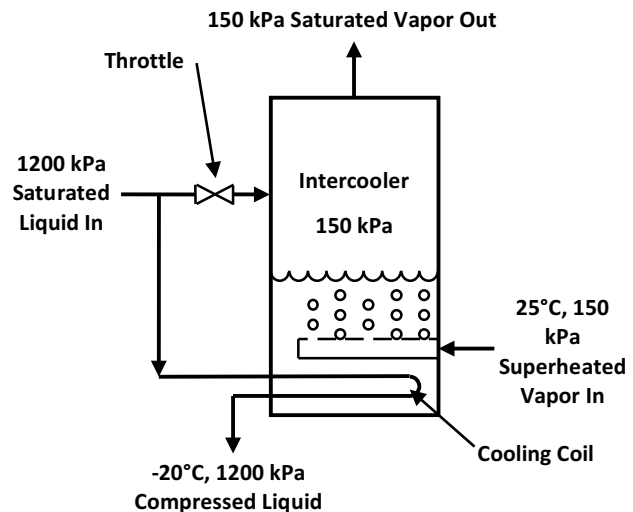

Thermodynamics - 1

The figure below shows the intercooler of a two-stage ammonia refrigeration system. The lower portion of the intercooler is filled with liquid, while the upper portion is filled with vapor. The entire interior of the intercooler is essentially at a uniform pressure, 150 kPa. It operates at steady state.

- Saturated liquid enters at 1200 kPa. Some of the liquid passes through a throttle valve in which it flashes into a two-phase mixture at 150 kPa and enters the intercooler. The remainder of the liquid enters a cooling coil that passes through the liquid-filled portion of the intercooler.
- Superheated vapor at 25°C and 150 kPa enters the intercooler through a perforated pipe so that it bubbles through the liquid in the intercooler.
- Saturated vapor at 150 kPa leaves the intercooler.
- Compressed liquid leaves the cooling coil at -20°C, 1200 kPa.



The mass flow rates of compressed liquid out and superheated vapor in are equal, 1.25 kg/s. The intercooler shell is well insulated.

- (25 points) What is the quality of the flow leaving the throttle, as it enters the intercooler?
- (25 points) What is the heat transfer rate (kW) from the liquid in the cooling coil to the liquid in the intercooler vessel?
- (50 points) What is the mass flow rate of saturated vapor leaving the intercooler?

Tables of ammonia properties are attached.

Suggestion: Draw your control volumes carefully and then do mass and enthalpy balances.

TABLE A-13 Properties of Saturated Ammonia (Liquid–Vapor): Temperature Table

Temp. °C	Press. bar	Specific Volume m ³ /kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		Temp. °C
		Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	
-50	0.4086	1.4245	2.6265	-43.94	1264.99	-43.88	1416.20	1372.32	-0.1922	6.1543	-50
-45	0.5453	1.4367	2.0060	-22.03	1271.19	-21.95	1402.52	1380.57	-0.0951	6.0523	-45
-40	0.7174	1.4493	1.5524	-0.10	1277.20	0.00	1388.56	1388.56	0.0000	5.9557	-40
-36	0.8850	1.4597	1.2757	17.47	1281.87	17.60	1377.17	1394.77	0.0747	5.8819	-36
-32	1.0832	1.4703	1.0561	35.09	1286.41	35.25	1365.55	1400.81	0.1484	5.8111	-32
-30	1.1950	1.4757	0.9634	43.93	1288.63	44.10	1359.65	1403.75	0.1849	5.7767	-30
-28	1.3159	1.4812	0.8803	52.78	1290.82	52.97	1353.68	1406.66	0.2212	5.7430	-28
-26	1.4465	1.4867	0.8056	61.65	1292.97	61.86	1347.65	1409.51	0.2572	5.7100	-26
-22	1.7390	1.4980	0.6780	79.46	1297.18	79.72	1335.36	1415.08	0.3287	5.6457	-22
-20	1.9019	1.5038	0.6233	88.40	1299.23	88.68	1329.10	1417.79	0.3642	5.6144	-20
-18	2.0769	1.5096	0.5739	97.36	1301.25	97.68	1322.77	1420.45	0.3994	5.5837	-18
-16	2.2644	1.5155	0.5291	106.36	1303.23	106.70	1316.35	1423.05	0.4346	5.5536	-16
-14	2.4652	1.5215	0.4885	115.37	1305.17	115.75	1309.86	1425.61	0.4695	5.5239	-14
-12	2.6798	1.5276	0.4516	124.42	1307.08	124.83	1303.28	1428.11	0.5043	5.4948	-12
-10	2.9089	1.5338	0.4180	133.50	1308.95	133.94	1296.61	1430.55	0.5389	5.4662	-10
-8	3.1532	1.5400	0.3874	142.60	1310.78	143.09	1289.86	1432.95	0.5734	5.4380	-8
-6	3.4134	1.5464	0.3595	151.74	1312.57	152.26	1283.02	1435.28	0.6077	5.4103	-6
-4	3.6901	1.5528	0.3340	160.88	1314.32	161.46	1276.10	1437.56	0.6418	5.3831	-4
-2	3.9842	1.5594	0.3106	170.07	1316.04	170.69	1269.08	1439.78	0.6759	5.3562	-2
0	4.2962	1.5660	0.2892	179.29	1317.71	179.96	1261.97	1441.94	0.7097	5.3298	0
2	4.6270	1.5727	0.2695	188.53	1319.34	189.26	1254.77	1444.03	0.7435	5.3038	2
4	4.9773	1.5796	0.2514	197.80	1320.92	198.59	1247.48	1446.07	0.7770	5.2781	4
6	5.3479	1.5866	0.2348	207.10	1322.47	207.95	1240.09	1448.04	0.8105	5.2529	6
8	5.7395	1.5936	0.2195	216.42	1323.96	217.34	1232.61	1449.94	0.8438	5.2279	8
10	6.1529	1.6008	0.2054	225.77	1325.42	226.75	1225.03	1451.78	0.8769	5.2033	10
12	6.5890	1.6081	0.1923	235.14	1326.82	236.20	1217.35	1453.55	0.9099	5.1791	12
16	7.5324	1.6231	0.1691	253.95	1329.48	255.18	1201.70	1456.87	0.9755	5.1314	16
20	8.5762	1.6386	0.1492	272.86	1331.94	274.26	1185.64	1459.90	1.0404	5.0849	20
24	9.7274	1.6547	0.1320	291.84	1334.19	293.45	1169.16	1462.61	1.1048	5.0394	24
28	10.993	1.6714	0.1172	310.92	1336.20	312.75	1152.24	1465.00	1.1686	4.9948	28
32	12.380	1.6887	0.1043	330.07	1337.97	332.17	1134.87	1467.03	1.2319	4.9509	32
36	13.896	1.7068	0.0930	349.32	1339.47	351.69	1117.00	1468.70	1.2946	4.9078	36
40	15.549	1.7256	0.0831	368.67	1340.70	371.35	1098.62	1469.97	1.3569	4.8652	40
45	17.819	1.7503	0.0725	393.01	1341.81	396.13	1074.84	1470.96	1.4341	4.8125	45
50	20.331	1.7765	0.0634	417.56	1342.42	421.17	1050.09	1471.26	1.5109	4.7604	50

Source: Tables A-13 through A-15 are calculated based on equations from L. Haar and J. S. Gallagher, "Thermodynamic Properties of Ammonia," *J. Phys. Chem. Reference Data*, Vol. 7, 1978, pp. 635–792.

TABLE A-14 Properties of Saturated Ammonia (Liquid–Vapor): Pressure Table

Press. bar	Temp. °C	Specific Volume m ³ /kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		Press. bar
		Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	
0.40	-50.36	1.4236	2.6795	-45.52	1264.54	-45.46	1417.18	1371.72	-0.1992	6.1618	0.40
0.50	-46.53	1.4330	2.1752	-28.73	1269.31	-28.66	1406.73	1378.07	-0.1245	6.0829	0.50
0.60	-43.28	1.4410	1.8345	-14.51	1273.27	-14.42	1397.76	1383.34	-0.0622	6.0186	0.60
0.70	-40.46	1.4482	1.5884	-2.11	1276.66	-2.01	1389.85	1387.84	-0.0086	5.9643	0.70
0.80	-37.94	1.4546	1.4020	8.93	1279.61	9.04	1382.73	1391.78	0.0386	5.9174	0.80
0.90	-35.67	1.4605	1.2559	18.91	1282.24	19.04	1376.23	1395.27	0.0808	5.8760	0.90
1.00	-33.60	1.4660	1.1381	28.03	1284.61	28.18	1370.23	1398.41	0.1191	5.8391	1.00
1.25	-29.07	1.4782	0.9237	48.03	1289.65	48.22	1356.89	1405.11	0.2018	5.7610	1.25
1.50	-25.22	1.4889	0.7787	65.10	1293.80	65.32	1345.28	1410.61	0.2712	5.6973	1.50
1.75	-21.86	1.4984	0.6740	80.08	1297.33	80.35	1334.92	1415.27	0.3312	5.6435	1.75
2.00	-18.86	1.5071	0.5946	93.50	1300.39	93.80	1325.51	1419.31	0.3843	5.5969	2.00
2.25	-16.15	1.5151	0.5323	105.68	1303.08	106.03	1316.83	1422.86	0.4319	5.5558	2.25
2.50	-13.67	1.5225	0.4821	116.88	1305.49	117.26	1308.76	1426.03	0.4753	5.5190	2.50
2.75	-11.37	1.5295	0.4408	127.26	1307.67	127.68	1301.20	1428.88	0.5152	5.4858	2.75
3.00	-9.24	1.5361	0.4061	136.96	1309.65	137.42	1294.05	1431.47	0.5520	5.4554	3.00
3.25	-7.24	1.5424	0.3765	146.06	1311.46	146.57	1287.27	1433.84	0.5864	5.4275	3.25
3.50	-5.36	1.5484	0.3511	154.66	1313.14	155.20	1280.81	1436.01	0.6186	5.4016	3.50
3.75	-3.58	1.5542	0.3289	162.80	1314.68	163.38	1274.64	1438.03	0.6489	5.3774	3.75
4.00	-1.90	1.5597	0.3094	170.55	1316.12	171.18	1268.71	1439.89	0.6776	5.3548	4.00
4.25	-0.29	1.5650	0.2921	177.96	1317.47	178.62	1263.01	1441.63	0.7048	5.3336	4.25
4.50	1.25	1.5702	0.2767	185.04	1318.73	185.75	1257.50	1443.25	0.7308	5.3135	4.50
4.75	2.72	1.5752	0.2629	191.84	1319.91	192.59	1252.18	1444.77	0.7555	5.2946	4.75
5.00	4.13	1.5800	0.2503	198.39	1321.02	199.18	1247.02	1446.19	0.7791	5.2765	5.00
5.25	5.48	1.5847	0.2390	204.69	1322.07	205.52	1242.01	1447.53	0.8018	5.2594	5.25
5.50	6.79	1.5893	0.2286	210.78	1323.06	211.65	1237.15	1448.80	0.8236	5.2430	5.50
5.75	8.05	1.5938	0.2191	216.66	1324.00	217.58	1232.41	1449.99	0.8446	5.2273	5.75
6.00	9.27	1.5982	0.2104	222.37	1324.89	223.32	1227.79	1451.12	0.8649	5.2122	6.00
7.00	13.79	1.6148	0.1815	243.56	1328.04	244.69	1210.38	1455.07	0.9394	5.1576	7.00
8.00	17.84	1.6302	0.1596	262.64	1330.64	263.95	1194.36	1458.30	1.0054	5.1099	8.00
9.00	21.52	1.6446	0.1424	280.05	1332.82	281.53	1179.44	1460.97	1.0649	5.0675	9.00
10.00	24.89	1.6584	0.1285	296.10	1334.66	297.76	1165.42	1463.18	1.1191	5.0294	10.00
12.00	30.94	1.6841	0.1075	324.99	1337.52	327.01	1139.52	1466.53	1.2152	4.9625	12.00
14.00	36.26	1.7080	0.0923	350.58	1339.56	352.97	1115.82	1468.79	1.2987	4.9050	14.00
16.00	41.03	1.7306	0.0808	373.69	1340.97	376.46	1093.77	1470.23	1.3729	4.8542	16.00
18.00	45.38	1.7522	0.0717	394.85	1341.88	398.00	1073.01	1471.01	1.4399	4.8086	18.00
20.00	49.37	1.7731	0.0644	414.44	1342.37	417.99	1053.27	1471.26	1.5012	4.7670	20.00

TABLE A-15 Properties of Superheated Ammonia Vapor

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K
$p = 0.4 \text{ bar} = 0.04 \text{ MPa}$ ($T_{\text{sat}} = -50.36^\circ\text{C}$)				$p = 0.6 \text{ bar} = 0.06 \text{ MPa}$ ($T_{\text{sat}} = -43.28^\circ\text{C}$)				
Sat.	2.6795	1264.54	1371.72	6.1618	1.8345	1273.27	1383.34	6.0186
-50	2.6841	1265.11	1372.48	6.1652				
-45	2.7481	1273.05	1382.98	6.2118				
-40	2.8118	1281.01	1393.48	6.2573	1.8630	1278.62	1390.40	6.0490
-35	2.8753	1288.96	1403.98	6.3018	1.9061	1286.75	1401.12	6.0946
-30	2.9385	1296.93	1414.47	6.3455	1.9491	1294.88	1411.83	6.1390
-25	3.0015	1304.90	1424.96	6.3882	1.9918	1303.01	1422.52	6.1826
-20	3.0644	1312.88	1435.46	6.4300	2.0343	1311.13	1433.19	6.2251
-15	3.1271	1320.87	1445.95	6.4711	2.0766	1319.25	1443.85	6.2668
-10	3.1896	1328.87	1456.45	6.5114	2.1188	1327.37	1454.50	6.3077
-5	3.2520	1336.88	1466.95	6.5509	2.1609	1335.49	1465.14	6.3478
0	3.3142	1344.90	1477.47	6.5898	2.2028	1343.61	1475.78	6.3871
5	3.3764	1352.95	1488.00	6.6280	2.2446	1351.75	1486.43	6.4257
$p = 0.8 \text{ bar} = 0.08 \text{ MPa}$ ($T_{\text{sat}} = -37.94^\circ\text{C}$)				$p = 1.0 \text{ bar} = 0.10 \text{ MPa}$ ($T_{\text{sat}} = -33.60^\circ\text{C}$)				
Sat.	1.4021	1279.61	1391.78	5.9174	1.1381	1284.61	1398.41	5.8391
-35	1.4215	1284.51	1398.23	5.9446				
-30	1.4543	1292.81	1409.15	5.9900	1.1573	1290.71	1406.44	5.8723
-25	1.4868	1301.09	1420.04	6.0343	1.1838	1299.15	1417.53	5.9175
-20	1.5192	1309.36	1430.90	6.0777	1.2101	1307.57	1428.58	5.9616
-15	1.5514	1317.61	1441.72	6.1200	1.2362	1315.96	1439.58	6.0046
-10	1.5834	1325.85	1452.53	6.1615	1.2621	1324.33	1450.54	6.0467
-5	1.6153	1334.09	1463.31	6.2021	1.2880	1332.67	1461.47	6.0878
0	1.6471	1342.31	1474.08	6.2419	1.3136	1341.00	1472.37	6.1281
5	1.6788	1350.54	1484.84	6.2809	1.3392	1349.33	1483.25	6.1676
10	1.7103	1358.77	1495.60	6.3192	1.3647	1357.64	1494.11	6.2063
15	1.7418	1367.01	1506.35	6.3568	1.3900	1365.95	1504.96	6.2442
20	1.7732	1375.25	1517.10	6.3939	1.4153	1374.27	1515.80	6.2816
$p = 1.5 \text{ bar} = 0.15 \text{ MPa}$ ($T_{\text{sat}} = -25.22^\circ\text{C}$)				$p = 2.0 \text{ bar} = 0.20 \text{ MPa}$ ($T_{\text{sat}} = -18.86^\circ\text{C}$)				
Sat.	0.7787	1293.80	1410.61	5.6973	0.59460	1300.39	1419.31	5.5969
-25	0.7795	1294.20	1411.13	5.6994				
-20	0.7978	1303.00	1422.67	5.7454				
-15	0.8158	1311.75	1434.12	5.7902	0.60542	1307.43	1428.51	5.6328
-10	0.8336	1320.44	1445.49	5.8338	0.61926	1316.46	1440.31	5.6781
-5	0.8514	1329.08	1456.79	5.8764	0.63294	1325.41	1452.00	5.7221
0	0.8689	1337.68	1468.02	5.9179	0.64648	1334.29	1463.59	5.7649
5	0.8864	1346.25	1479.20	5.9585	0.65989	1343.11	1475.09	5.8066
10	0.9037	1354.78	1490.34	5.9981	0.67320	1351.87	1486.51	5.8473
15	0.9210	1363.29	1501.44	6.0370	0.68640	1360.59	1497.87	5.8871
20	0.9382	1371.79	1512.51	6.0751	0.69952	1369.28	1509.18	5.9260
25	0.9553	1380.28	1523.56	6.1125	0.71256	1377.93	1520.44	5.9641
30	0.9723	1388.76	1534.60	6.1492	0.72553	1386.56	1531.67	6.0014