Low Temperature Refrigeration

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ME 415: Refrigeration & Building Mechanical Systems

Critical Temperatures & Pressures for Common Substances

Substance	Critical temperature T_c°C [K]	Critical pressure, p_c (bar)
Water (H_2O)	374 [647]	221.2
Methane (CH_4)	−82 [191]	46.4
Ethane (C_2H_6)	32 [305]	49.4
Propane (C_3H_8)	96 [369]	43.6
Butane (C_4H_{10})	153 [426]	36.5
Carbon dioxide (CO_2)	31 [304]	89
Oxygen (O_2)	−130 [143]	51
Hydrogen (H_2)	−243 [30]	13
Nitrogen (N_2)	−147 [126]	34

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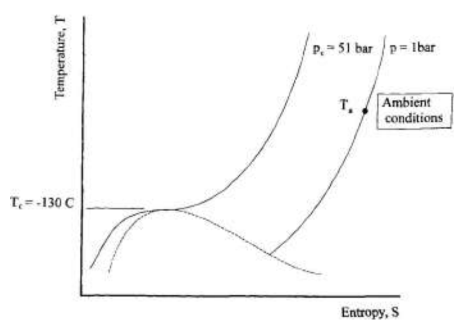
If the temperature and pressure of a gas can be brought into the region between the saturated liquid and saturated vapour lines then the gas will become 'wet' and this 'wetness' will condense giving a liquid.

Liquefaction by Cooling

This method is satisfactory if the liquefaction process does not require very low temperatures. Example butane, propane, Examples of these are the hydrocarbons butane and propane, which can both exist as liquids at room temperature if they are contained at elevated pressures. Mixtures of hydrocarbons can also be obtained as liquids and these include liquefied petroleum gas (LPG) and liquefied natural gas (LNG).



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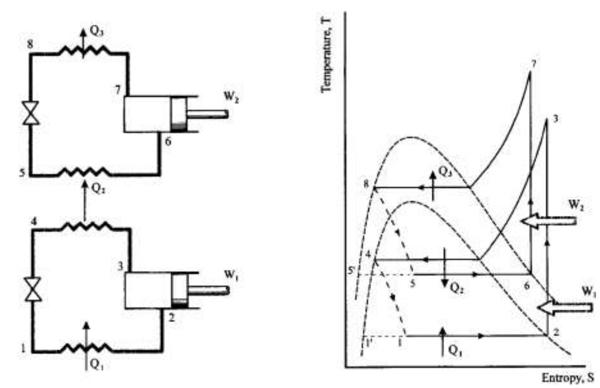
Cascade Refrigeration Systems



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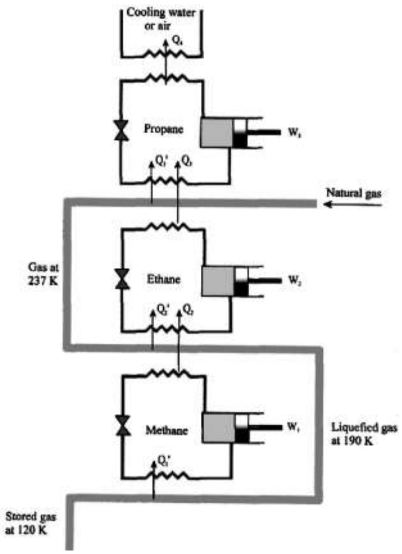
Conventional single compressor, mechanical refrigeration systems are capable of achieving temperatures of about -40°C. A two-state cascade system uses two refrigeration systems connected in series to achieve temperatures of around -85°C.

Liquefaction of Natural Gas by Cascade Refrigeration



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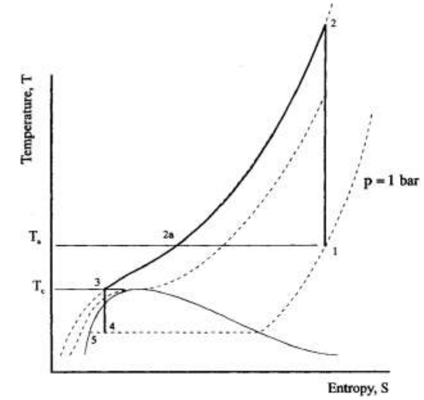
Liquefaction by Expansion



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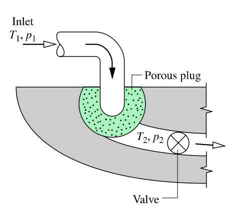
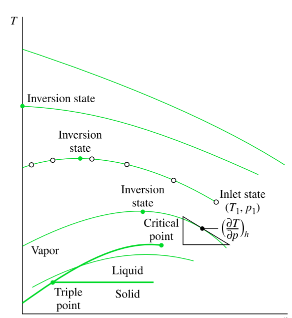
1. Compress isentropically to 2, where $P_2 > P_c$
2. As $T_2 > T_a$, cool it to T_a using ambient sources, and further cool to T_3 using available cold sources.
3. Expand isentropically form 3 to 4 ⇒ liquid formation.

Gas Expansion & Joule-Thomson coefficient

The temperature behaviour of a fluid during a throttling process is described by Joule-Thomson coefficient, μ_{JT}.





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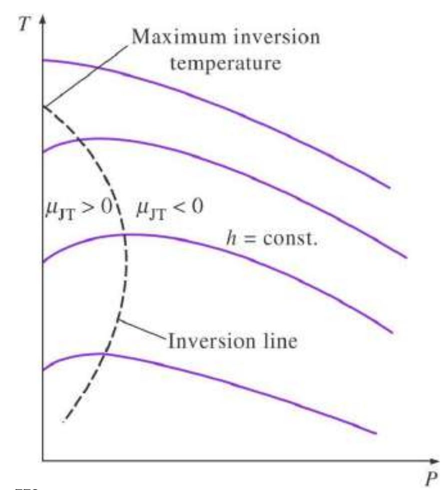
$$\mu_{JT} \equiv \left(\frac{\partial T}{\partial P}\right)_h = \begin{cases} -ve & : \textit{temperature increase} \\ 0 & : \textit{temperature same} \\ +ve & : \textit{temperature drop} \end{cases}$$



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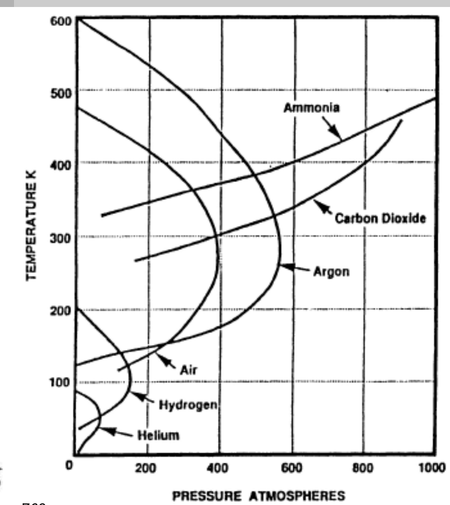

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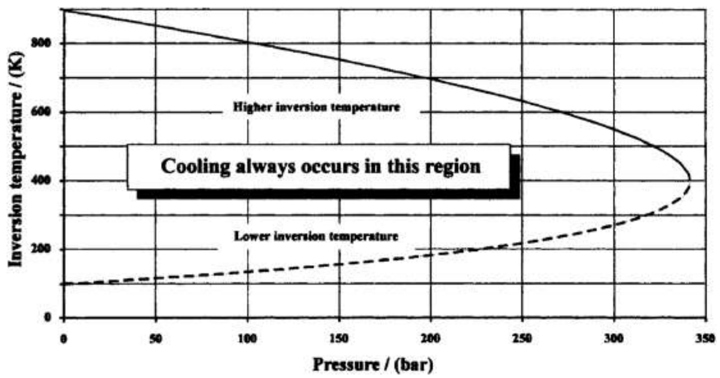
A cooling effect cannot be achieved by throttling unless the fluid is below its **maximum inversion temperature**. For hydrogen its value is -68°C and hydrogen must be cooled below this temperature if further cooling is to be achieved.



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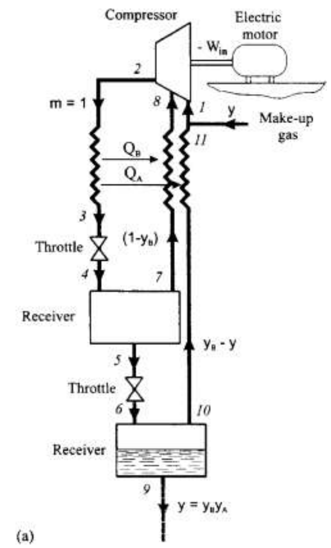
- $P = \frac{RT}{v-b} - \frac{a}{v^2} \Longrightarrow \mu_{JT} = \frac{1}{C_P}\left[\frac{RT}{\left(P+\frac{a}{v^2}\right)-(v-b)\left(\frac{2a}{v^3}\right)} - v\right]$
- *Maximum inversion temperature* $= 6.75T_c$
- *Minimum inversion temperature* $= 0.75T_c$

Linde Liquefaction Plant



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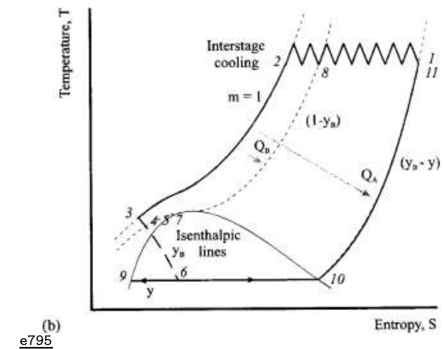

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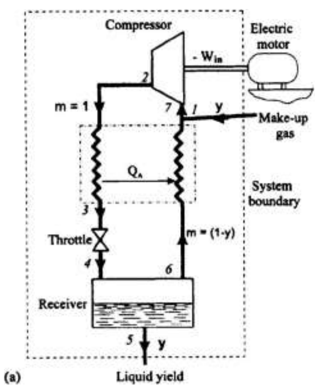
Simplified Linde Liquefaction Plant



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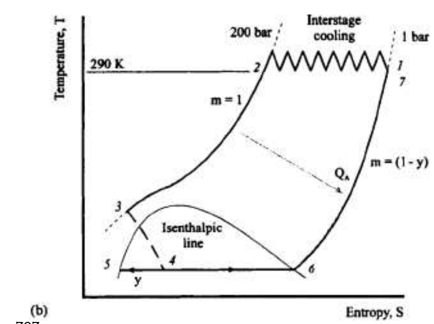

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Two performance parameters:

- Yield, z: mass of liquid produced per unit mass of gas compressed.
- Sp. work required, w_z: work per unit mas of liquid produced.

$$z = \frac{y}{m} = \frac{h_7 - h_2}{h_7 - h_5} \qquad w_z = \frac{W_{in}}{z}$$