CRYOGENIC ENGINEERING

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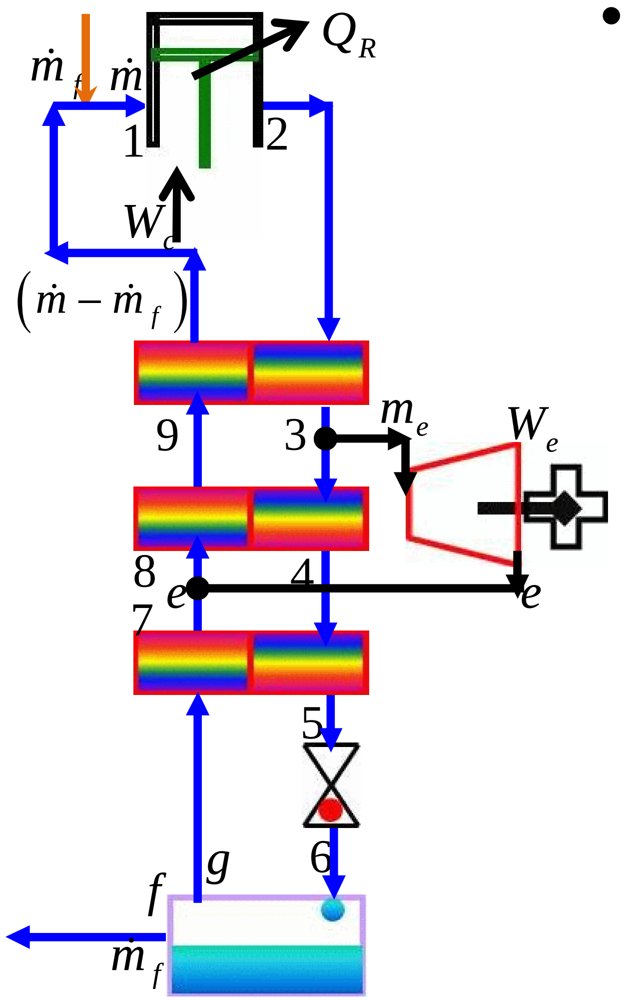
Lecture No - 16

Earlier Lecture



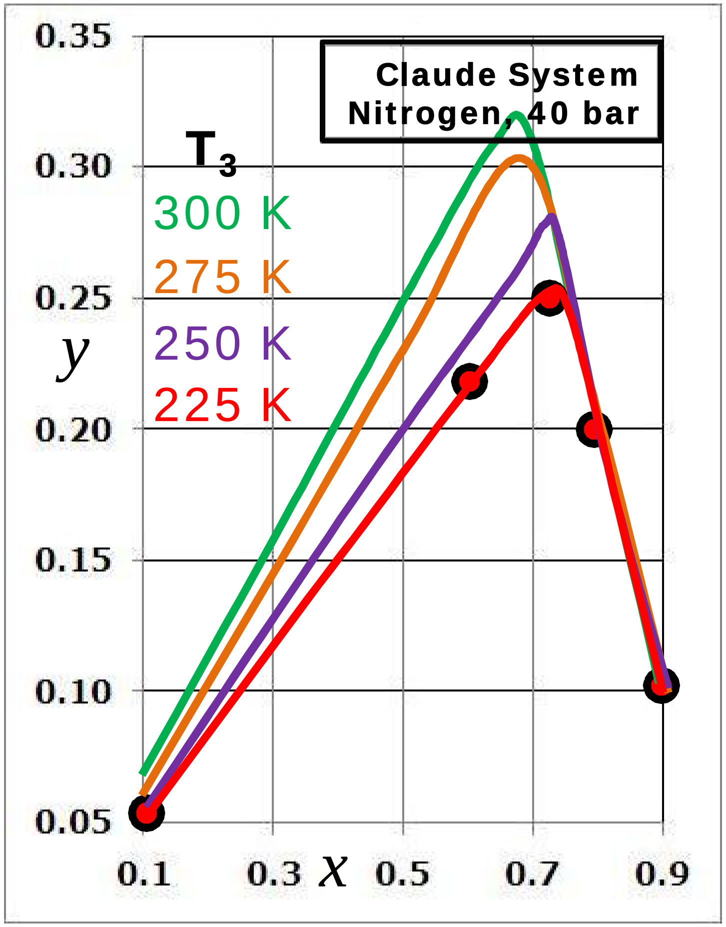
- In the earlier lecture, we have seen a Claude system, in which the energy content in the gas is removed by allowing it to do some work in an expansion device. **y** and **W / m** are given by

$$y = \left(\frac{h_1 - h_2}{h_1 - h_f}\right) + x\left(\frac{h_3 - h_e}{h_1 - h_f}\right)$$

$$-\frac{W_{net}}{\dot{m}} = \begin{cases} \left(T_1\left(s_1 - s_2\right) - \left(h_1 - h_2\right)\right) \\ -x\left(h_3 - h_e\right) \end{cases}$$

Earlier Lecture

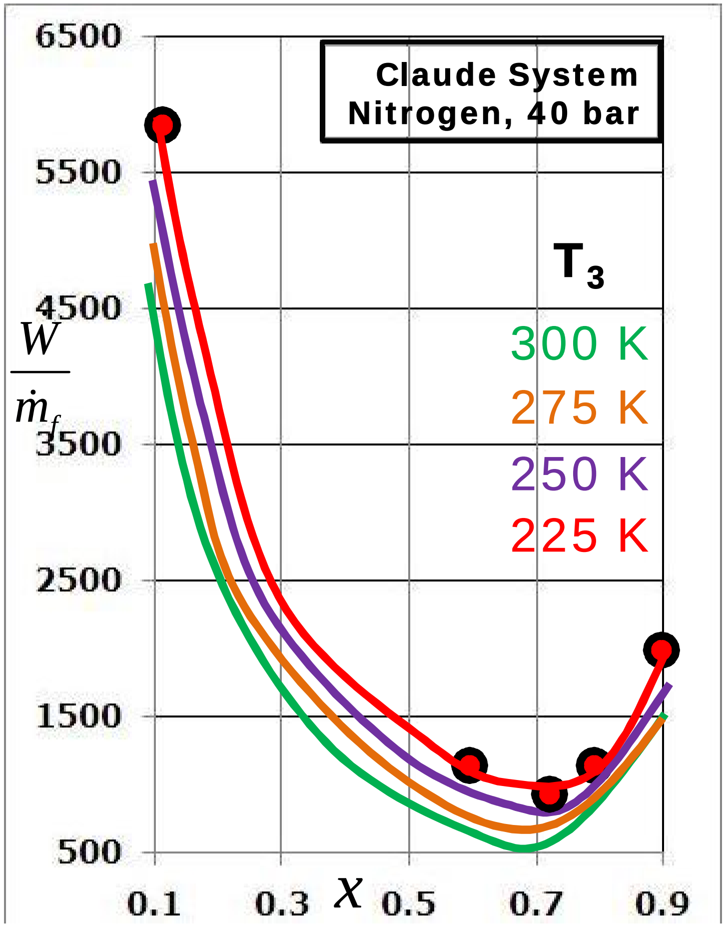
- **Liquid yield v/s. x**



- In a reversible Claude system, if $\mathbf{T_1}$, $\mathbf{T_2}$, $\mathbf{T_3}$ are held constant
  - The yield **y** goes through a maxima with the increase in the value of **x**.
  - Also, this maxima shifts to the right and decreases with the decrease in $\mathbf{T_3}$.

Earlier Lecture

- **W / m_f v / s. x**



- In a reversible Claude system, if **T_1**, **T_2**, **T_3** are held constant
  - **W / m_f** of the system goes through a minima with an increase in **x**.
  - Also, the position of the minima shifts to the right and increases with the decrease in the value of **T_3**.

Outline of the Lecture

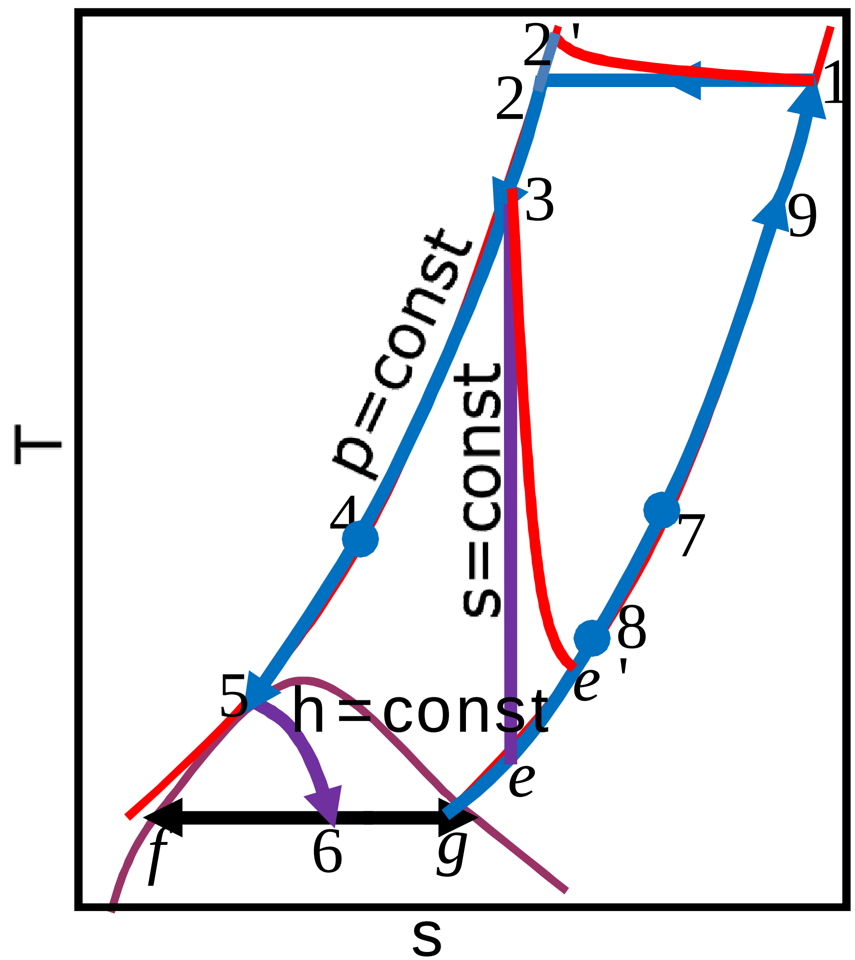
Topic : Gas Liquefaction and Refrigeration Systems (contd)

- Claude System with irreversibilities in Compressor and Expander
- Kapitza System
- Heylandt System
- Collins System
  - Liquid yield
  - Work requirement

Introduction

- The compression and expansion processes in an actual Claude cycle are irreversible.
- These irreversibilities cause inefficiencies and deteriorate the performance of the system.
- To study the effect of these inefficiencies, a tutorial problem is solved.
- The results are graphically plotted and compared with a reversible system solved in the previous lecture.

Claude System



- The T – s diagram for a reversible Claude system is as shown.
- The compressor irreversibility is shown by the process **1 → 2'**.
- Similarly, the expander irreversibility is denoted by the process **3 → e'**.

Claude System

- The compressor inefficiency is due to both frictional losses ($\eta_{mech,c}$) and non – isothermal process ($\eta_{iso,c}$).

- The net irreversibility is given by $\eta_{oval,c} = \eta_{mech,c} \times \eta_{iso,c}$

- Similarly, the expander inefficiency is due to both frictional losses ($\eta_{mech,e}$) and non – isentropic process ($\eta_{ad,e}$).

- The net irreversibility is given by $\eta_{oval,e} = \eta_{mech,e} \times \eta_{ad,e}$

Claude System

- With these inefficiencies taken into account, the yield of the system decreases and the work requirement increases.

- The yield and work requirement of the system are given by

$$y = \left(\frac{h_1 - h_2}{h_1 - h_f} \right) + x\left(\eta_{ad,e}\right)\left(\frac{h_3 - h_e}{h_1 - h_f} \right)$$

$$-\frac{W_{net}}{\dot{m}} = \frac{\left(T_1\left(s_1 - s_2\right) - \left(h_1 - h_2\right)\right)}{\eta_{oval,c}} - x\left(\eta_{oval,e}\right)\left(h_3 - h_e\right)$$

Tutorial

A. Determine **W / m_f** for a Claude Cycle with N_2 as working fluid. The system operates between 1.013 bar (1 atm) and 50.65 bar (50 atm). The expander inlet **T_3** is at 250 K. The expander flow ratio is varied between 0.1 and 0.9. The efficiencies are as given below.

Comp.	$\eta_{oval,c} = 0.75$
Expd.	$\eta_{mech,e} = 0.86$
	$\eta_{ad,e} = 0.86$

B. Repeat the above problem for **T_3** = 300 K, 275 K and 250 K. Plot the data **y**, **W / m_f** versus **x** graphically and comment on the results.

Tutorial

Given
Cycle : Claude System
Working Pressure : 1 atm → 50 atm
Working Fluid : Nitrogen
T_3 : 300 K, 275 K, 250 K
Mass flow ratio : x = 0.1 → 0.9
Efficiencies : $\eta_{oval,c} = 0.75$, $\eta_{mech,e} = 0.86$, $\eta_{ad,e} = 0.86$

For above System, Calculate	
1	Work/unit mass of gas liquefied

N_2	Point 3
I	300 K
II	275 K
III	250 K

Methodology

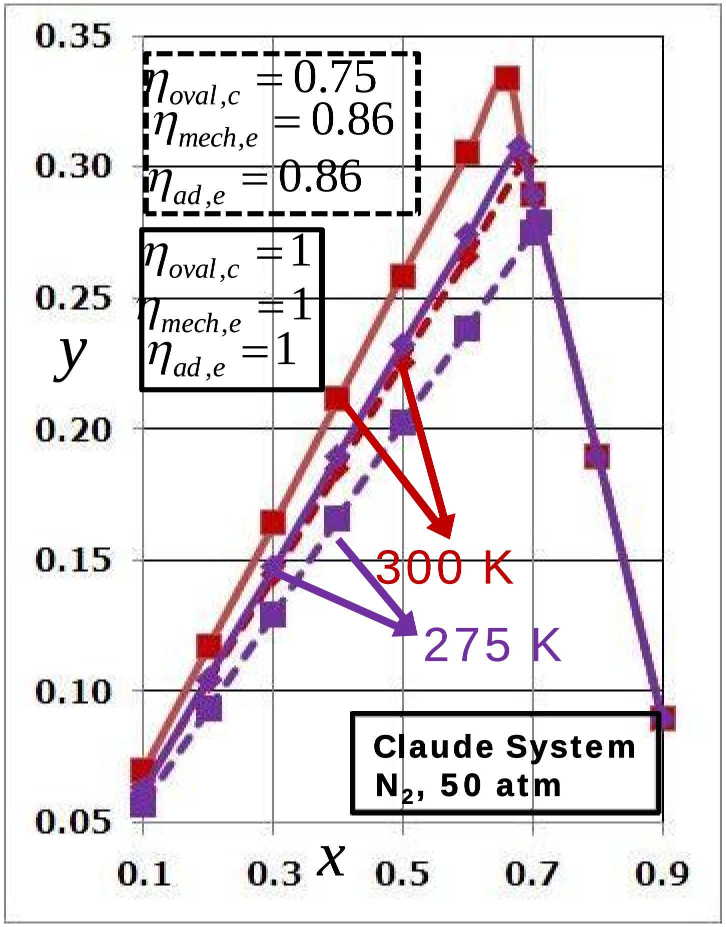
- In the earlier lecture, an assignment problem on a reversible Claude cycle with the answers was given.

- As stated earlier, the same problem is taken up and the effects of inefficiencies of the compressor and the expander are studied.

- All the calculations are left as an exercise for the students and the final results are graphically plotted.

Tutorial

- **Liquid yield v/s. x**



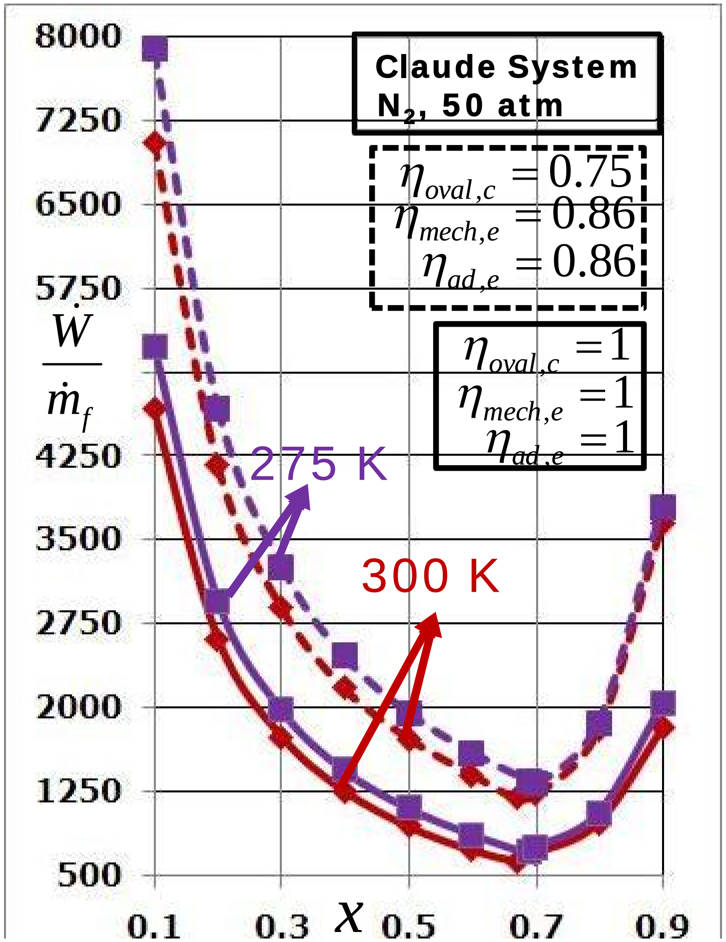
- The plot for **y** v/s **x** for a **T_3= 300** and **275 K** is shown.

- It is clear that maximum yield of the system decreases due to the irreversibility.

- The % decrease in the **y_{max}** is 10% and 9% for **300** and **275 K** respectively.

Tutorial

- **W / m_f v / s. x**



- The plot for **W / m_f** v/s **x** for a **T_3 = 300** and **275 K** is shown.

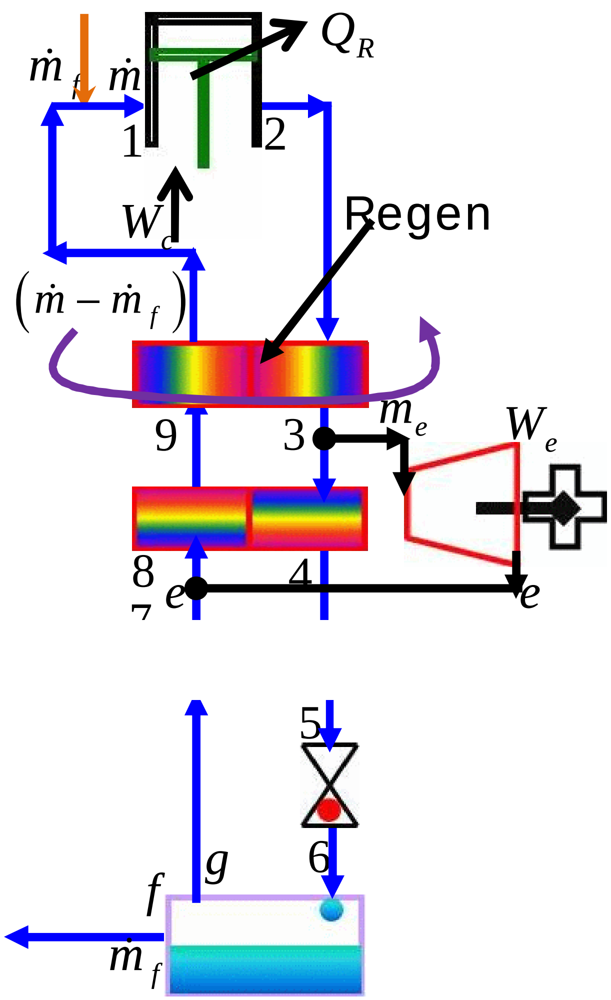
- It is clear that minimum work requirement of the system increases due to the irreversibility.

- The % increase in the **W / m_{fmin}** is 89% and 87% for **300** and **275 K** respectively.

Kapitza & Heylandt System

- The transportation of gases across the world is done in liquid state by storing them at cryogenic temperatures.
- The air liquefaction is of primary importance because LN_2 and LOX are separated from LAir.
- Kapitza and Heylandt systems are the two different modifications of the Claude System which are generally used in the air liquefaction.
- Collins system, also a modification of Claude system, is widely used in liquefaction of Helium.

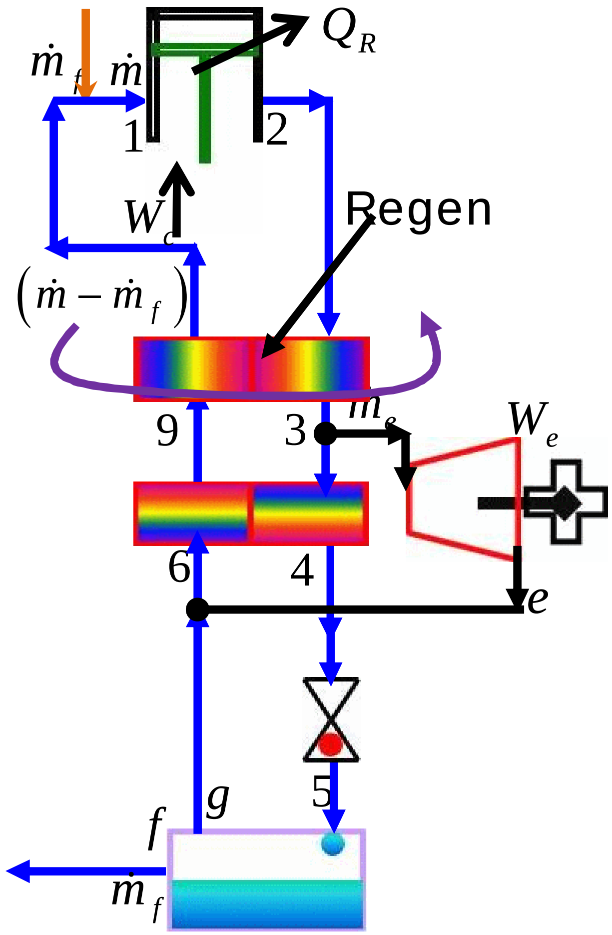
Kapitza System



- A Kapitza system is a low – pressure system which is used in Air liquefaction.

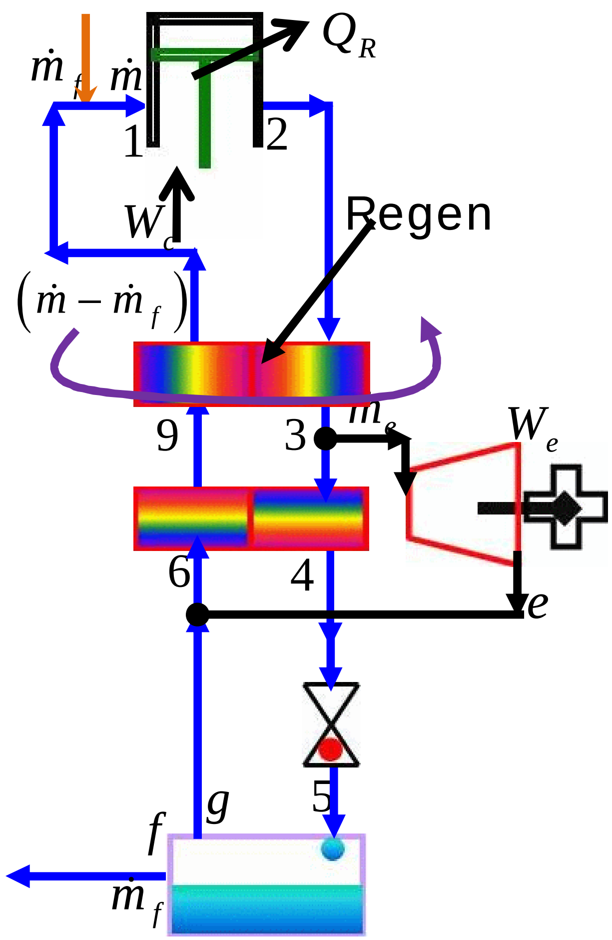
- It was invented in 1939 by Pyotr Kapitza, in which
  - The first heat exchanger is replaced by a set of valved regenerators.
  - The third heat exchanger is eliminated in the Claude system.

Kapitza System



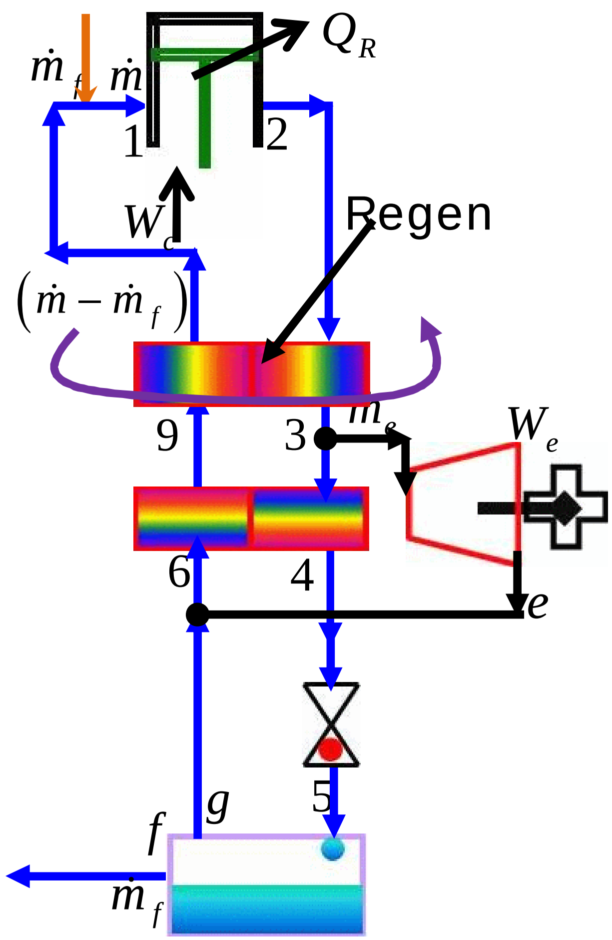
- The regenerator/heat exchanger performs two different operations
  - Gas cooling/warming
  - Gas purification
- During one cycle, one unit purifies by freezing the impurities and cools the incoming hot gas.

Kapitza System



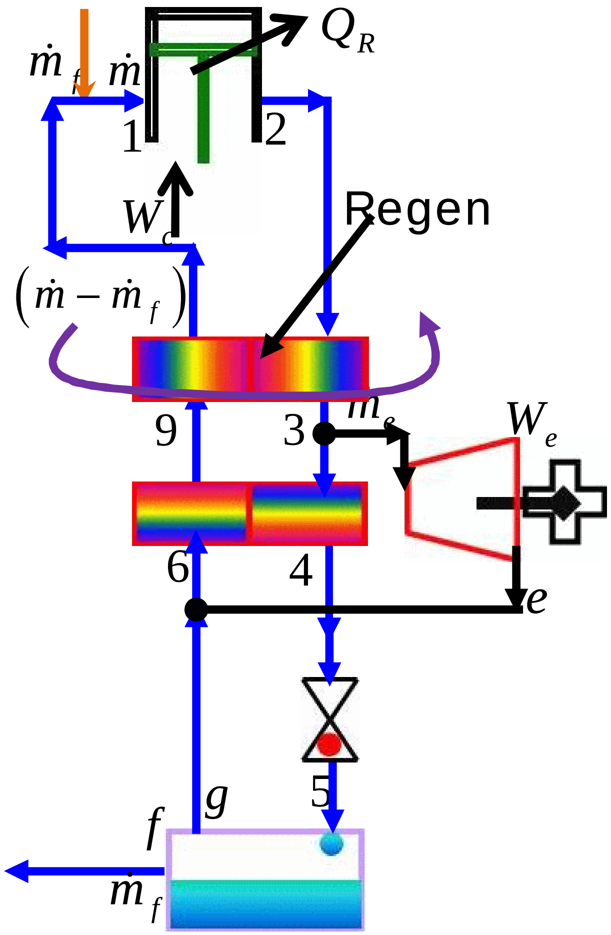
- While the other unit warms the outgoing gas and simultaneously removes the frozen impurities by evaporation.
- The valve mechanism is used to periodically change over from one unit to another (not shown in the figure).

Kapitza System



- This periodic alternation of units along with the counter – blow arrangement ensures a continuous performance.
- This system was the first one to use a turbo – expander (rotary type) instead of a reciprocating expander.
- This modification allowed the elimination of third heat exchanger in Claude system.

Kapitza System



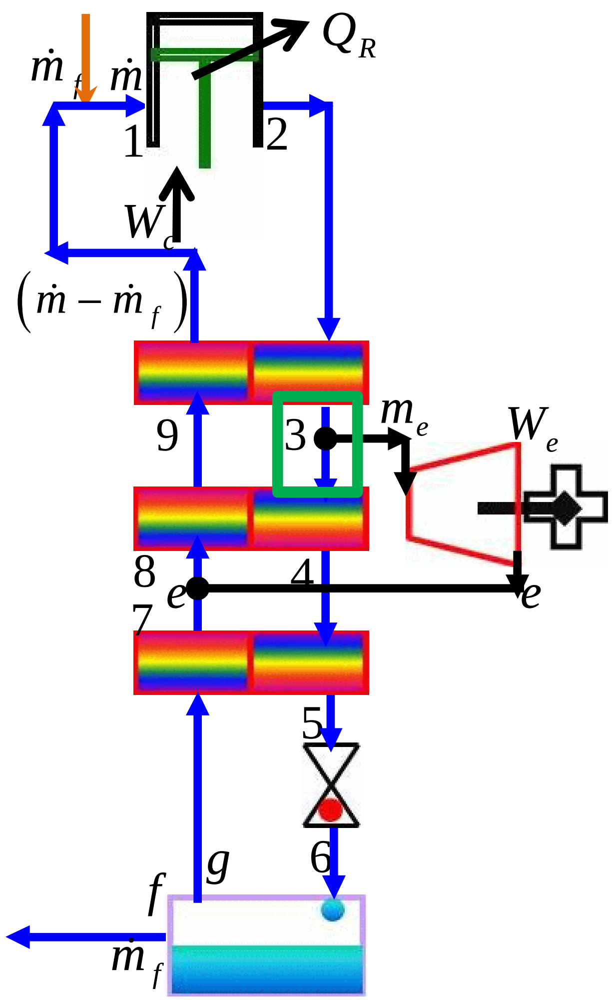
- The yield and work requirement of the system are given by the following equations.

$$y = \left(\frac{h_1 - h_2}{h_1 - h_f}\right) + x\left(\frac{h_3 - h_e}{h_1 - h_f}\right) \qquad x = \frac{\dot{m}_e}{\dot{m}}$$

$$-\frac{W_{net}}{\dot{m}} = \begin{cases} \left(T_1\left(s_1 - s_2\right) - \left(h_1 - h_2\right)\right) \\ -x\left(h_3 - h_e\right) \end{cases}$$

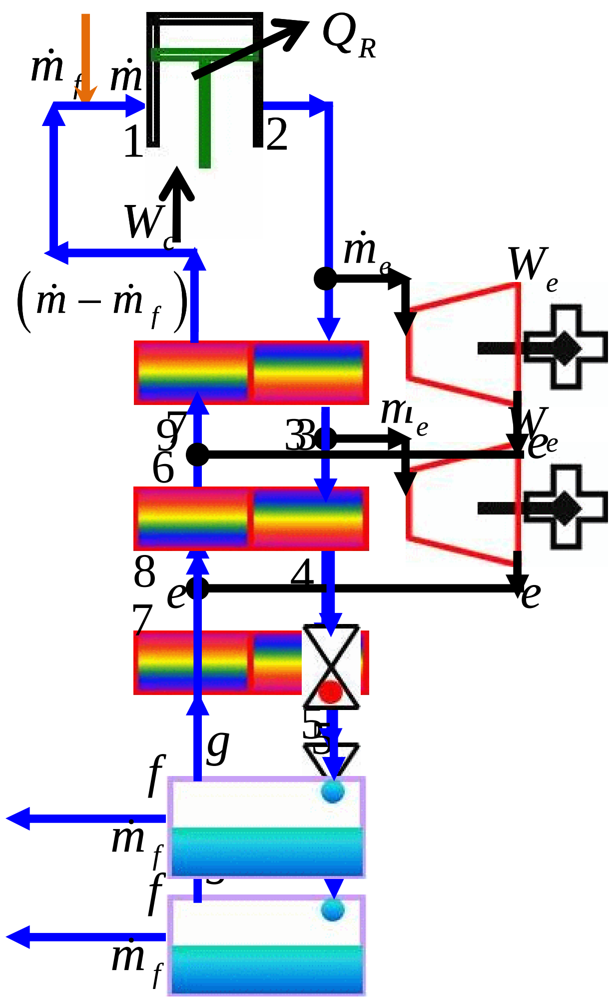
- Where, the expander mass flow ratio is denoted by **x**.

Heylandt System



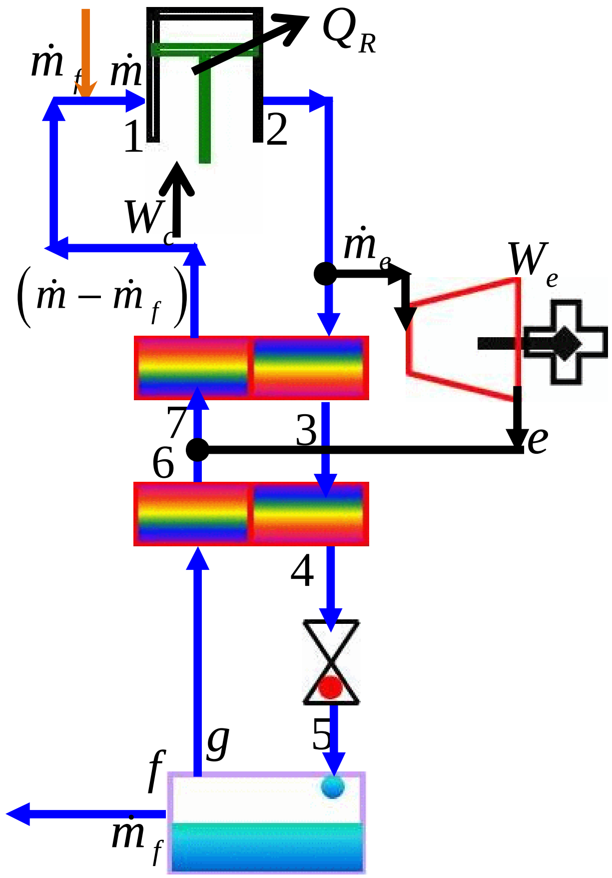
- Heylandt System is a high – pressure system, which is used in Air liquefaction.
- The typical operating pressure is around 200 atm.
- In 1949, Heylandt observed that, when a Claude system operated on Air with 200 atm and x=0.6, the optimum value of $\mathbf{T_3}$ before the expansion engine is close to ambient.

Heylandt System



- He then eliminated the first heat exchanger.
- This modified system is called as Heylandt system.
- In this system, the inlet to the expander is at ambient and hence, the lubrication on the high pressure side and the operation of the expander are greatly simplified.

Heylandt System



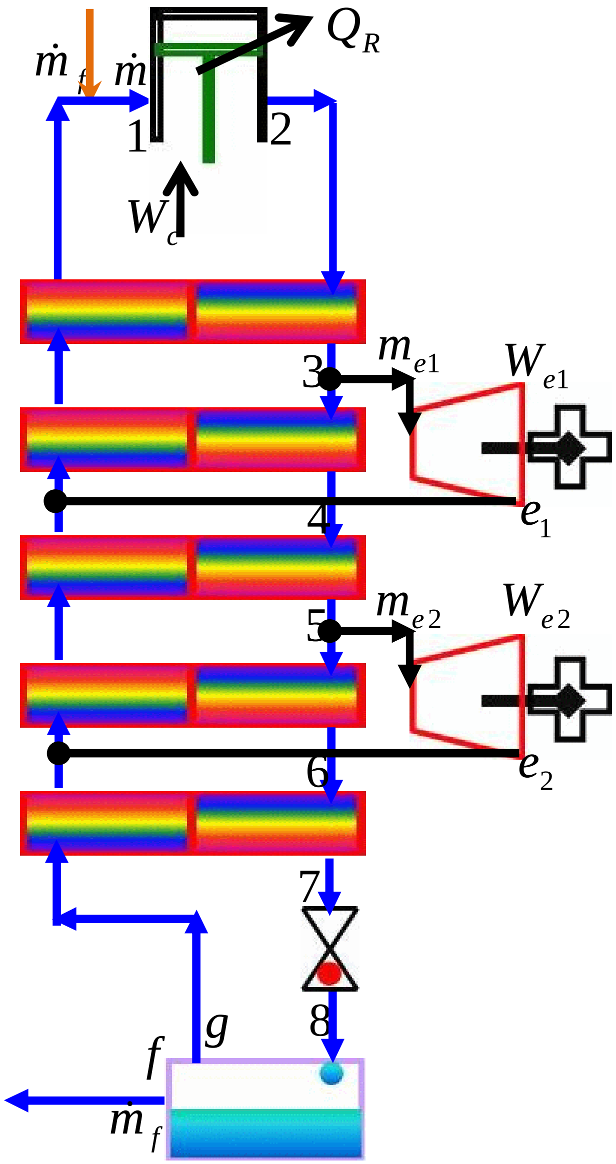
- The yield and work requirement of the system are given by the following equations.

$$y=\left(\frac{h_1-h_2}{h_1-h_f}\right)+x\left(\frac{h_3-h_e}{h_1-h_f}\right)$$

$$x=\frac{\dot{m}_e}{\dot{m}}$$

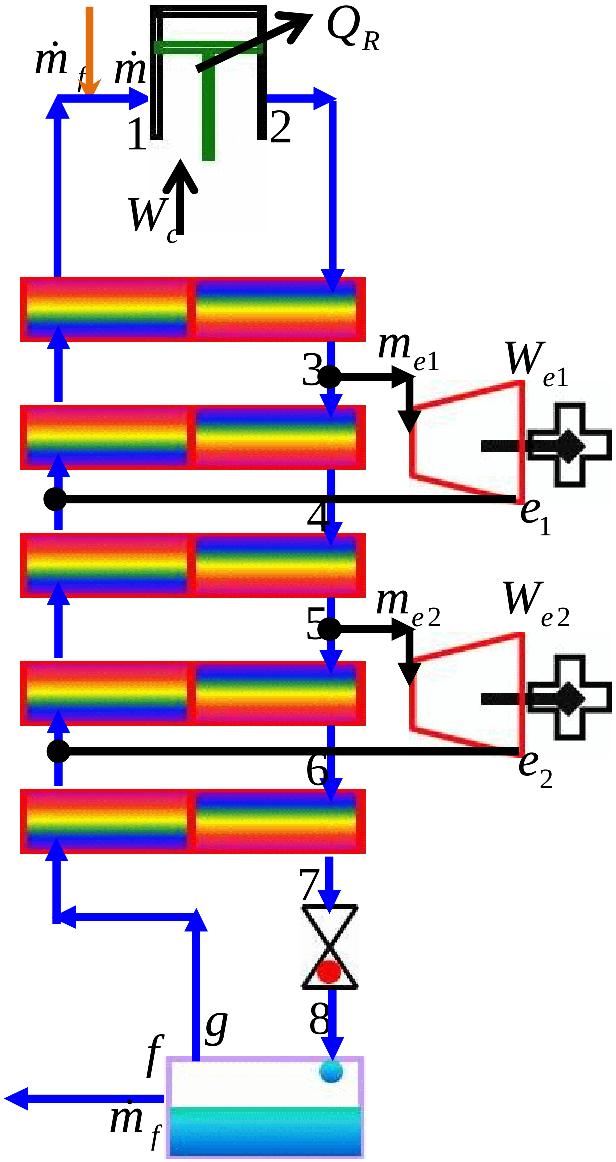
$$-\frac{W_{net}}{\dot{m}}=\begin{cases}\left(T_1\left(s_1-s_2\right)-\left(h_1-h_2\right)\right)\\ -x\left(h_3-h_e\right)\end{cases}$$

- Where, the expander mass flow ratio is denoted by **x**.



Collins System

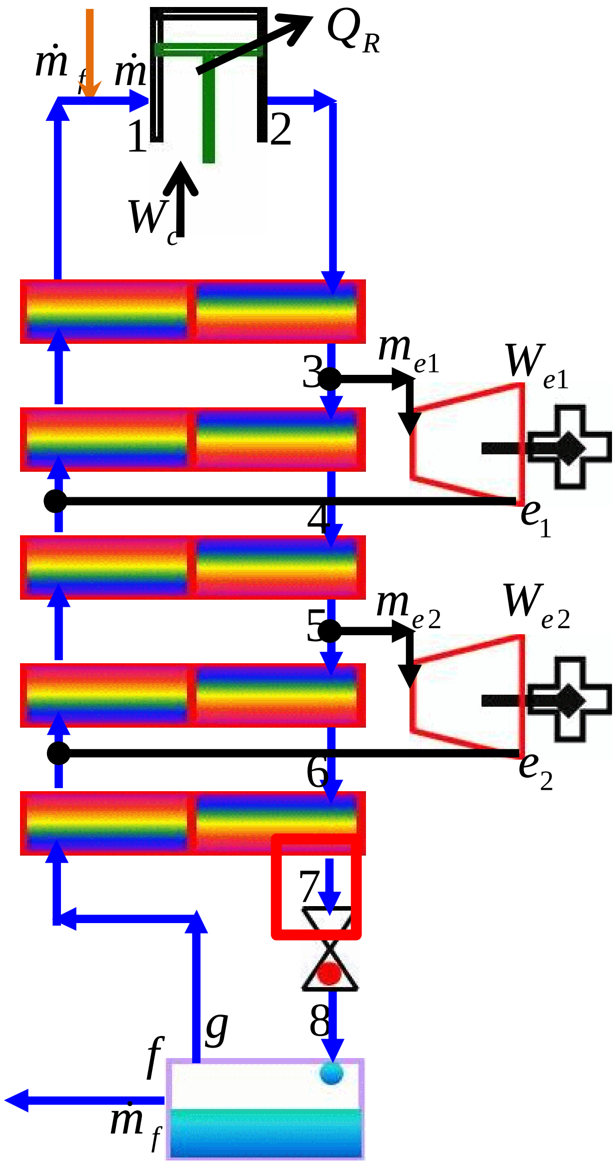
- The schematic of the Collins System is as shown.
- It was invented in the year 1946 by Samuel C. Collins at MIT, USA.
- This system is considered as one of the biggest milestones in Cryogenic Engineering.



Collins System

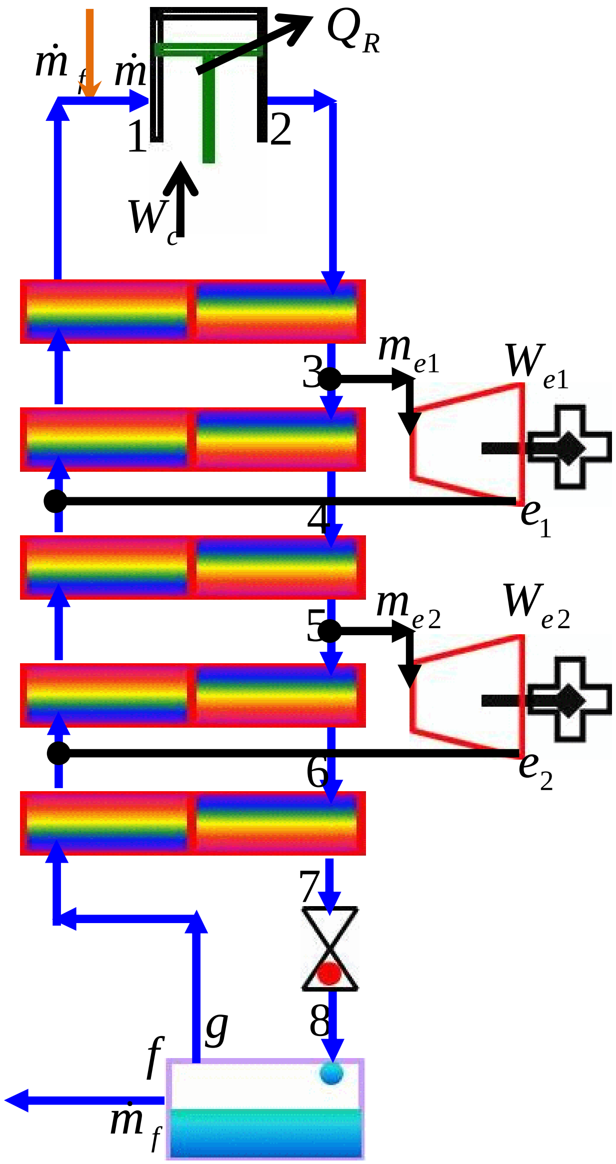
- This system is an extension to the Claude System.
- The system has a compressor, a J – T expansion device, a make up gas connection, five 2 – fluid heat exchangers and two turbo – expanders.
- Depending on the helium inlet pressure, two to six expansion devices are used.

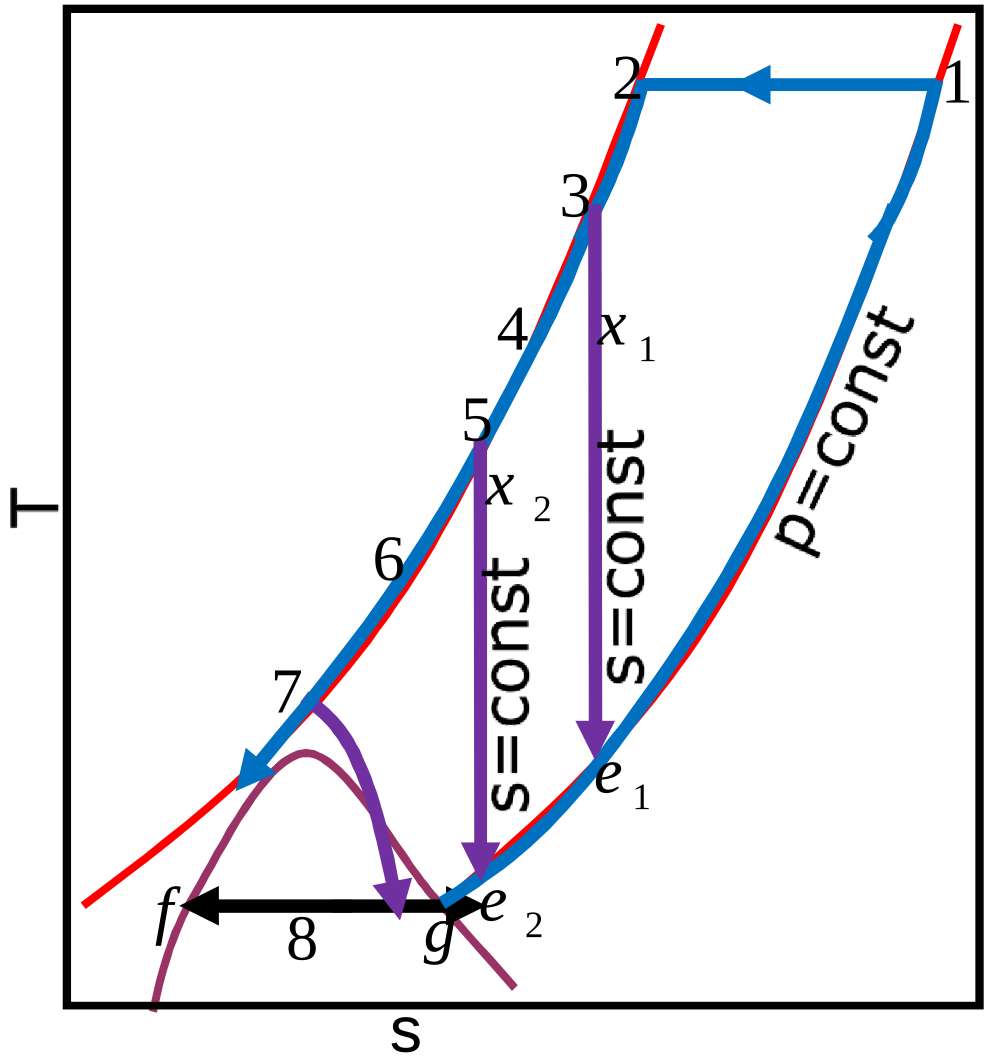
Collins System

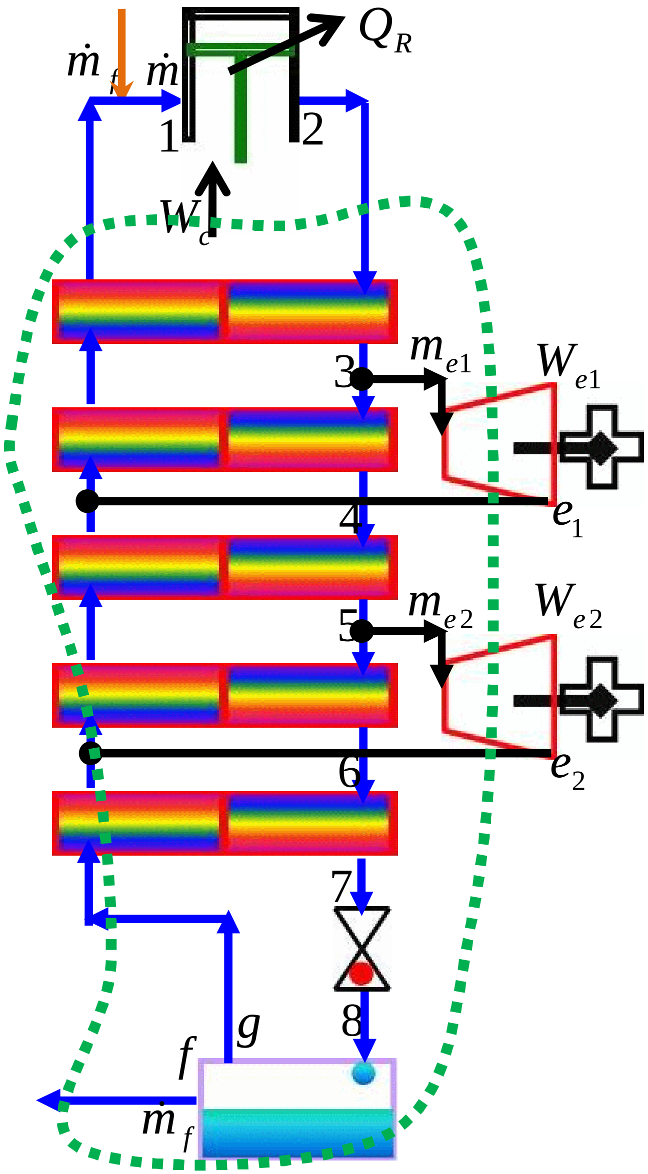


- Expansion engines are used to remove the heat from the gas and thereby to reach lower and lower temperatures.
- The inversion temperature of Helium is around 45 K and in order to have a yield, $\mathbf{T_7}$ should be less than 7.5 K.
- Depending upon the mass flow rates, two to six expanders are used.

Collins System







Collins System

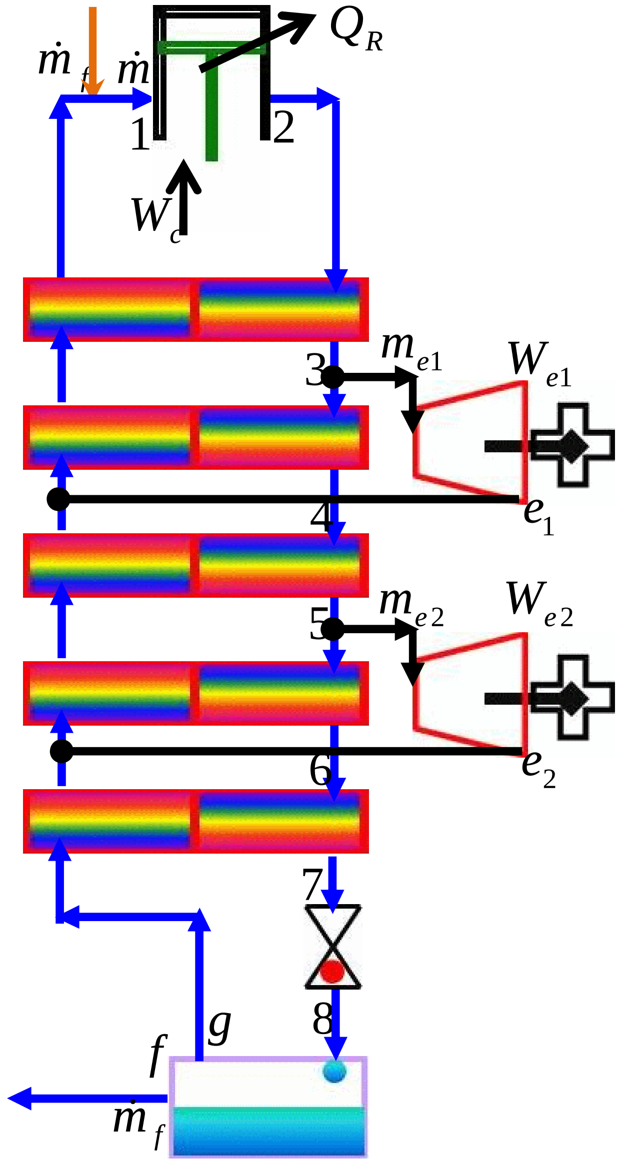
- Consider a control volume as shown in the figure.

IN	OUT
m @ 2	W_{e1}
	W_{e2}
	$m - m_f$ @ 1
	m_f @ f

- Applying 1st Law, we have

$$E_{in} = E_{out}$$

$$\dot{m}h_2 = W_{e1} + W_{e2} + \left(\dot{m} - \dot{m}_f\right)h_1 + \dot{m}_f h_f$$



Collins System

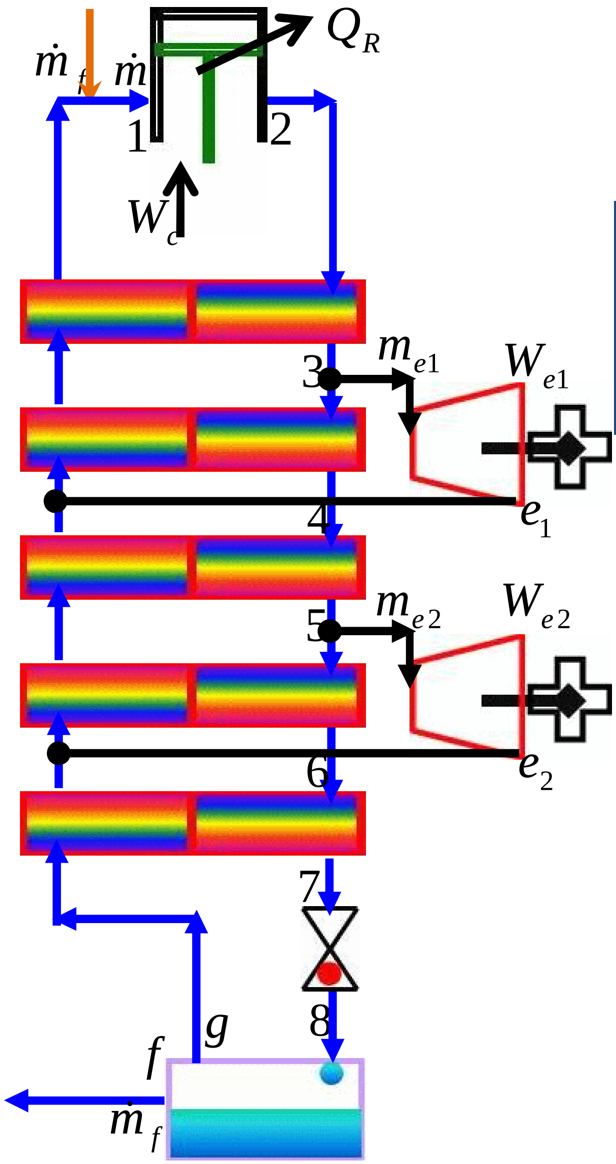
- Let the work done by each of the expander be

$$W_{e1} = \dot{m}_{e1}\left(\Delta h_1\right) \qquad W_{e2} = \dot{m}_{e2}\left(\Delta h_2\right)$$

- Δh_1 and Δh_2 are the enthalpy drops across the expander **1** and **2** respectively.

- Substituting, we get

$$\dot{m}h_2 = \begin{cases} \dot{m}_{e1}\left(\Delta h_1\right) + \dot{m}_{e2}\left(\Delta h_2\right) \\ +\left(\dot{m} - \dot{m}_f\right)h_1 + \dot{m}_f h_f \end{cases}$$



Collins System

- Rearranging, we have

$$y = \left(\frac{h_1 - h_2}{h_1 - h_f}\right) + x_1\left(\frac{\Delta h_1}{h_1 - h_f}\right) + x_2\left(\frac{\Delta h_2}{h_1 - h_f}\right)$$

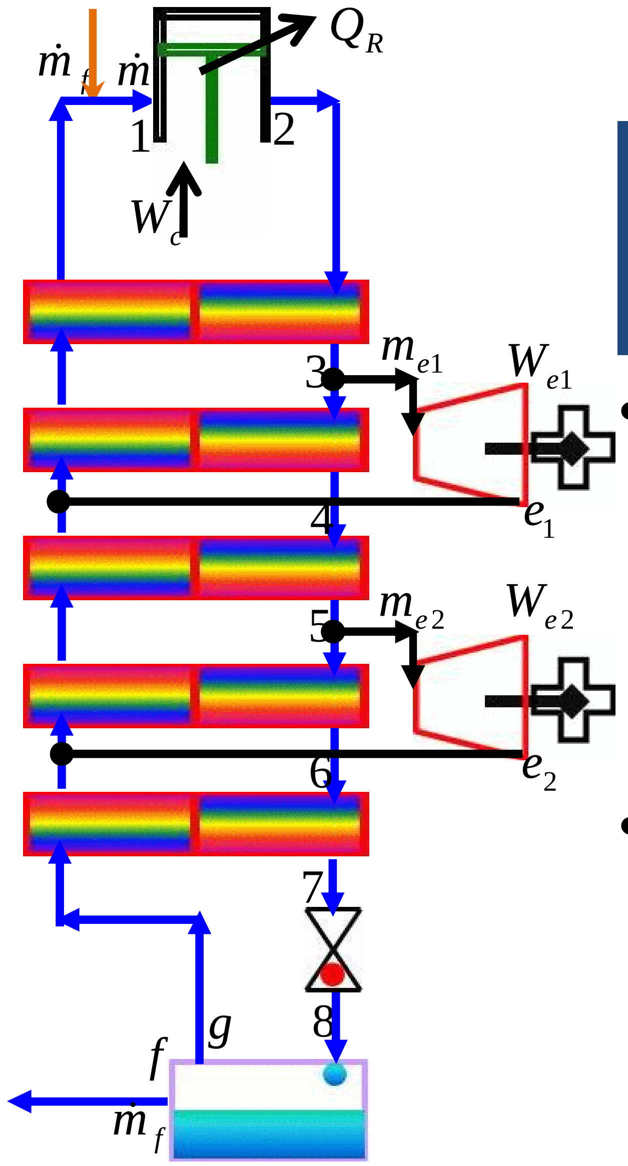
$$x_1 = \frac{\dot{m}_{e1}}{\dot{m}} \qquad x_2 = \frac{\dot{m}_{e2}}{\dot{m}}$$

$$\Delta h_1 = \left(h_3 - h_{e1}\right)$$

$$\Delta h_2 = \left(h_5 - h_{e2}\right)$$

- The 1st term is the yield for a simple L – H system.

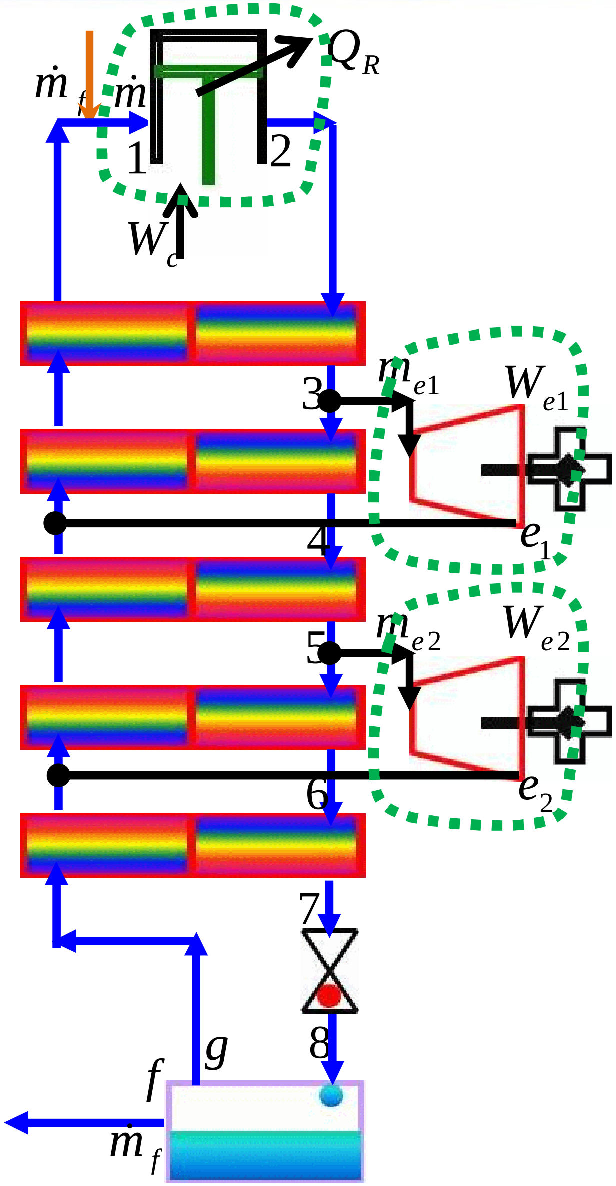
- The 2nd term is the change in the yield occurring due to the modification.



Collins System

$$y = \left(\frac{h_1 - h_2}{h_1 - h_f}\right) + x_1\left(\frac{h_3 - h_{e1}}{h_1 - h_f}\right) + x_2\left(\frac{h_5 - h_{e2}}{h_1 - h_f}\right)$$

- For a given initial and final conditions of **p**, the yield **y** depends on $\mathbf{h_3(T_3)}$, $\mathbf{h_5(T_5)}$, $\mathbf{x_1}$ and $\mathbf{x_2}$.
- Like in the Claude system, the values of $\mathbf{T_3}$, $\mathbf{T_5}$, $\mathbf{x_1}$ and $\mathbf{x_2}$ have to optimized to obtain a maximum yield.



Collins System

- As stated earlier, using a control volume, 1st and 2nd Laws for a compressor, we get

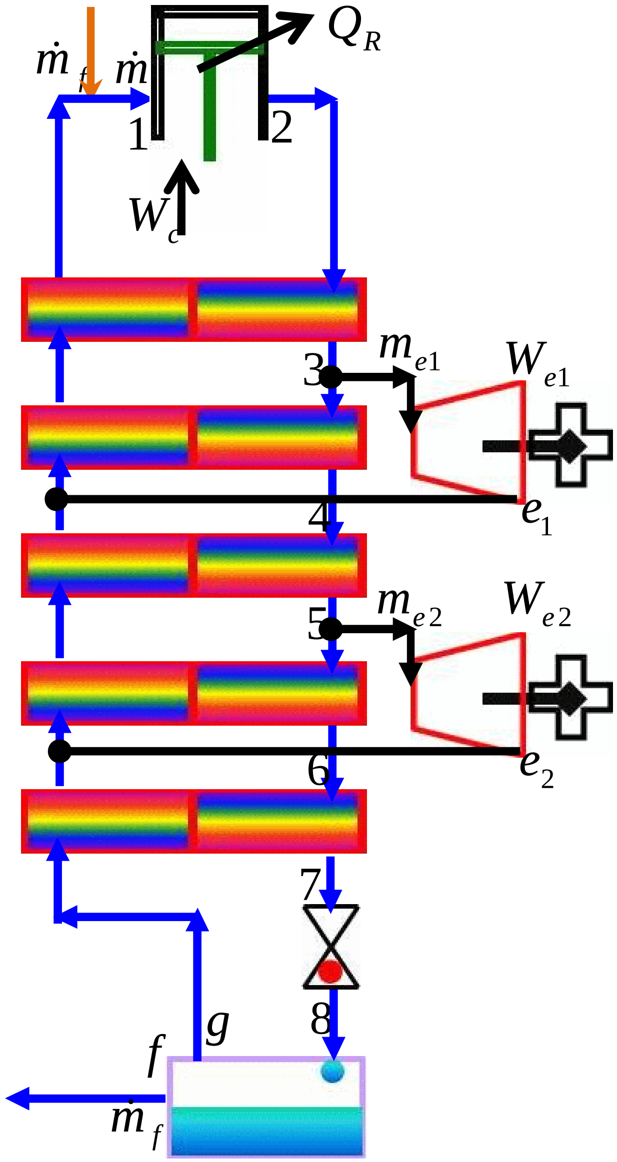
$$-W_c = \dot{m}\left(T_1\left(s_1 - s_2\right) - \left(h_1 - h_2\right)\right)$$

- Similarly, the control volume for an expansion engines, we get

$$W_{e1} = \dot{m}_{e1}\left(\Delta h_1\right) \qquad W_{e2} = \dot{m}_{e2}\left(\Delta h_2\right)$$

- The net work done is given by

$$\therefore \frac{-W_{net}}{\dot{m}} = -\frac{W_c}{\dot{m}} - \frac{W_{e1}}{\dot{m}} - \frac{W_{e2}}{\dot{m}}$$



Collins System

- Substituting, we have

$$\frac{-W_{net}}{\dot{m}} = \left\{ \begin{array}{l} \left(T_1\left(s_1 - s_2\right) - \left(h_1 - h_2\right)\right) \\ -x_1\left(\Delta h_1\right) - x_2\left(\Delta h_2\right) \end{array} \right.$$

$$x_1 = \dot{m}_{e1} / \dot{m} \qquad x_2 = \dot{m}_{e2} / \dot{m}$$

- The 1st term is the work requirement for a simple L – H system.
- The 2nd term is the reduction in work requirement occurring due to the modification.

Tutorial

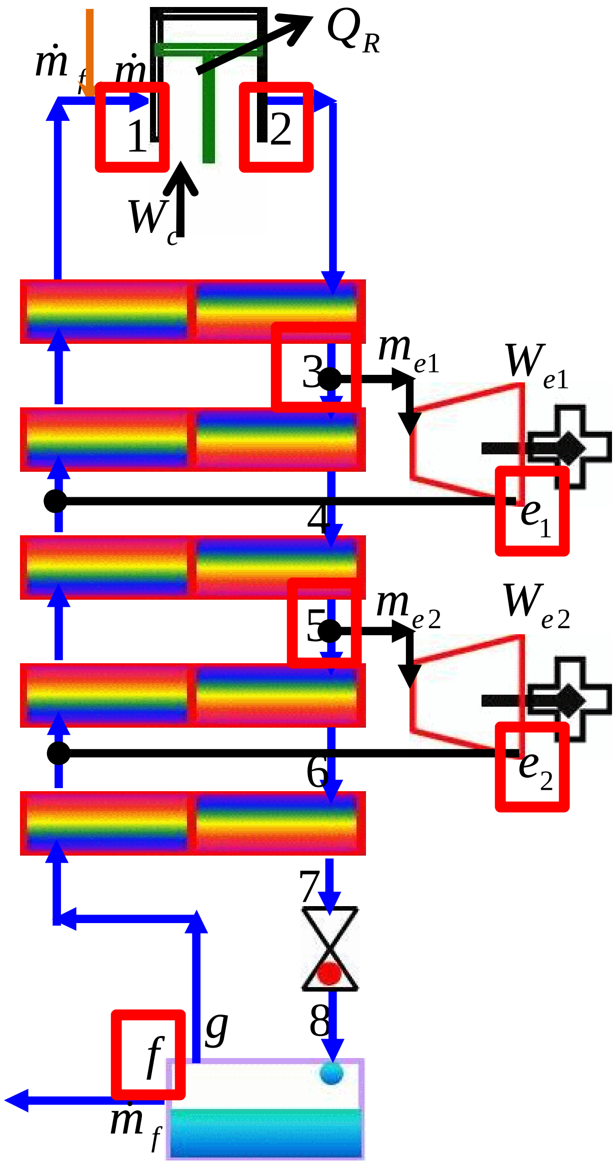
- Determine **y**, **W / m_f**, **FOM** for a Collins System with Helium as working fluid. The system operates between 1.013 bar (1 atm) and 15.19 bar (15 atm). The expander flow ratios are **x_1=0.6**, **x_2=0.2** respectively. The expander inlet conditions are as mentioned below.

Exp. Inlet Cond.	
I	60 K, 15 atm
II	15 K, 15 atm

Tutorial

Given
Cycle : Collins System
Working Pressure : 1 atm → 15 atm
Working Fluid : Helium
Expander 1: 15 atm, 60 K, x_1=0.4
Expander 2: 15 atm, 15 K, x_2=0.2

For above System, Calculate	
1	Work/unit mass of gas liquefied
2	FOM



Tutorial

	1	2	3
p (bar)	1.013	15.19	15.19
T (K)	300	300	60
h (J/g)	1587	1570	328
s (J/gK)	31.5	25.6	17.5

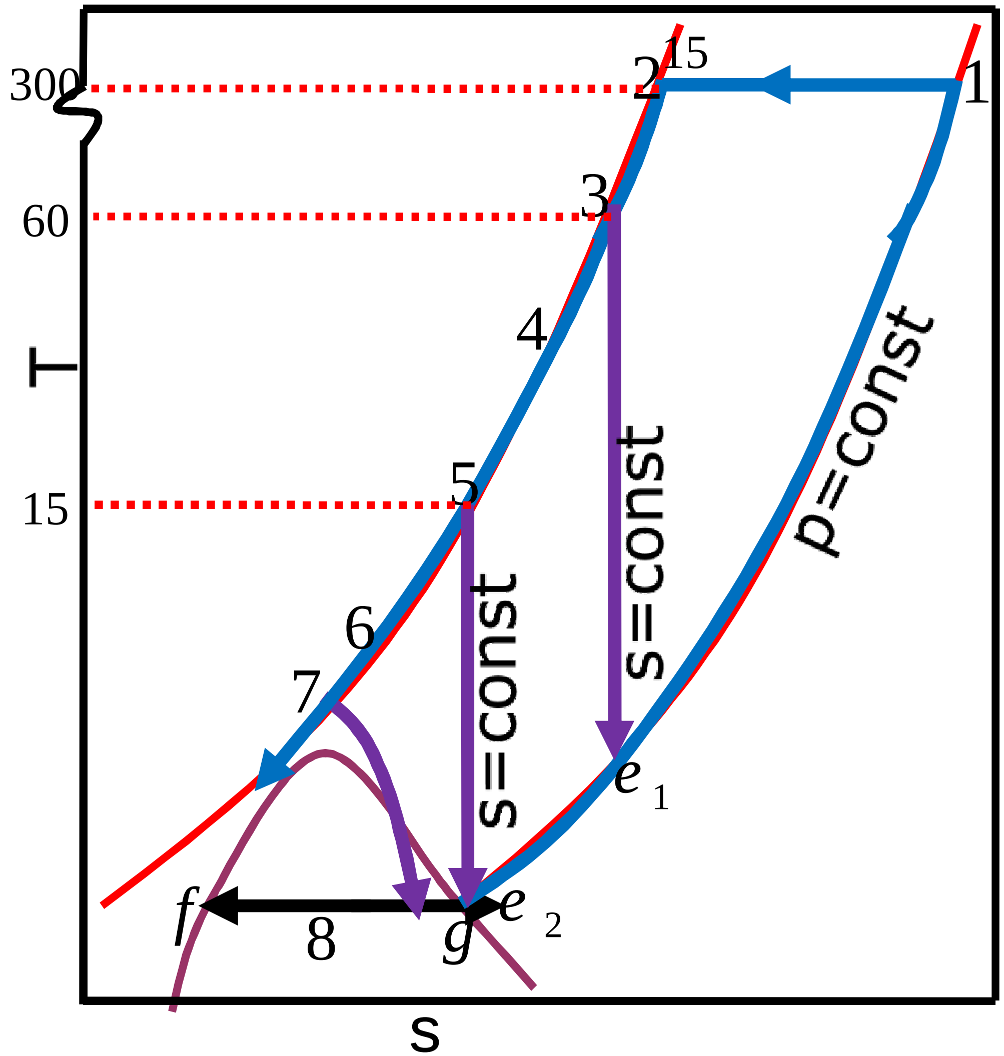
	5	e_1	e_2	f
p (bar)	15.19	1.013	1.013	1.01
T (K)	15	22	4.8	4.2
h (J/g)	81	130.0	38	9.5
s (J/gK)	9.25	17.5	9.25	3.4

* Points **e_1** and **e_2** are located on p=1bar line by drawing vertical lines from point **3** and **5**.

Tutorial

- The T – s diagram for a Collins System is as shown (not to scale).

- The expander inlet conditions are
  - 60 K
  - 15 K



Tutorial

- **Liquid yield**

$$y=\left(\frac{h_1-h_2}{h_1-h_f}\right)+x_1\left(\frac{h_3-h_{e1}}{h_1-h_f}\right)+x_2\left(\frac{h_5-h_{e2}}{h_1-h_f}\right)$$

	1	2	3	5	e_1	e_2	f
p	1.013	15.19	15.19	15.19	1.013	1.013	1.01
T	300	300	60	15	22	4.8	4.2
h	1587	1570	328	81	130.0	38	9.5
s	31.5	25.6	17.5	9.25	17.5	9.25	3.4

$$y=\frac{(1587-1570)}{(1587-9.5)}+0.4\frac{(328-130.0)}{(1587-9.5)}+0.2\frac{(81-38)}{(1587-9.5)}=0.066$$

Tutorial

- **Work / unit mass of He compressed**

$$\frac{-W_{net}}{\dot{m}} = \left(T_1\left(s_1 - s_2\right) - \left(h_1 - h_2\right)\right) - x_1\left(h_3 - h_{e1}\right) - x_2\left(h_5 - h_{e2}\right)$$

	1	2	3	5	e_1	e_2	f
p	1.013	15.19	15.19	15.19	1.013	1.013	1.01
T	300	300	60	15	22	4.8	4.2
h	1587	1570	328	81	130.0	38	9.5
s	31.5	25.6	17.5	9.25	17.5	9.25	3.4

$$-\frac{W_{net}}{\dot{m}} = \begin{cases} 300\left(31.5 - 25.6\right) - \left(1587 - 1570\right) \\ -0.4\left(328 - 130.0\right) - 0.2\left(81 - 38\right) \end{cases} = 1665.2\ J/g$$

Tutorial

- **Work / unit mass of He liquefied**

$$-\frac{\dot{W}_{net}}{\dot{m}} = 1665.2$$

$$y = 0.066$$

$$-\frac{\dot{W}_{net}}{\dot{m}_f} = -\frac{\dot{W}_{net}}{y\dot{m}} = \frac{1665.2}{0.066} = 25230.3 J/g$$

- **Figure of Merit (FOM)**

$$-\frac{\dot{W}_{net}}{\dot{m}_f} = 25230.3$$

$$-\frac{\dot{W}_i}{\dot{m}_f} = 6837$$

$$FOM = \frac{\dot{W}_i}{\dot{m}_f} / \frac{\dot{W}_{net}}{\dot{m}_f} = \frac{6837}{25230.3} = 0.271$$

Summary

- The compression and expansion processes in an actual Claude cycle are irreversible. These cause inefficiencies and deteriorate the performance of the system.
- Kapitza and Heylandt systems are the two modifications of the Claude System.
- In a Kapitza cycle, the regenerator/heat exchanger performs both gas cooling/warming and gas purification.

Summary

- Also, it was first system to use a turbo –expander (rotary type) instead of a reciprocating expander.

- Heylandt System is a high – pressure system, which is used in Air liquefaction (~200 atm).

- In this system, the inlet to the expander is ambient and hence, the lubrication on the high pressure side and the operation of the expander is greatly simplified.

Summary

- The Collins system is an extension to the Claude System and depending on the helium inlet pressure, two to six expansion devices are used.

- The yield and work requirement are given by

$$y = \left(\frac{h_1 - h_2}{h_1 - h_f}\right) + x_1\left(\frac{h_3 - h_{e1}}{h_1 - h_f}\right) + x_2\left(\frac{h_5 - h_{e2}}{h_1 - h_f}\right)$$

$$\frac{-W_{net}}{\dot{m}} = \left(T_1\left(s_1 - s_2\right) - \left(h_1 - h_2\right)\right) - x_1\left(h_3 - h_{e1}\right) - x_2\left(h_5 - h_{e2}\right)$$

- A self assessment exercise is given after this slide.

- Kindly asses yourself for this lecture.

Self Assessment

In a reversible Claude system, if $\mathbf{T_1}$, $\mathbf{T_2}$, $\mathbf{T_3}$ are held constant,

1. The $\mathbf{y_{max}}$ ________ with the decrease in $\mathbf{T_3}$.
2. $\mathbf{W / m_{fmin}}$ ________ with the decrease in $\mathbf{T_3}$.
3. The overall inefficiency of compressor is _____
4. The overall inefficiency of an expander is _____
5. Kapitza and Heylandt systems are the modifications of the _____ System.
6. ______ system is widely used in helium liquefaction.
7. The regenerator/heat exchanger performs both _____ & ________.

Self Assessment

8. ______ system was the first one to use a turbo – expander.
9. ______ system is a high – pressure Air liquefaction system.
10. In a Heylandt system, the inlet to the expander is at ________.
11. ______ system is considered as one of the biggest milestones in Cryogenic Engineering.
12. The inversion temperature of Helium is around _____.

Answers

1. Decreases
2. Increases
3. $\eta_{oval,c} = \eta_{mech,c} \times \eta_{iso,c}$
4. $\eta_{oval,e} = \eta_{mech,e} \times \eta_{ad,e}$
5. Claude
6. Collins
7. Gas cooling/warming, Gas purification
8. Kapitza
9. Heylandt

Answers

10. Ambient
11. Collins
12. 45 K

Thank You!