, What is the maximum temperature change for an enlargement in the pipe? [3]

b. Natural gas (which is assumed as pure CH_4) is liquefied in a Claude process. Compression is at 60 bar and precooling is to 300 K. The expander and throttle exhaust to a pressure of 1 bar. Recycle methane at this pressure leaves the exchanger system (point 15, Figure QB2a) at 295 K. Assume no heat leaks into the system from the surroundings, an expander efficiency of 75%, and an expander exhaust of saturated vapour. For a draw-off to the expander of 25% of the methane entering the exchanger system ($x = 0.25$),

i) What fraction, z of CH_4 is liquefied? [8]

ii) What is the temperature of the high pressure stream entering the throttle valve? [9]

The data of CH_4 are given in the Tables at the end of the Question paper.

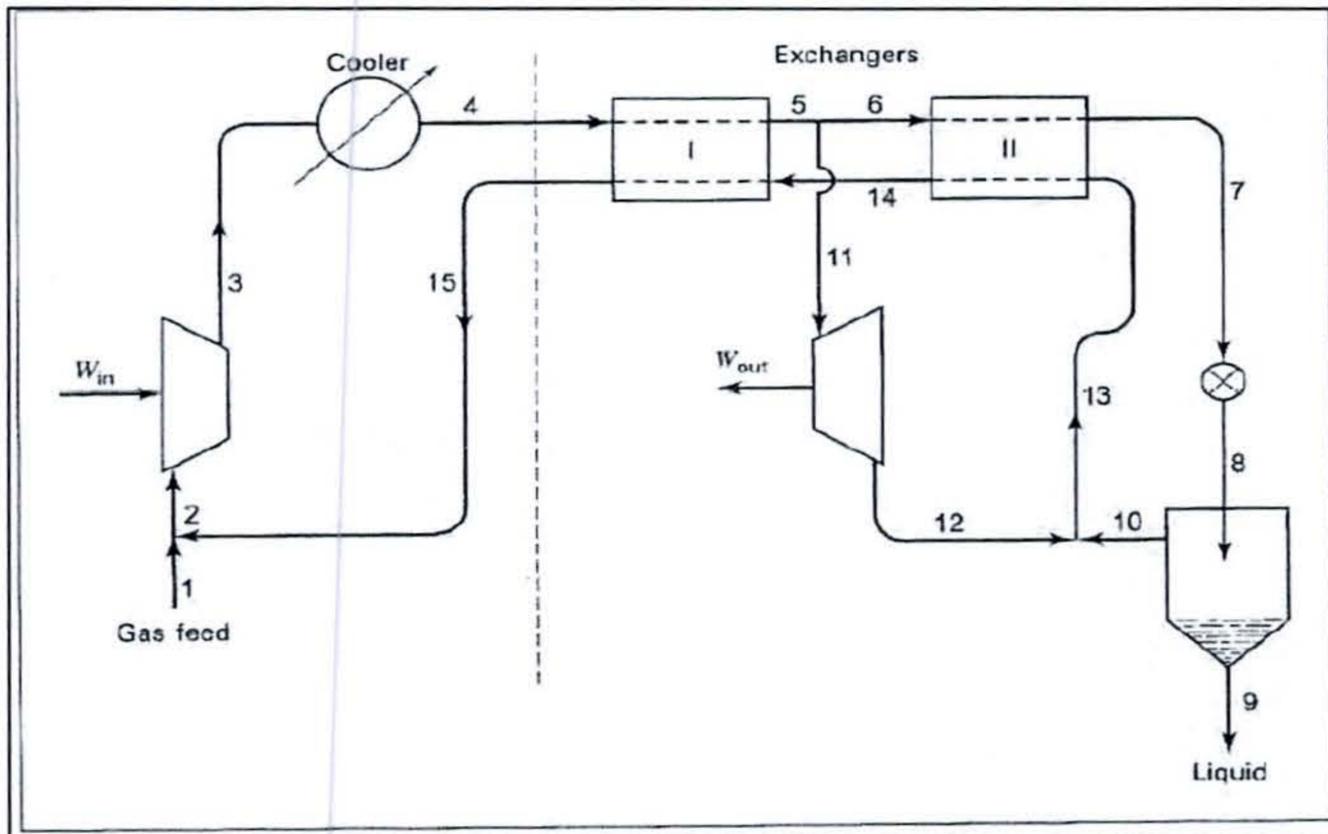


Figure QB2a: Claude liquefaction process

TABLE 2-281 Saturated Methane*

T, K	P, bar	$v_f, \text{m}^3/\text{kg}$	$v_g, \text{m}^3/\text{kg}$	$h_f, \text{kJ}/\text{kg}$	$h_g, \text{kJ}/\text{kg}$	$s_f, \text{kJ}/(\text{kg}\cdot\text{K})$	$s_g, \text{kJ}/(\text{kg}\cdot\text{K})$	$c_{pf}, \text{kJ}/(\text{kg}\cdot\text{K})$	$\mu_f, 10^{-4} \text{ Pa}\cdot\text{s}$	$k_f, \text{W}/(\text{m}\cdot\text{K})$
90.7 ^t	0.117	2.215.-3	3.976	216.4	759.9	4.231	10.225	3.288	2.02	0.225
95	0.198	2.244.-3	2.463	232.5	769.0	4.406	10.034	3.318	1.71	0.215
100	0.345	2.278.-3	1.479	246.3	776.9	4.556	9.862	3.369	1.56	0.206
105	0.565	2.316.-3	0.940	263.2	785.7	4.719	9.710	3.425	1.33	0.197
110	0.884	2.353.-3	0.625	280.1	794.5	4.882	9.558	3.478	1.22	0.189
115	1.325	2.396.-3	0.430	297.7	802.5	5.035	9.436	3.525	1.09	0.181
120	1.919	2.438.-3	0.306	315.3	810.4	5.188	9.314	3.570	0.98	0.173
125	2.693	2.487.-3	0.223	333.5	817.3	5.332	9.062	3.620	0.89	0.165
130	3.681	2.536.-3	0.167	351.7	824.1	5.476	8.810	3.679	0.81	0.158
135	4.912	2.594.-3	0.127	370.6	829.5	5.614	8.871	3.755	0.73	0.150
140	6.422	2.652.-3	0.098	389.5	834.8	5.751	8.932	3.849	0.66	0.143
145	8.246	2.722.-3	0.077	409.5	844.4	5.885	8.891	3.965	0.61	0.136
150	10.41	2.792.-3	0.061	429.4	853.9	6.019	8.849	4.101	0.56	0.129
155	12.97	2.882.-3	0.049	450.8	848.5	6.151	8.725	4.27	0.51	0.122
160	15.94	2.971.-3	0.039	472.1	843.0	6.283	8.601	4.47	0.46	0.115
165	19.39	3.095.-3	0.032	495.4	840.0	6.417	8.513	4.75	0.42	0.108
170	23.81	3.218.-3	0.026	518.6	837.0	6.551	8.424	5.16	0.38	0.101
175	27.81	3.419.-3	0.020	545.8	827.6	6.697	8.315	5.89	0.34	0.094
180	32.86	3.619.-3	0.016	572.9	818.1	6.843	8.205	7.27	0.30	0.088
185	38.59	3.979.-3	0.012	605.4	797.7	7.017	8.049	11.1	0.25	0.085
190	45.20	4.900.-3	0.008	661.6	750.7	7.293	7.762	70.	0.19	0.090
190.6 ^c	45.99	6.233.-3	0.006	704.4	704.4	7.516	7.516	∞	0.17	∞

*Values reproduced or converted from Goodwin, NBS Tech. Note 653, 1974. t = triple point; c = critical point. The notation 2.215.-3 signifies 2.215×10^{-3} .

TABLE 2-282 Superheated Methane*

P, bar	Temperature, K									
	100	150	200	250	300	350	400	450	500	
1	v	0.00228	0.7661	1.0299	1.2915	1.5521	1.8122	2.0719	2.3669	2.5911
	h	246.4	879.0	984.3	1090.4	1199.8	1314.8	1437.4	1568.8	1708.9
	s	4.555	10.152	10.757	11.230	11.629	11.983	12.310	12.618	12.914
5	v	0.00228	0.1434	0.2006	0.2549	0.3083	0.3611	0.4136	0.4657	0.5181
	h	247.0	865.0	976.1	1084.7	1195.5	1311.5	1434.7	1566.6	1706.9
	s	4.553	9.256	9.896	10.381	10.785	11.142	11.471	11.781	12.066
10	v	0.00227	0.0643	0.0968	0.1254	0.1528	0.1798	0.2063	0.2327	0.2590
	h	247.8	843.6	965.5	1077.9	1190.6	1307.9	1432.0	1564.1	1705.3
	s	4.549	8.797	9.501	10.002	10.414	10.775	11.106	11.417	11.715
20	v	0.00227	0.00277	0.0446	0.0606	0.0751	0.0891	0.1027	0.1162	0.1295
	h	249.4	429.8	941.9	1063.6	1180.7	1300.6	1426.5	1560.3	1702.1
	s	4.542	6.003	9.059	9.603	10.030	10.400	10.736	11.050	11.349
40	v	0.00226	0.00274	0.0176	0.0281	0.0363	0.0438	0.0510	0.0579	0.0648
	h	252.5	430.8	879.3	1032.9	1160.5	1286.0	1415.7	1552.1	1696.0
	s	4.528	5.973	8.465	9.155	9.621	10.008	10.354	10.674	10.978
60	v	0.00226	0.00271	0.00615	0.0173	0.0234	0.0287	0.0338	0.0386	0.0432
	h	255.7	432.2	734.0	999.8	1140.0	1271.7	1405.1	1544.2	1690.0
	s	4.515	5.946	7.623	8.847	9.359	9.765	10.121	10.440	10.756
80	v	0.00225	0.00268	0.00411	0.0119	0.0171	0.0213	0.0252	0.0289	0.0324
	h	258.9	433.8	660.5	964.4	1119.7	1257.7	1394.9	1536.6	1684.4
	s	4.502	5.920	7.209	8.590	9.158	9.584	9.951	10.283	10.595
100	v	0.00224	0.00266	0.00375	0.00888	0.0133	0.0169	0.0201	0.0231	0.0260
	h	262.1	435.5	644.5	928.5	1099.6	1244.2	1385.2	1529.4	1679.0
	s	4.489	5.897	7.090	8.364	8.991	9.437	9.814	10.153	10.469
150	v	0.00223	0.00261	0.00337	0.00555	0.00852	0.0111	0.0134	0.0155	0.0175
	h	270.2	440.7	630.2	860.0	1054.1	1213.1	1362.8	1513.0	1667.0
	s	4.458	5.843	6.930	7.953	8.664	9.155	9.555	9.907	10.233
200	v	0.00221	0.00256	0.00318	0.00447	0.00644	0.00837	0.0101	0.0118	0.0133
	h	278.3	446.5	626.5	825.0	1019.8	1187.2	1343.8	1498.9	1656.9
	s	4.429	5.796	6.829	7.719	8.426	8.944	9.362	9.727	10.060
300	v	0.00218	0.00249	0.00296	0.00369	0.00474	0.00593	0.00708	0.00818	0.00924
	h	294.7	459.6	629.2	804.4	982.9	1153.6	1316.8	1478.5	1642.2
	s	4.373	5.714	6.690	7.471	8.122	8.649	9.085	9.465	9.811
400	v		0.00244	0.00282	0.00336	0.00406	0.00486	0.00569	0.00660	0.00729
	h		473.8	637.7	802.4	970.1	1137.8	1303.0	1467.7	1634.7
	s		5.645	6.588	7.323	7.935	8.451	8.893	9.280	9.633
500	v		0.00239	0.00272	0.00315	0.00368	0.00428	0.00492	0.00555	0.00616
	h		488.8	648.9	807.7	969.0	1132.8	1297.8	1464.2	1633.2
	s		5.584	6.507	7.215	7.802	8.307	8.748	9.139	9.496

*Converted and rounded off from the tables of Goodwin, NBS Tech. Note 654, 1974. v = specific volume, m³/kg; h = specific enthalpy, kJ/kg; s = specific entropy, kJ/(kg·K).

For a thermodynamic diagram from 0.1 to 400 bar and 620°C, see the 1993 ASHRAE *Handbook—Fundamentals* (SI ed.). Saturation and superheat tables and a chart to 6000 psia, 680°F appear in Stewart, R. B., R. T. Jacobsen, et al., *Thermodynamic Properties of Refrigerants*, ASHRAE, Atlanta, GA, 1986 (521 pp.). For specific heat, thermal conductivity, and viscosity, see *Thermophysical Properties of Refrigerants*, ASHRAE, 1993. See also Friend, D. G., J. F. Ely, et al., *J. Phys. Chem. Ref. Data*, 18, 2 (1989): 583–638.

(END OF QUESTION PAPER)