CRYOGENIC ENGINEERING

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Lecture No - 8

Earlier Topics

- Introduction to Cryogenic Engineering
  - An introductory knowledge of Cryogenic Engineering.
- Properties of Cryogenic Fluids
  - Properties of Cryogens, T – s diagram, Hydrogen, Helium.
- Properties of Materials at Low Temperature
  - Mechanical, Electrical, Thermal, SC properties of materials.

Current Topic

Topic : Gas Liquefaction and Refrigeration Systems

- Basics of Refrigeration/Liquefaction
- Production of low temperatures
- Ideal thermodynamic cycle
- Various liquefaction cycles

- The current topic will be covered in 7 lectures.

- Tutorials and assignments are included at the end of each lecture.

Introduction

- LN_2 is used as precoolant in most of the cryogenic systems and also it is used to provide an inert atmosphere in welding industries.
- Cryogens like LOX, LH_2 are used in rocket propulsion and in the recent past LH_2 is being considered for automobile.
- The transportation of these gases across the world is done in liquid state.
- Gas refrigeration can also be used as precoolant for liquefiers and also in applications where low temperature gases are required.

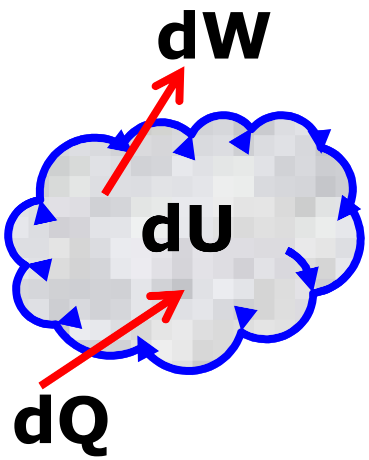
Introduction

Basics of Refrigeration

- The technique of preserving food and perishable goods is an idea of prehistoric times.
- A system which produces cold or maintains such low temperatures is called as a Refrigerating System.
- This process is called as Refrigeration.
- A refrigerating system normally operates in a closed cycle system.

Basics of Refrigeration

First Law of Thermodynamics

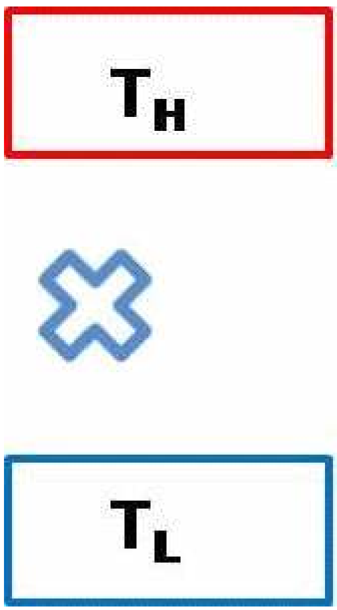


- It is the manifestation of Law of Conservation of Energy.
- The change in Heat (Q) in a system is equal to sum of changes in the Internal energy (U) and the Work (W).

$$dQ = dU + dW$$

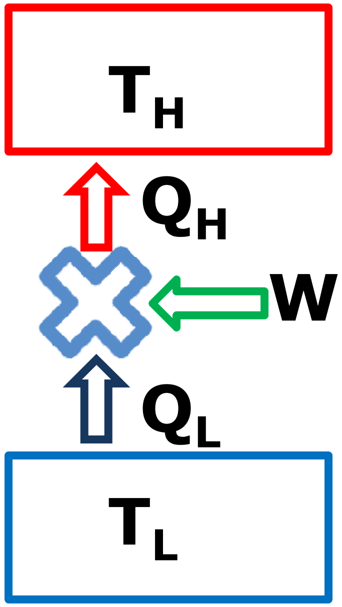
Introduction

Second Law of Thermodynamics



- Heat flows from high temperature to low temperature.
- The second law states that the work is required to pump the heat from low temperature to high temperature.
- Hence, work input is needed to generate and maintain low temperatures.

Basics of Refrigeration



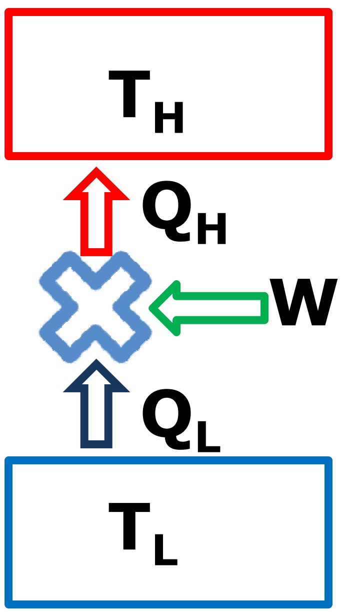
- Coefficient of Performance (COP) is defined as the ratio of heat extracted (Q_L) to the work input (W) at a particular temperature.

- Mathematically,

$$COP = \frac{Q_L}{W}$$

$$COP = \frac{Q_L}{Q_H - Q_L}$$

Basics of Refrigeration

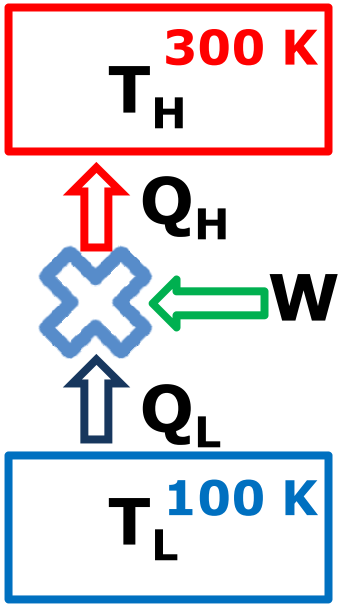


- The best performance is delivered by a system, when it adapts a reverse Carnot Cycle as the working cycle.
- The COP of such a system is called as Carnot COP and is given by

$$COP = \frac{T_L}{T_H - T_L}$$

- Carnot COP is often used as a benchmark to compare the performances of refrigerating systems

Basics of Refrigeration



- COP represents watt of cooling effect obtained per Watt of power input at a particular temperature.

- For example, if it is desired to maintain T_L as 100 K with 1 W as cooling power. T_H is at 300 K. The Carnot COP is

$$COP = \frac{T_L}{T_H - T_L} = \frac{100}{300 - 100} = \frac{1}{2}$$

- It means that 2 W of input power is required to deliver 1 W of cooling power at 100 K.

Comparative Study

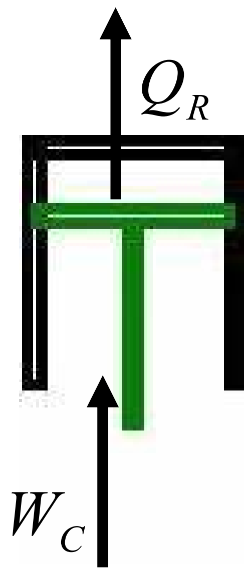
T	W_P/W_C	Carnot COP	Actual COP
270	0.11	9	3.33 ~ 2.0
100	2	0.5	0.1 ~ 0.05
20	14	0.0714	0.01 ~ 0.005
4	74	0.0135	0.0014 ~ 0.0007

- W_P and W_C are the work input and the cooling effect in watts respectively.
- As T_L decreases, the Carnot COP decreases.

Symbols

Symbols used in Liquefaction Cycle Schematics

- The symbols used in different cycle schematics of refrigeration/liquefaction systems are as given below.



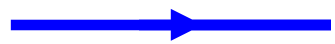
Compressor

- A compressor increases the pressure of the gas. It interacts with the surroundings in the following ways.
  - Q_R – Heat of compression.
  - W_C – Work required for compression.

Symbols

Connecting Flow Lines

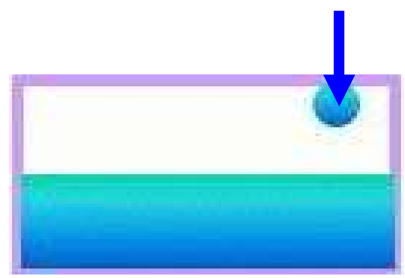
- The flow of liquid is assumed to be frictionless and there is no pressure drop during this flow.



- The direction of the arrow indicates the flow direction.

Liquid Container

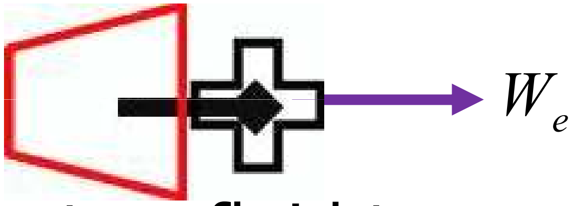
- It is assumed that the container is perfectly insulated from the surroundings.



Symbols

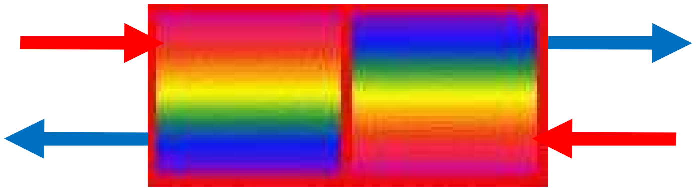
Expander

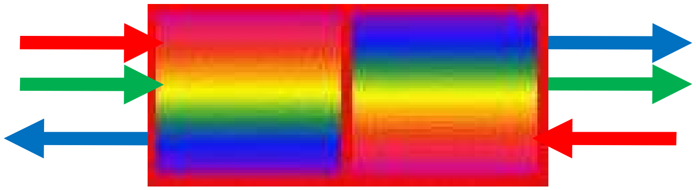
- The schematic for a expander is as shown. The expansion is isentropic and during expansion it produces work W_e.



Heat Exchanger

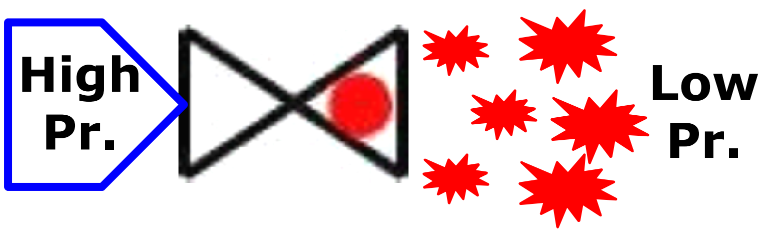
- It can either be a two-fluid type or triple-fluid type depending upon the number of inlets and outlets attached to the HX.



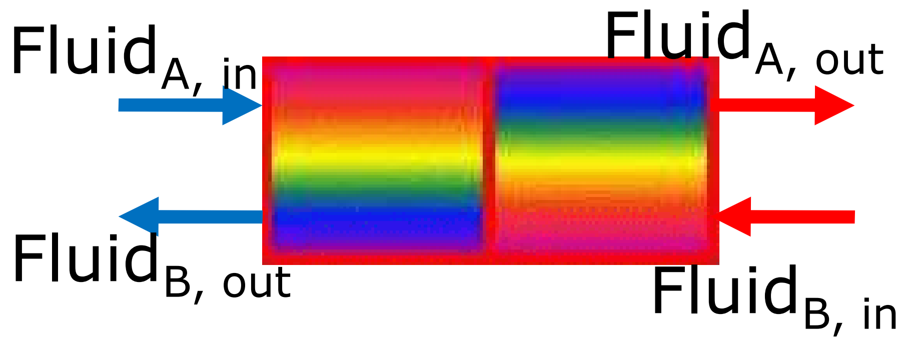


Methods of Production

1. Throttling Method



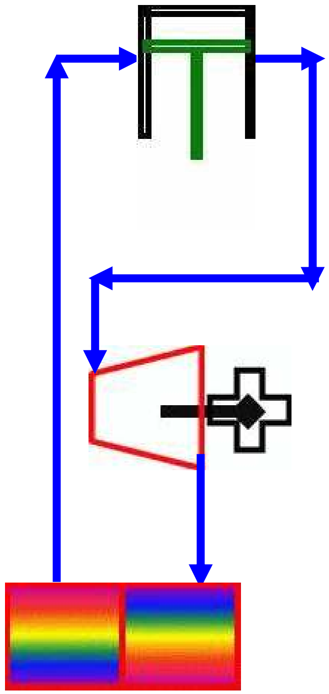
2. Heat Exchanger



- Large systems may be formed by combination of above two methods
  - to increase the capacity of the system or
  - to reach very low temperatures.

Methods of Production

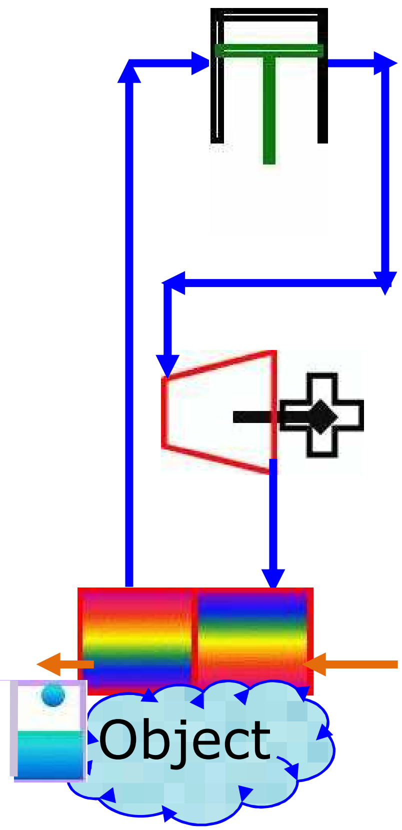
3.Compression/ Expansion



Cold Heat Exchanger

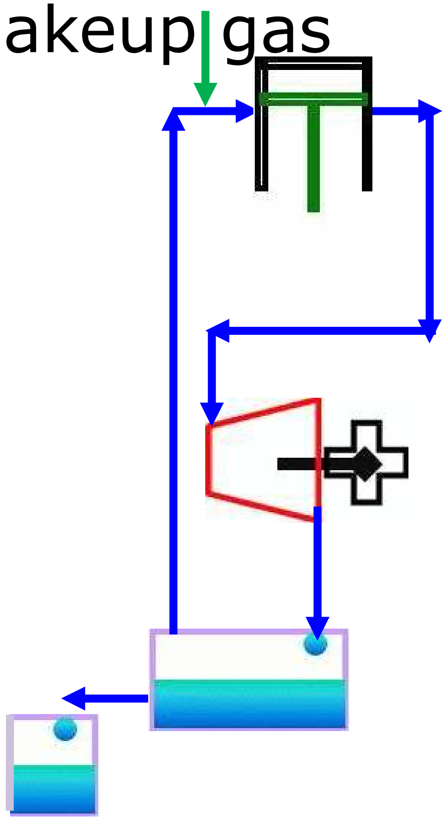
- Arrangements like precooling, Joule – Thompson expansion, expansion devices like reciprocating or turbo-expanders may be used in these systems.
- COP and capacity of the system can be improved.

Refrigerator



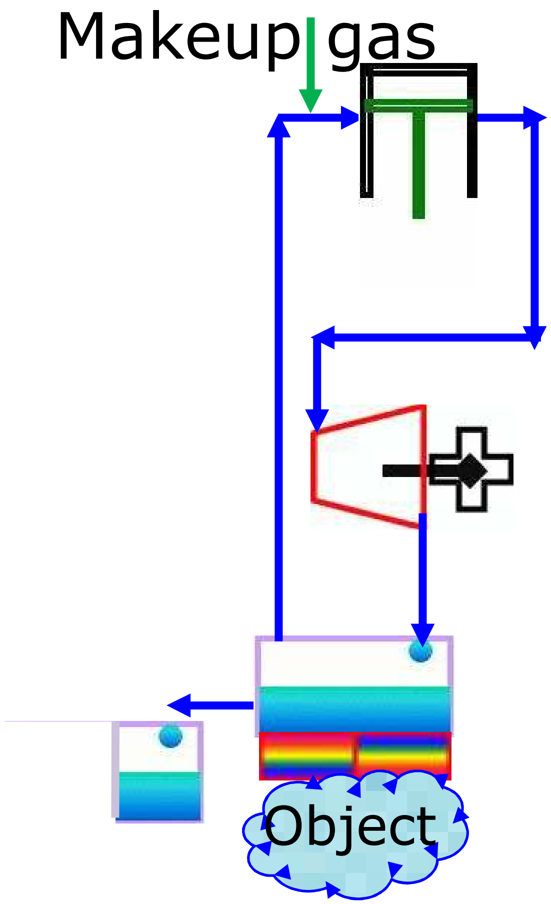
- A refrigerator operates in a closed thermodynamic cycle.
- The rate of mass flow is same at any point inside the system.
- The heat is exchanged between the cold end and the object to be cooled.
- This cold end heat exchanger can also be used to liquefy gases.

Liquefier



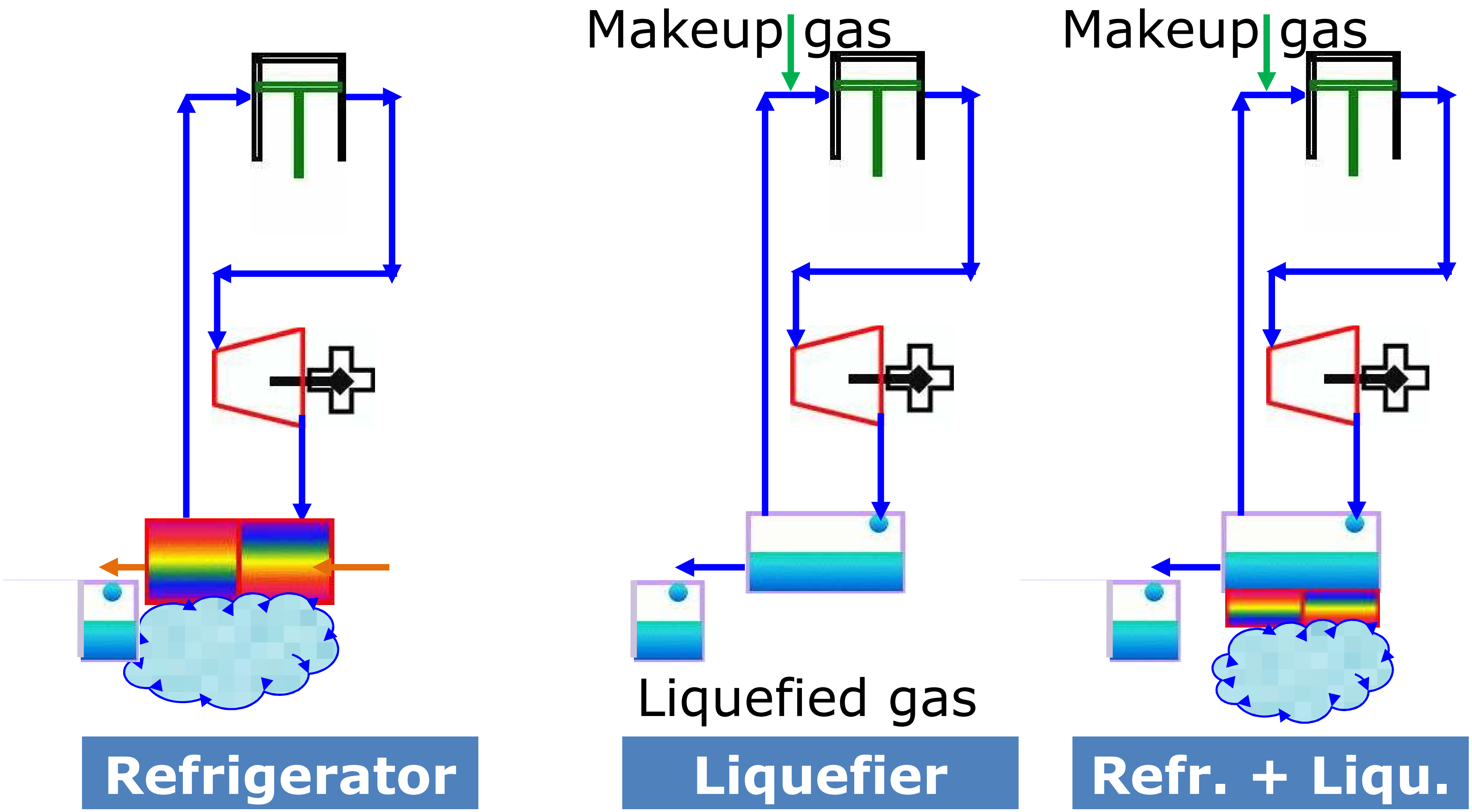
- A Liquefier often produces cold liquid, that is drawn off from the system. For example, a nitrogen liquefier produces LN_2.
- Since the mass is drawn out from the system, it operates in an open thermodynamic cycle.
- The mass deficit occurring due to loss of the working fluid is replenished by a Makeup Gas connection.

Refrigerator & Liquefier

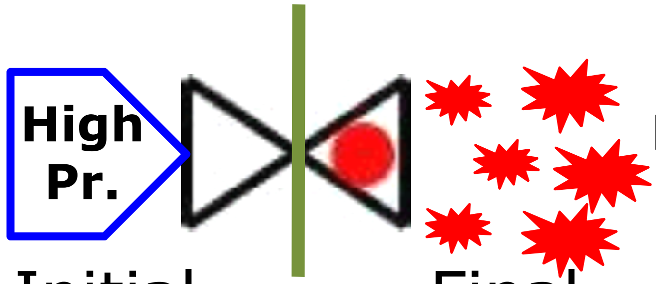


- Systems can also be used to liquefy gas (liquefier) as well as to cool the object (refrigerator).
- One such arrangement is as shown in the schematic.
- A cold heat exchanger is used to transfer cold from the liquid container to the object to be cooled.

Comparative Study



Joule – Thompson Expansion



Parameter	Initial	Final
Mass flow	$\dot{m}_i$	$\dot{m}_f$
Enthalpy	h_i	h_f
Velocity	v_i	v_f
Datum	z_i	z_f
Heat	Q_{net}	
Work	W_{net}	

- From 1st Law of Thermodynamics,

$$dQ - dW = dU$$

$$Q_{net} - W_{net} = \sum_{out} U - \sum_{in} U$$

Joule – Thompson Expansion

- Applying the 1st Law

$$\cancel{Q_{net}} - \cancel{W_{net}} = \dot{m}_f\left(h_f + \cancel{\frac{v_f^2}{2g}} + \cancel{gz_f}\right) - \dot{m}_i\left(h_i + \cancel{\frac{v_i^2}{2g}} + \cancel{gz_i}\right)$$

- The changes in Heat (Q_{net}) and Work (W_{net}) are zero for this expansion device.

- The changes in the velocities and datum levels are very small and can be neglected.

Joule – Thompson Expansion

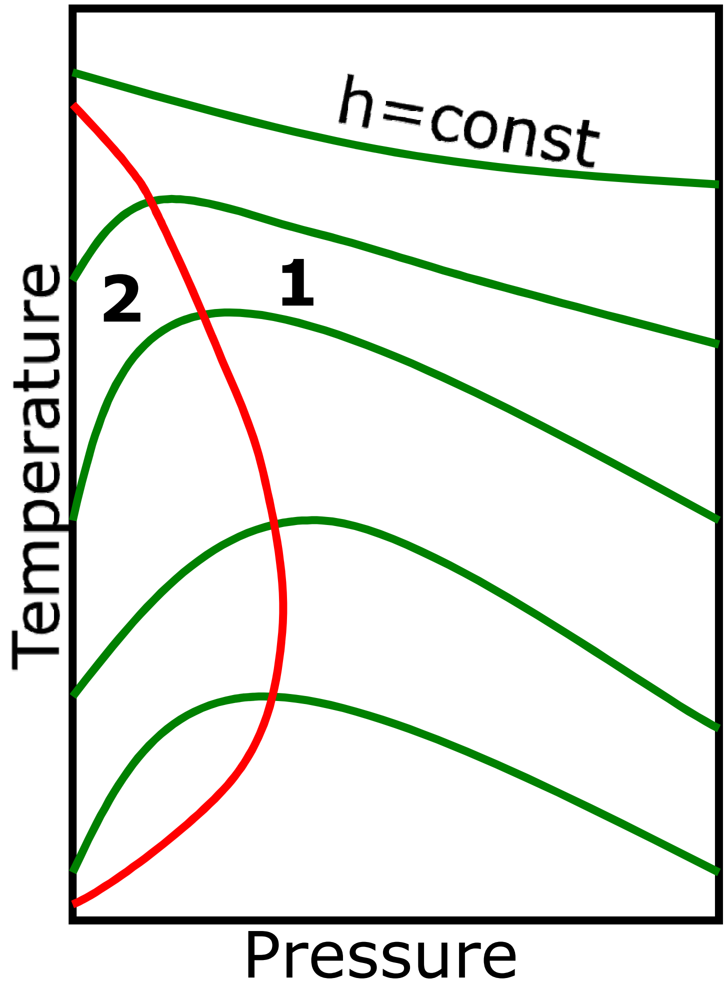
$$\dot{Q}_{net} - \dot{W}_{net} = \dot{m}_f \left(h_f + \frac{v_f^2}{2g} + gz_f \right) - \dot{m}_i \left(h_i + \frac{v_i^2}{2g} + gz_i \right)$$

- Mass flows are equal at inlet and outlet sections.

$$h_f = h_i$$

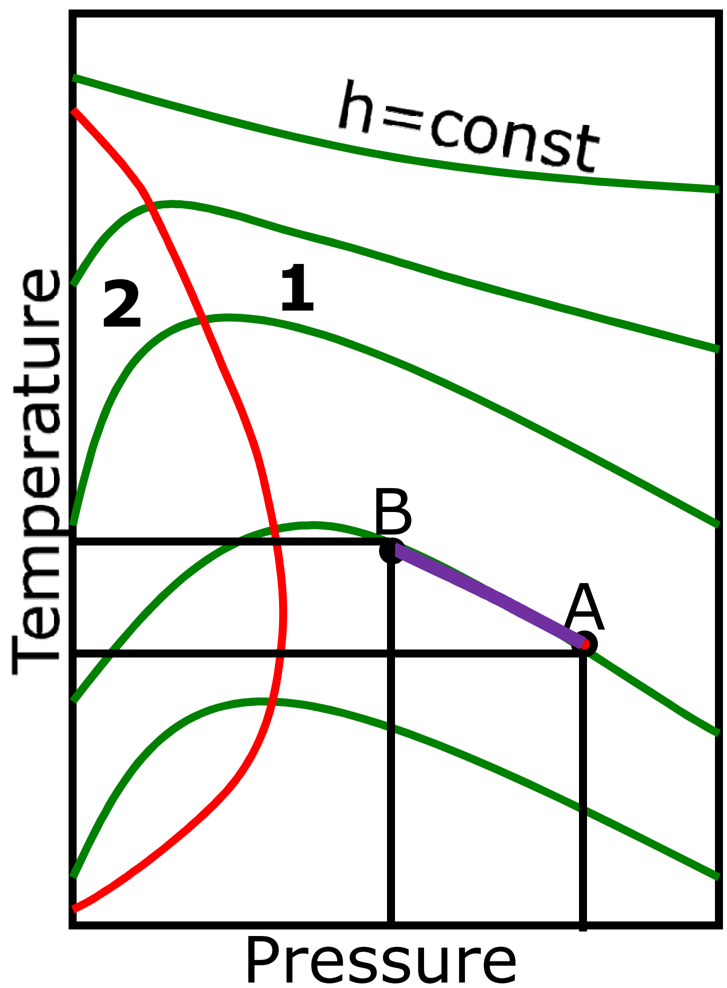
- Hence, a Joule – Thompson expansion is an isenthalpic expansion.

Joule – Thompson Effect



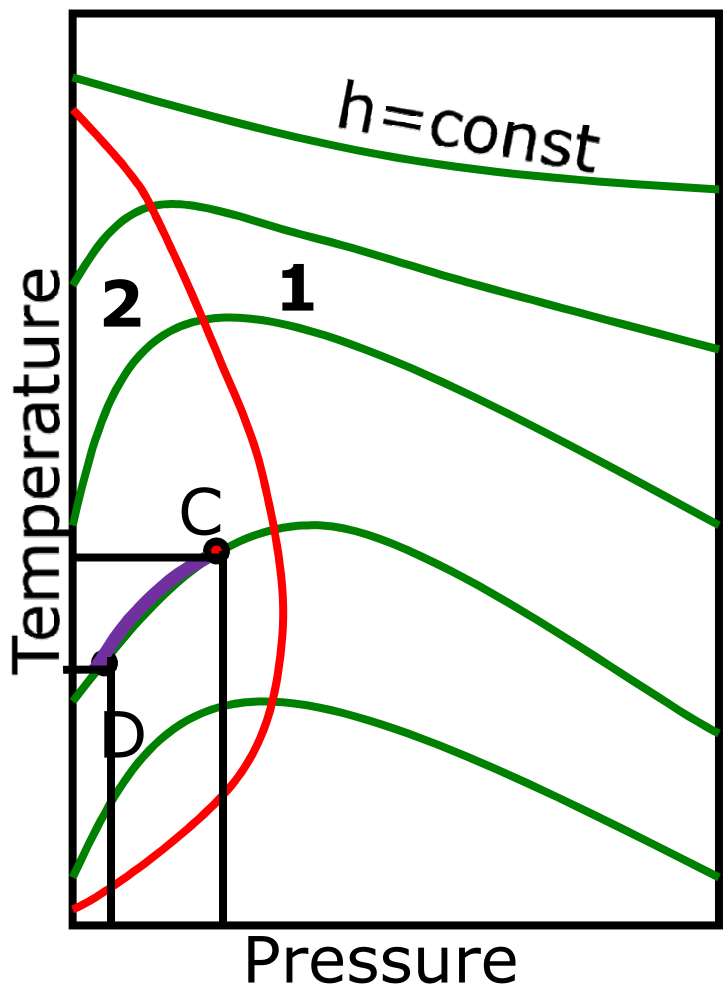
- T – p plot for any gas at constant enthalpies are as shown.
- As can be seen from the figure, the constant enthalpy line shows a maxima at a particular temperature.
- The line joining maximas divides the space into **Region-1** and **Region-2**.

Joule – Thompson Effect



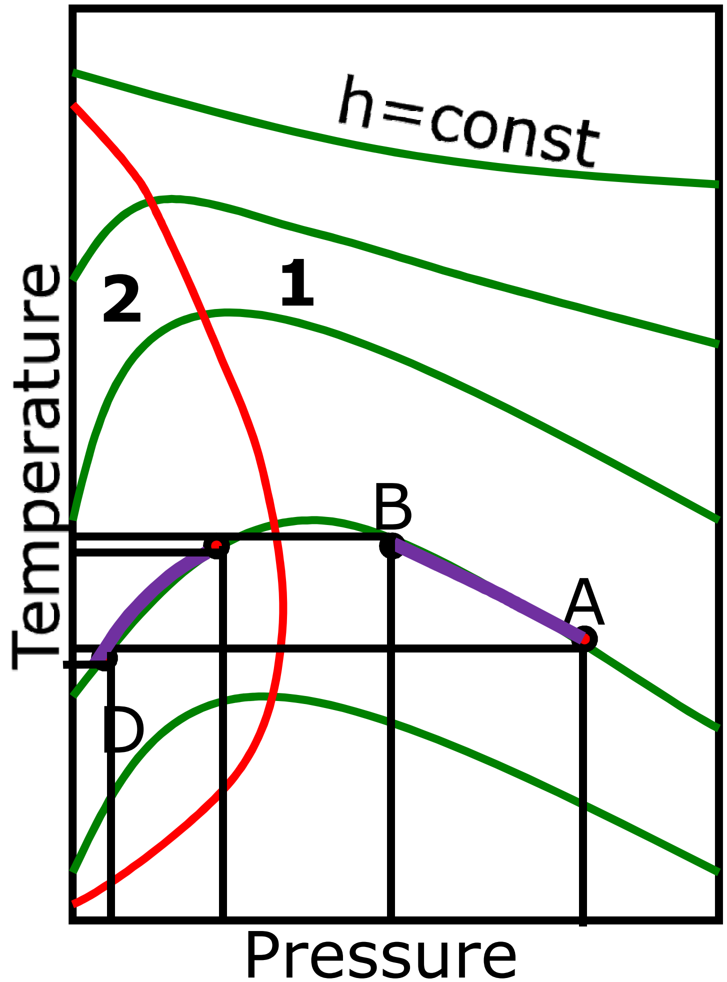
- Consider gas at state **A** in the region-1 with pressure and temperature as shown.
- It is expanded from state **A** to state **B** at a constant enthalpy.
- As can be seen, this results in increase in temperature of the gas.

Joule – Thompson Effect



- Now, consider the gas sample at state **C** in region-2 with pressure and temperature as shown.
- The gas is expanded from state **C** to state **D** at constant enthalpy.
- This decrease in pressure results in drop in temperature.

Joule – Thompson Effect



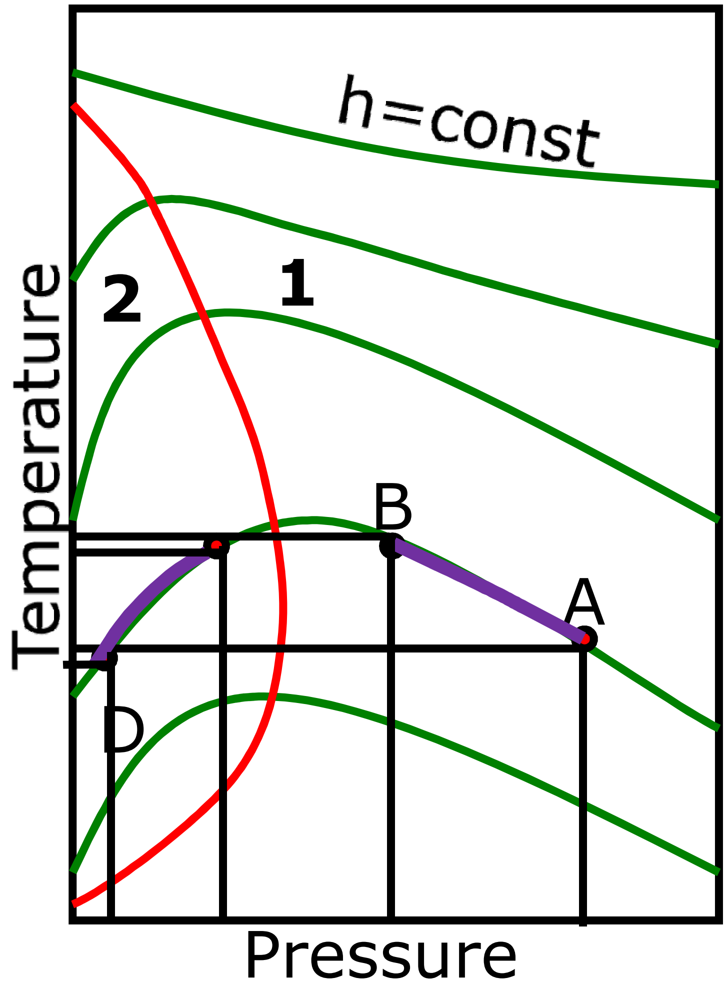
- The ratio

$$\left(\frac{\partial T}{\partial p}\right)_h$$

- is negative for **A→B** where as, it is positive for **C→D**.

- This ratio is called as **Joule – Thompson coefficient** and this effect is called as **Joule – Thompson Effect (J – T)**.

Joule – Thompson Effect

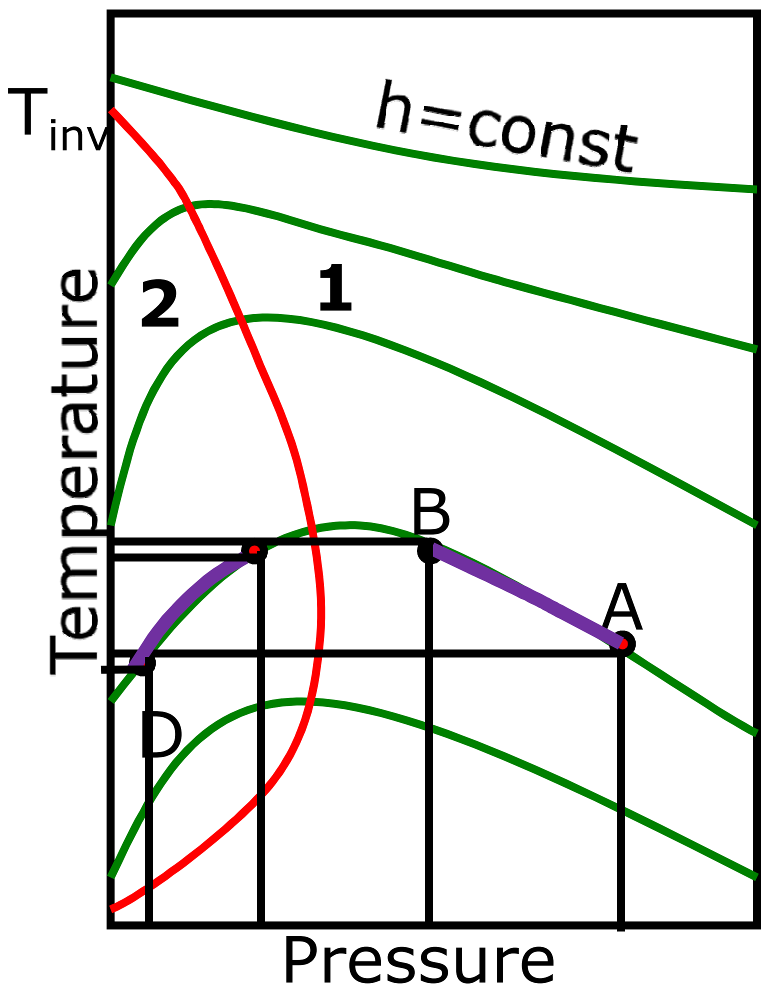


- Mathematically,

$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h$$

μ_{JT}	Effect
>0	Cooling
<0	Heating
=0	No effect

Joule – Thompson Effect



- This dividing line is called as Inversion Curve.
- The temperature on the inversion curve at p=0 is called as **Maximum Inversion Temperature, T_{inv}.**
- It is clear that the initial state of the gas should be inside the region-2 or below T_{inv} to have a cooling effect.

Joule – Thompson Effect

- From the earlier plot, Enthalpy (h) is a function of both pressure (p) and temperature (T).

$$h = f\left(p, T\right)$$

- Using the calculus, the following can be derived.

$$\left(\frac{\partial h}{\partial p}\right)_T \left(\frac{\partial p}{\partial T}\right)_h \left(\frac{\partial T}{\partial h}\right)_p = -1$$

- Rearranging the terms, we have

$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h = -\left(\frac{\partial T}{\partial h}\right)_p \left(\frac{\partial h}{\partial p}\right)_T$$

Joule – Thompson Effect

- Also, using the calculus, the following can be derived.

$$s = f\left(T, p\right)$$

$$ds = \left(\frac{\partial s}{\partial T}\right)_p dT + \left(\frac{\partial s}{\partial p}\right)_T dp$$

$$Tds = T\left(\frac{\partial s}{\partial T}\right)_p dT + T\left(\frac{\partial s}{\partial p}\right)_T dp$$

$$T\left(\frac{\partial s}{\partial T}\right)_p \rightarrow c_p \qquad \left(\frac{\partial s}{\partial p}\right)_T \rightarrow -\left(\frac{\partial v}{\partial T}\right)_p$$

Maxwell's Equation

$$Tds = c_p dT - T\left(\frac{\partial v}{\partial T}\right)_p dp$$

$$dh = Tds + vdp$$

$$dh = c_p dT - \left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right] dp$$

Joule – Thompson Effect

- Also, using the calculus, the following can be derived.

$$h = f\left(p, T\right)$$

$$dh = \left(\frac{\partial h}{\partial T}\right)_p dT + \left(\frac{\partial h}{\partial p}\right)_T dp$$

$$dh = c_p dT - \left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right] dp$$

$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h = -\left(\frac{\partial T}{\partial h}\right)_p \left(\frac{\partial h}{\partial p}\right)_T$$

$$\mu_{JT} = \frac{1}{c_p}\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right]$$

Joule – Thompson Effect

- For an ideal gas, the equation of state is

$$v = \frac{RT}{p}$$

- Differentiating w.r.t **T** at constant **p**, we get

$$\left(\frac{\partial v}{\partial T}\right)_p = \frac{R}{p} = \frac{v}{T}$$

- On substitution, we get

$$\mu_{JT} = \frac{1}{c_p}\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right] = \frac{1}{c_p}\left[T\left(\frac{v}{T}\right) - v\right] = 0$$

- For an ideal gas $\mu_{JT} = 0$. It means that the ideal gas does not show any change in temperature when it undergoes J – T expansion.

Summary

- Basics of refrigeration/liquefaction systems, definition of COP, Carnot COP.
- As the required low temperature (T_L) decreases, the Carnot COP decreases.
- Methods like J – T expansion, Heat exchanger and compression/expansion systems are used to produce low temperatures.
- Different combinations of methods shown above are formed to increase the capacity or COP of the system.

Summary

- Difference between Refrigerator and Liquefier and a combination of above two systems.
- The ratio $\left(\frac{\partial T}{\partial p}\right)_h$ defines the J – T expansion coefficient, which should be positive to have a cooling effect.
- The J – T expansion is an isenthalpic process.
- J – T coefficient is given by $\mu_{JT} = \frac{1}{c_p}\left[T\left(\frac{\partial v}{\partial T}\right)_p - v\right]$

Summary

- For an ideal gas $\mu_{JT} = 0$. It does not show any change in temperature when it undergoes J – T expansion.

- The temperature on the inversion curve at p=0 is called as **Maximum Inversion Temperature, T_{INV}.**

- In order to have cooling effect during the expansion, the initial state of a gas should lie inside the inversion curve or the initial temperature should be below the Maximum Inversion Temperature.

- A self assessment exercise is given after this slide.

- Kindly asses yourself for this lecture.

Self Assessment

1. Process of producing cold or maintaining low temperatures is called as ________.

2. Mathematical representation of 1st Law of thermodynamics is ___________.

3. _______ is required to pump the heat from low temperature to high temperature.

4. ______ is the ratio of heat extracted (Q_L) to the work input (W) at a particular temperature.

5. Mathematical representation of COP is _______.

Self Assessment

6. COP at 100 K is 0.5. It means that ______W of input power is required to deliver _____ W of cooling power at 100 K.

7. A refrigerator operates in a ______ thermodynamic cycle.

8. A liquefier operates in a ______ thermodynamic cycle.

9. A Joule – Thompson expansion is an __________ expansion.

Self Assessment

10. Fill the following table.

μ_{JT}	Effect
>0	________
<0	________
=0	________

11. ________ does not show any change in temperature when it undergoes J – T expansion.

Answers

1. Refrigeration
2. $dQ = dU + dW$
3. work
4. COP
5. $COP = \frac{Q_L}{W}$
6. 2 W, 1W
7. closed
8. open

Answers

9. Isenthalpic

10.

μ_{JT}	Effect
>0	Cooling
<0	Heating
=0	No effect

11. Ideal gas

Thank You!