Cryogenics (Final Exam)

M2794.008500 Dec. 16, 2019

1. Please determine the number of theoretical plates required to yield 95% of liquid nitrogen as the top product stream and 95% of liquid oxygen (5% nitrogen) as the bottom product stream in a rectification column under the following conditions.

    (1) 50:50 of nitrogen and oxygen feed stream composition (by mole fraction) in the saturated liquid state.

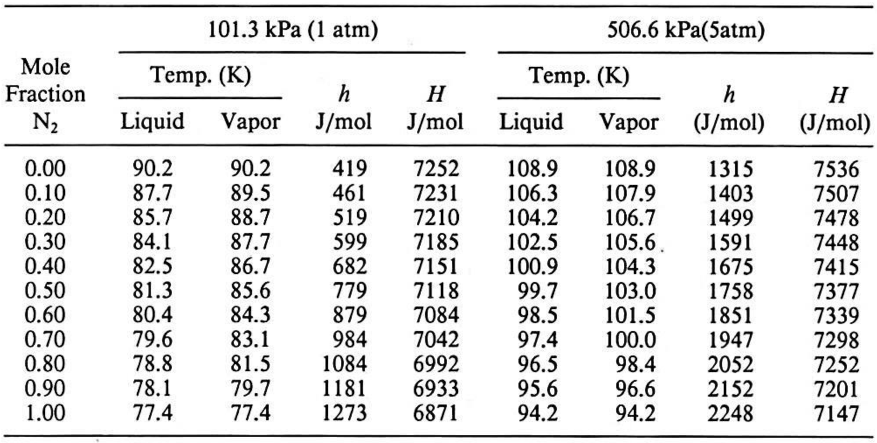
    (2) Top product flow rate is 70 mole/s.

    (3) The pressure inside the rectification column is 101.3 kPa.

    (4) The heat of 900 kW is supplied in the boiler.

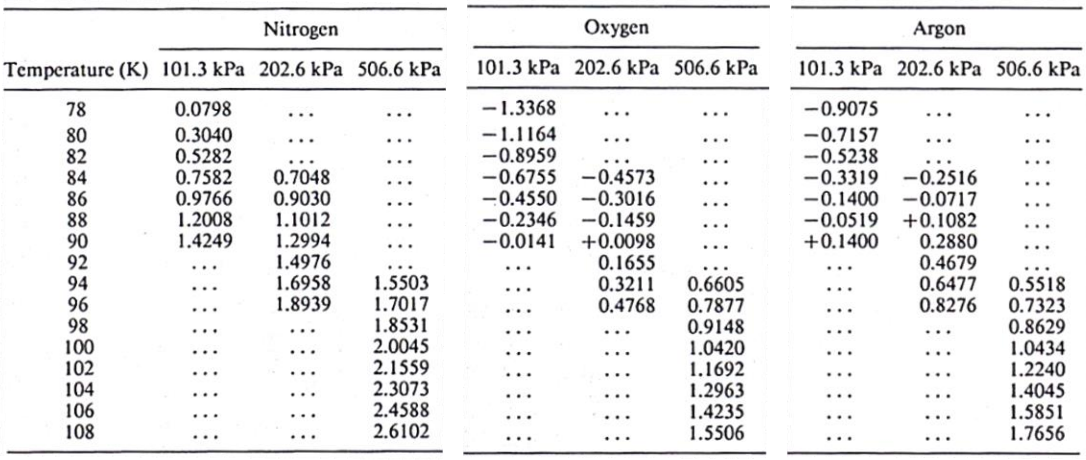
    You may also need the tables below for your reference.

Table 1. Enthalpy of nitrogen-oxygen mixtures. *h* = enthalpy of the saturated liquid at the bubble point; *H* = enthalpy of the saturated vapor at the dew point.



Mole Fraction N_2	101.3 kPa (1 atm) Temp. (K) Liquid	Vapor	*h* J/mol	*H* J/mol	506.6 kPa(5atm) Temp. (K) Liquid	Vapor	*h* (J/mol)	*H* (J/mol)
0.00	90.2	90.2	419	7252	108.9	108.9	1315	7536
0.10	87.7	89.5	461	7231	106.3	107.9	1403	7507
0.20	85.7	88.7	519	7210	104.2	106.7	1499	7478
0.30	84.1	87.7	599	7185	102.5	105.6	1591	7448
0.40	82.5	86.7	682	7151	100.9	104.3	1675	7415
0.50	81.3	85.6	779	7118	99.7	103.0	1758	7377
0.60	80.4	84.3	879	7084	98.5	101.5	1851	7339
0.70	79.6	83.1	984	7042	97.4	100.0	1947	7298
0.80	78.8	81.5	1084	6992	96.5	98.4	2052	7252
0.90	78.1	79.7	1181	6933	95.6	96.6	2152	7201
1.00	77.4	77.4	1273	6871	94.2	94.2	2248	7147

Table 2. Distribution coefficient function, $\ln(Kp/p_0)$, for nitrogen, oxygen, and argon. The value of the reference pressure is $p_0 = 101.3\,\text{kPa}\,(1\,\text{atm})$. Here, the distribution coefficient K (sometimes called the equilibrium ratio) is defined by $K_j = y_j/x_j$ where x and y is the mole fractions in the liquid and vapor phase of j component, respectively.



	Nitrogen			Oxygen			Argon		
Temperature (K)	101.3 kPa	202.6 kPa	506.6 kPa	101.3 kPa	202.6 kPa	506.6 kPa	101.3 kPa	202.6 kPa	506.6 kPa
78	0.0798	...	...	−1.3368	...	...	−0.9075	...	...
80	0.3040	...	...	−1.1164	...	...	−0.7157	...	...
82	0.5282	...	...	−0.8959	...	...	−0.5238	...	...
84	0.7582	0.7048	...	−0.6755	−0.4573	...	−0.3319	−0.2516	...
86	0.9766	0.9030	...	−0.4550	−0.3016	...	−0.1400	−0.0717	...
88	1.2008	1.1012	...	−0.2346	−0.1459	...	−0.0519	+0.1082	...
90	1.4249	1.2994	...	−0.0141	+0.0098	...	+0.1400	0.2880	...
92	...	1.4976	...	...	0.1655	...	...	0.4679	...
94	...	1.6958	1.5503	...	0.3211	0.6605	...	0.6477	0.5518
96	...	1.8939	1.7017	...	0.4768	0.7877	...	0.8276	0.7323
98	...	...	1.8531	...	...	0.9148	...	...	0.8629
100	...	...	2.0045	...	...	1.0420	...	...	1.0434
102	...	...	2.1559	...	...	1.1692	...	...	1.2240
104	...	...	2.3073	...	...	1.2963	...	...	1.4045
106	...	...	2.4588	...	...	1.4235	...	...	1.5851
108	...	...	2.6102	...	...	1.5506	...	...	1.7656

2. In an actual air separation system, not only nitrogen and oxygen but also around 0.93% of argon is included in the feed air. It is known that this argon, in the feed, has adverse impact on the purification of the oxygen and nitrogen from the system. For example, it is practically impossible to attain oxygen product greater than 95% purification by volume from the air-separation. Therefore, argon-separation system is demanded in a field of air separation.

   The argon-separation system usually consists of two basic parts; (a) a recovery subsystem, and (b) the (argon) purification subsystem. When the recovery subsystem (a) is installed with an air-separation system as follows, please describe the operation of the whole system referring the number of lines.

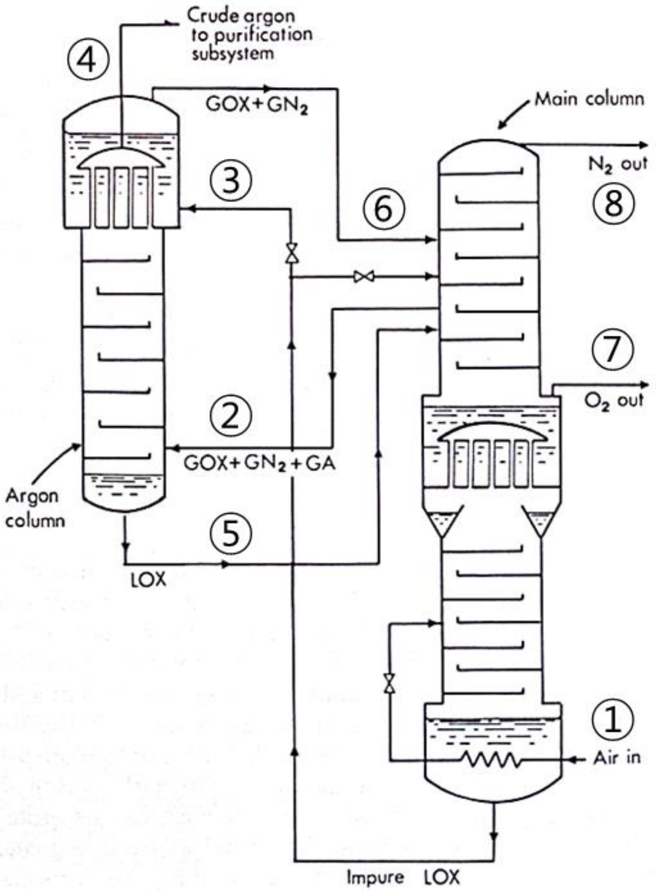


Fig. 1. Argon recovery subsystem. The $\mathrm{Ar}-\mathrm{O}_2-\mathrm{N}_2$ mixture is withdrawn from the upper column at the point at which the argon concentration is the largest.

3. The ideal Philips refrigerator using helium 4 as a working fluid operates on the Stirling cycle for use in a hot-air engine. When ambient temperature is 60 K, heat source temperature is 40 K, initial density is 0.1 $\mathrm{mole/L}$, and the final density is 2 $\mathrm{mole/L}$ under the compression, please answer the questions below.

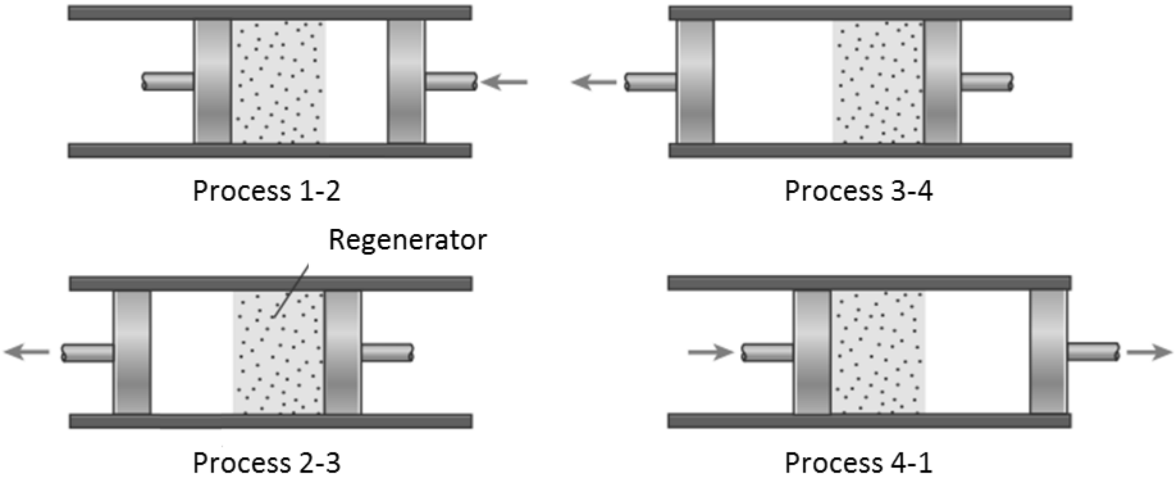


Fig. 2. Philips refrigerator schematic.

(1) Plot the temperature-entropy diagram of the ideal Philips refrigeration cycle suggested.

(2) Determine the specific heat absorbed (J/mole), work requirement (J/mole) and coefficient of performance (COP).

(3) Describe the expected performance change when the processes are not ideal, and the regenerator effectiveness is below unity.

4. A schematic of the Gifford-McMahon refrigerator is shown below. This system consists of a compressor, a cylinder closed at both ends, a displacer within the cylinder, and a regenerator. The displacer takes a role of moving the gas from one expansion space to another. Please answer the following questions on the Gifford-McMahon refrigerator.

   (1) Explain an advantage of the Gifford-McMahon refrigerator over the Solvay refrigerator.

   (2) Plot the temperature-entropy diagram of the ideal Gifford-McMahon refrigeration cycle of the system below.

   (3) Please mention the change on the system when the effectiveness of the regenerator is less than unity.

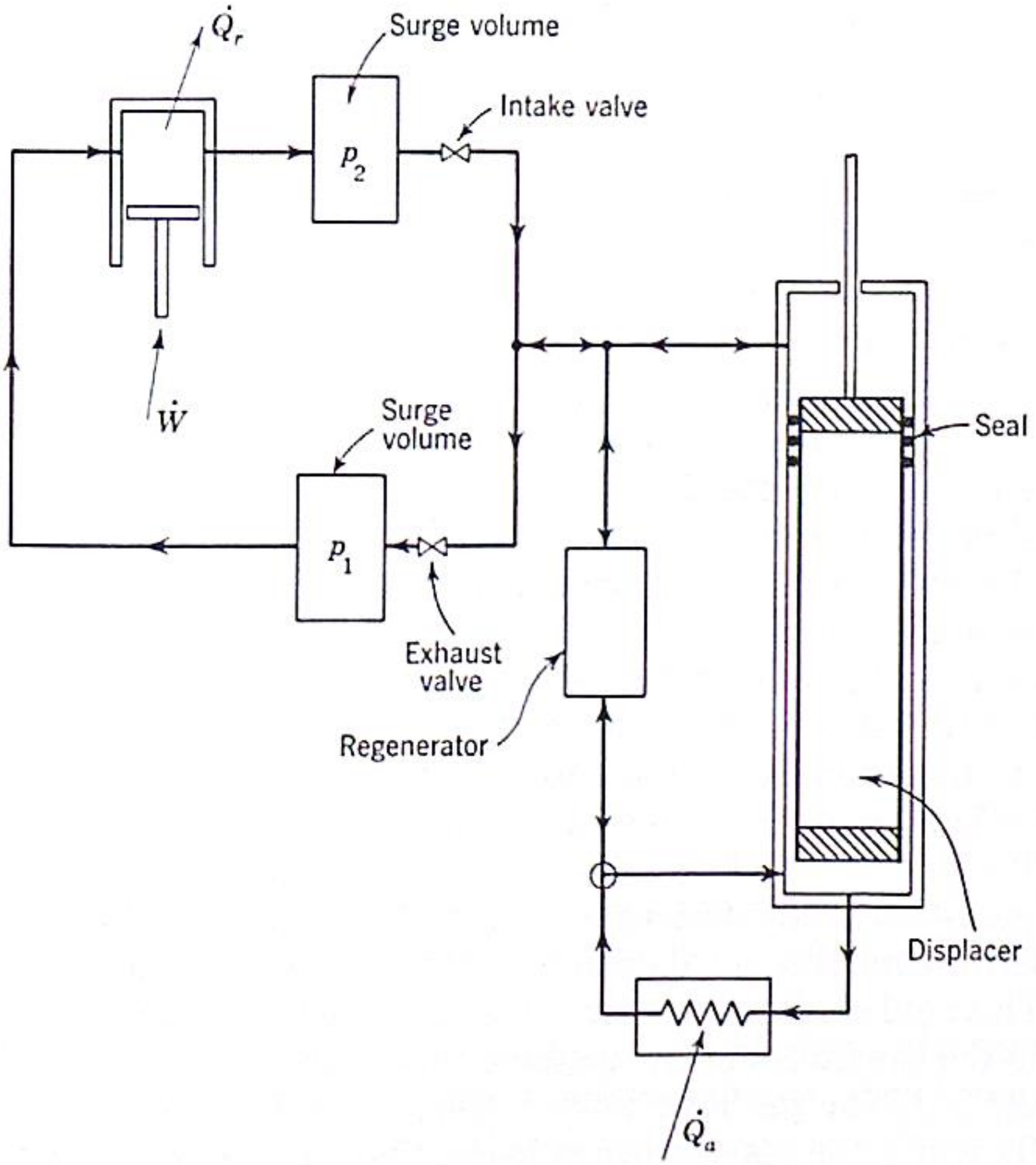


Fig. 3. Gifford-McMahon refrigerator schematic.

5. Thermodynamic liquid-level probes are based on the principle that a liquid undergoes a large change in volume when it is evaporated. A schematic of one of the thermodynamic liquid-level gauges is shown below. This gauge consists of a thin capillary tube that is slightly heated by electric current, dead volume connected to the capillary tube, the same gas as the fluid in the bath which fills up the tube and the dead volume, and a pressure gauge which indicates the pressure inside the liquid-level gauge.

   Please describe the principle of the thermodynamic liquid-level gauge in terms of the volume change in the capillary tube and the dead volume.

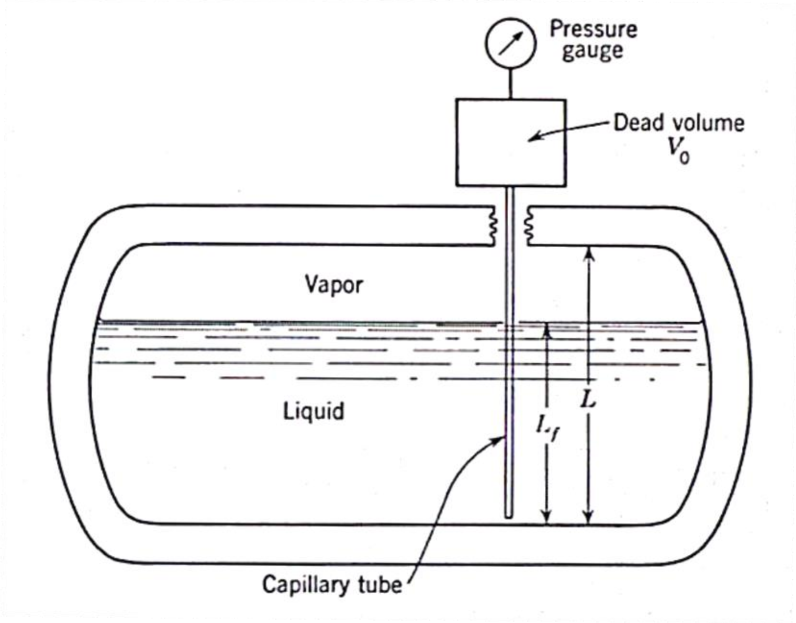


Fig. 4. Thermodynamic liquid-level gauge.

6. Suppose you transfer liquid nitrogen into small Dewar from a supply tank as shown below. In a circumstance that you also have another compressed nitrogen gas, please describe how to accomplish moving the liquid nitrogen in a safe way. Please draw the tube connection with your explanation as well.

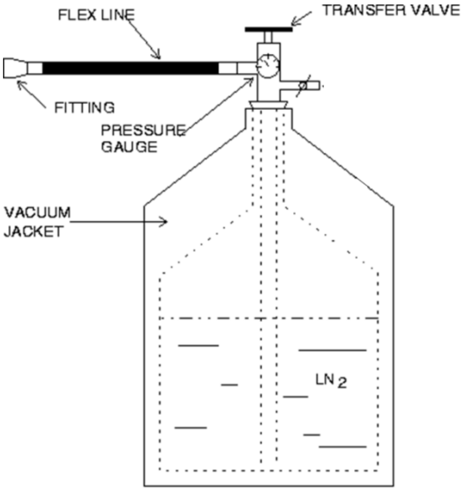


Fig. 5 Liquid nitrogen supply tank

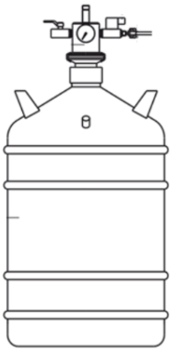


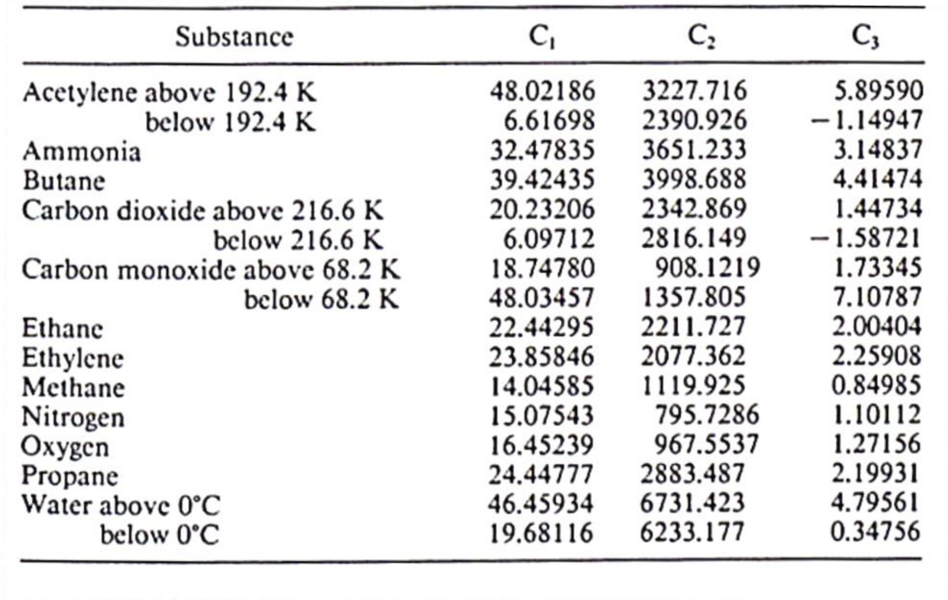
Fig. 6 Liquid nitrogen Dewar

Fig. 7 Compressed nitrogen gas

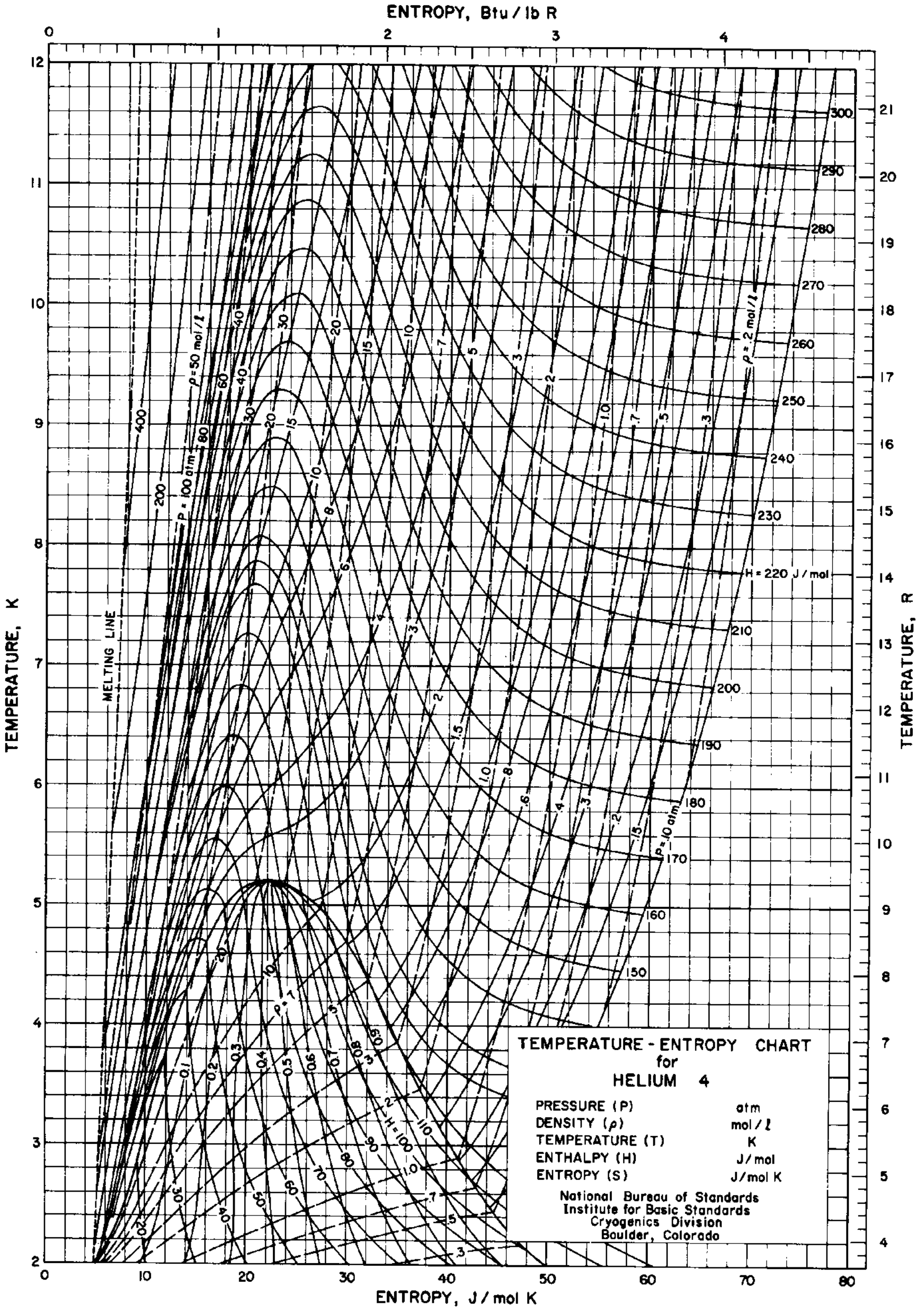
7. Please draw a proper schematic diagram of a vacuum system to reach the pressure level of 0.10 to 0.01 mPa (10^{-6} to 10^{-7} torr) in a vessel using a mechanical vacuum pump and a diffusion pump and explain the operation of your vacuum system. You also need to apply liquid-nitrogen-cooled cold trap in your system.

8. Impure nitrogen gas having a composition of 95% of nitrogen, 5% of carbon dioxide enters a refrigeration purifier at 300K and atmospheric pressure (101.325 kPa). Assuming all the gases obey the ideal-gas equation of state, determine the partial pressure of carbon dioxide in the gas leaving the purifier. The exit temperature of the gas is 150 K and the exit pressure is 101.325 kPa. You may need the table below.

Table 2. Constants for the vapor-pressure equation, $\ln(p/p_0) = C_1 - C_2/T - C_3 \ln T$ where p_0 = 101.325 kPa and T is expressed in Kelvin



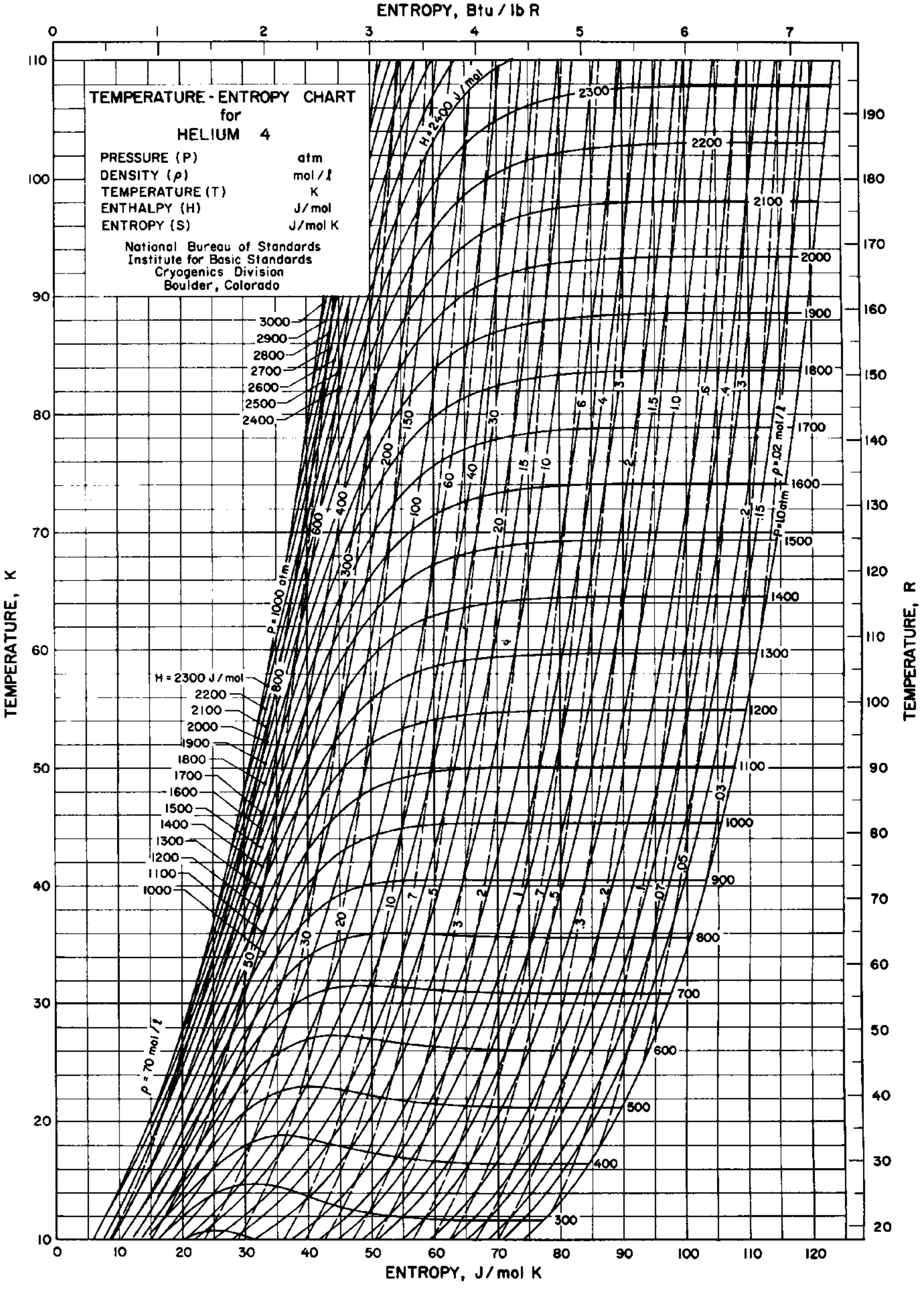
Substance	C_1	C_2	C_3
Acetylene above 192.4 K	48.02186	3227.716	5.89590
below 192.4 K	6.61698	2390.926	−1.14947
Ammonia	32.47835	3651.233	3.14837
Butane	39.42435	3998.688	4.41474
Carbon dioxide above 216.6 K	20.23206	2342.869	1.44734
below 216.6 K	6.09712	2816.149	−1.58721
Carbon monoxide above 68.2 K	18.74780	908.1219	1.73345
below 68.2 K	48.03457	1357.805	7.10787
Ethane	22.44295	2211.727	2.00404
Ethylene	23.85846	2077.362	2.25908
Methane	14.04585	1119.925	0.84985
Nitrogen	15.07543	795.7286	1.10112
Oxygen	16.45239	967.5537	1.27156
Propane	24.44777	2883.487	2.19931
Water above 0°C	46.45934	6731.423	4.79561
below 0°C	19.68116	6233.177	0.34756



TEMPERATURE - ENTROPY CHART
for
HELIUM 4

PRESSURE (P)	atm
DENSITY (ρ)	mol / ℓ
TEMPERATURE (T)	K
ENTHALPY (H)	J/mol
ENTROPY (S)	J/mol K

National Bureau of Standards
Institute for Basic Standards
Cryogenics Division
Boulder, Colorado


TEMPERATURE - ENTROPY CHART
for
HELIUM 4
PRESSURE (P) atm
DENSITY (ρ) mol / ℓ
TEMPERATURE (T) K
ENTHALPY (H) J/mol
ENTROPY (S) J/mol K
National Bureau of Standards
Institute for Basic Standards
Cryogenics Division
Boulder, Colorado
ENTROPY, Btu / lb R
0
1
2
3
4
5
6
7
ENTROPY, J/mol K
0
10
20
30
40
50
60
70
80
90
100
110
120
TEMPERATURE, K
10
20
30
40
50
60
70
80
90
100
110
TEMPERATURE, R
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190
H = 2400 J/mol
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2800
2700
2600
2500
2400
H = 2300 J / mol
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
P = 1000 atm
800
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15
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2
1.5
1.0
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.4
.3
.2
.15
.1
P = 1.0 atm
ρ = 70 mol / ℓ
50
30
20
10
7
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3
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1
.7
.5
.3
.2
.1
.07
.05
.03
ρ = .02 mol / ℓ