



## Improved collin system for liquefaction of helium

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### Abstract

A mathematical model was developed for Collin system and second law (energy-exergy analysis) is carried out by considering different input parameters. It was observed that the Second law efficiency of Collin system is 17.29 % and COP is 0.8687 when input at ambient condition and compressor pressure is 15 bar, but both start decreasing with further increases of compressor pressure whereas liquefaction mass ratio and Total work done is increases with increase in compressor pressure. Increase in Intermediate mass ratio of expander decrease the COP ,increase the second law efficiency, total work done and liquefaction mass of helium.

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*Keywords:* Collin system and second law (energy-exergy analysis)

### 1. Introduction

Cryogenics has been an important area of refrigeration because of its application in industrial and commercial utilization, and many scientific and engineering researches are going on by using low temperature liquefied gases. Cryogenics is a branch of physics which deals with the achieving very low temperatures (below the 173 K.) and study their effects on matter. Cryogenic study presents broad goals for cryogenic support for various gas liquefaction systems. Due to industrial revolution, various issues like cost, efficiency and reliability are the challenges factors in employment of cryogenic support technology. In past many fantastic claims have been made as to the degree of improve performance achieved by employing cryogenics technology. Cryogenic engineering is the application of low temperatures that cannot be observed on Earth or in the atmosphere around earth under natural conditions to practical problems. In refrigeration, the temperature from  $-100^{\circ}\text{C}$  to  $-273^{\circ}\text{C}$  (or absolute Zero) are treated as low temperatures and Cryogenics is the science connected with reaching and applying temperatures below 120K ( $-153^{\circ}\text{C}$ ) Today for achieving cryostat we uses many fluid but in due course some fluid considered as the main fluid to achieve cryostat and the temperature range of cryostat mostly depend upon the fluid we uses in apparatus.

### 2. Literature Review

Rijo Jacob Thomas [1] done exergy analysis to system on large

helium liquefier to get optimum parameters for geometric design. (I.e.compressor pressure, expander flow rates, heat exchanger surface area) by considering presence and absence of pressure drop (both) in the heat exchangers.

Ibrahim Dincer [2] is presented comprehensive exergy analysis of a multistage cascade refrigeration cycle used for natural gas liquefaction, which is a cryogenic process. The multistage cascade cryogenic system is described and an exergy analysis of the cycle components and the minimum work required for liquefaction are provided Rijo Jacob Thomas, et.al, [3] concluded that When one Brayton stage is split into two modified Brayton stages in the liquefaction of helium system without changing HX area is showed improvement and when two Brayton stages are combined to make one modified Brayton stages, the system performance deteriorates

W. K. Erdt, [4] pointed out the Linde helium refrigeration system combined an extremely compact construction by arranging three expansion turbines in the temperature region below 20 K, and one of which expands to roughly saturated liquid and obtained during more than one year of operation and observed that the results of system performance measurements, remarkably for good cycle efficiency

Yongliang Li, Xiang Wang and Yulong Ding, [5] proposed optimization methodology for thermodynamic design of large scale gas liquefaction Systems. This methodology take care of expander cycle design of liquefaction processes. Low exergy still the problem in all system of cryogenics. Various research methodology like computational, experimental can be done to

improve the efficiency Moses Minta, Joseph L. Smith Jr. (6) used "Entropy Flow Optimization Technique in the Helium Liquefaction Cycles

### 3. Thermodynamic Model

The main fluids to achieve very low temperature are methane, oxygen, nitrogen, neon, hydrogen and helium.

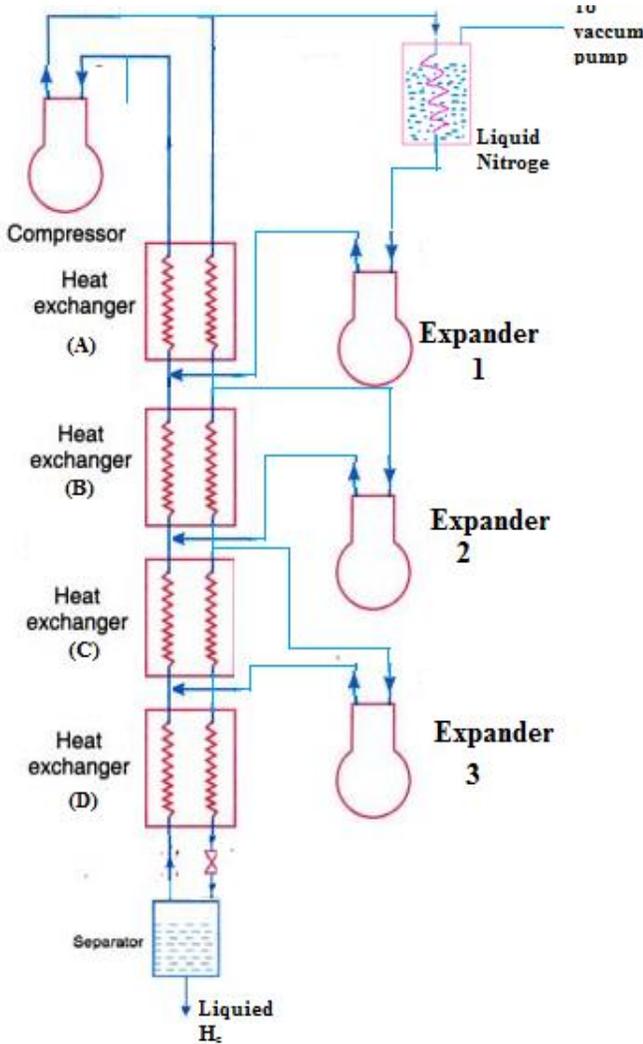


Figure 1: Block diagram of modified Helium liquefaction system

### 4. Mathematic modeling of Improved Collin system for liquefaction of Helium

$R\$ = 'Helium', P_1 = 1, T_1 = 77, T_0 = 298, P_2 = 11$   
 $T_1 = T_2$   
 $rx = 0.7, r1 = 0.1, r2 = 0.1, x = \frac{m_x}{m}, r1 = \frac{m_{e1}}{m}$   
 $r2 = \frac{m_{e2}}{m}, P_2 = P_3, P_2 = P_5, m = 10, T_f = T_g$   
 $x_0 = 0$   
 $W_{e1} = m_{e1} * (h_3 - h_{e1})$   
 $W_{e2} = m_{e2} * (h_4 - h_{e2})$   
 $W_{ex} = m_x * (h_x - h_{ex})$

$$Ed_{W_{e1}} = (m_{e1} * T_0 * (s_3 - s_{e1}))$$

$$Ed_{W_{e2}} = (m_{e2} * T_0 * (s_4 - s_{e2}))$$

$$Ed_{W_{ex}} = (m_x * T_0 * (s_x - s_{ex}))$$

$$y = \frac{m_f}{m}$$

Compressor

$$W_c = m * (T_1 * (s_1 - s_2) - (h_1 - h_2))$$

$$W_{net} = W_c + W_{e1} + W_{e2} + W_{ex}$$

Work done per mass of gas  $-\frac{W_{net}}{m} = Z$   
 Work done per mass of liq gas  $-\frac{W_{net}}{m_f} = T$

$$COP = \left( \frac{h_1 - h_f}{W_{net}} \right)$$

$$Q = m * (h_2 - h_1)$$

$$Ed_{comp} = \left( m * T_1 * (s_1 - s_2) - \left( Q * \left( \frac{T_0}{T_1} \right) \right) \right)$$

$$Eta_{2nd\%} = \left( \left( \frac{(h_f - h_1) - T_0 * (s_f - s_1)}{W_{net}} * m_f \right) * 100 \right)$$

#### 4.1 First Heat Exchanger (HX\_1) analysis

TypeHX<sub>1</sub>\$ = 'counterflow'  
 $epsilon_{HX1} = 0.85$   
 $T_{13} = T_{14}$   
 $T_{hi} = T_2$   
 $T_{15} = T_{c_o}$   
 $m_{h_{HX1}} = m - m_x$   
 $m_{c_{HX1}} = m - m_f$   
 $T_{h_o} = T_3$   
 $T_{c_i} = T_{14}$   
 $C_{h_{HX1}} = m_{h_{HX1}} * cp_{hotfluid_{HX1}}$   
 $C_{c_{HX1}} = m_{c_{HX1}} * cp_{coldfluid_{HX1}}$   
 $q_{HX1} = C_{h_{HX1}} * (T_{hi} - T_{h_o})$   
 $q_{HX1} = C_{dot_{c_{HX1}}} * (T_{c_o} - T_{c_i})$   
 $q_{max\_HX1} = C_{min\_HX1} * (T_{h_i} - T_{c_i})$   
 $epsilon_{HX1} = q_{HX1} / q_{max\_HX1}$

$$Ntu_{HX1} = \frac{q_{HX1}}{C_{min\_HX1} * (T_{h_i} - T_{c_i})}$$

$$Ntu_{HX1} = (G_{HX1}) / C_{min\_HX1}$$

$$Ex_{in_{HX1}} = m * ((h_2 - h_3) - (T_0 * (s_2 - s_3)))$$

$$Ex_{out_{HX1}} = (m - m_f) * ((h_{14} - h_{15}) - (T_0 * (s_{14} - s_{15})))$$

$$Ed_{HX1} = ((Ex_{in_{HX1}}) - (Ex_{out_{HX1}}))$$

#### 4.2 Second Heat Exchanger (HX\_2) analysis

TypeHX<sub>2</sub>\$ = 'counterflow'  
 $epsilon_{HX2} = 0.85$   
 First Mixing temperature  
 $T_{13} * (m - m_f) = m_{e1} * T_{e1} +$

$$\begin{aligned}
 &(m - m_f - m_{e1}) * T_{12} \\
 m_{h_{HX2}} &= m - m_{e1} - m_x \\
 m_{c_{HX2}} &= m - m_f - m_x \\
 C_{h_{HX2}} &= m_{h_{HX2}} * cp_{hotfluid_{HX2}} \\
 C_{c_{HX2}} &= m_{c_{HX2}} * cp_{coldfluid_{HX2}} \\
 q_{HX2} &= C_{h_{HX2}} * (T_3 - T_4) \\
 q_{HX2} &= C_{c_{HX2}} * (T_{13} - T_{12}) \\
 q_{max\_HX2} &= C_{min\_HX2} * (T_3 - T_{12}) \\
 \epsilon_{HX2} &= q_{HX2} / q_{max\_HX2} \\
 Ntu_{HX2} &= HX(TypeHX_{2\$}, \epsilon_{HX2}, C_{h_{HX2}}, C_{c_{HX2}}, 'Ntu') \\
 Ntu_{HX2} &= (G_{HX2}) / C_{dot\_min\_HX2} \\
 Ex_{in_{HX2}} &= (m - m_{e1} - m_x) * ((h_3 - h_4) - (T_0 * (s_3 - s_4))) \\
 Ex_{out_{HX2}} &= (m - m_f - m_x) * ((h_{12} - h_{13}) - (T_0 * (s_{12} - s_{13}))) \\
 Ed_{HX2} &= ((Ex_{in_{HX2}}) - (Ex_{out_{HX2}}))
 \end{aligned}$$

#### 4.3 Third Heat Exchanger( HX\_3) analysis

$$\begin{aligned}
 &TypeHX_{3\$} = 'counterflow' \\
 \epsilon_{HX3} &= 0.85 \\
 T_{10} &= T_9 \\
 \left\{ c_{pfluid} = 1.004 \left[ \frac{kJ}{kgK} \right] \right\} \\
 m_{h_{HX3}} &= m - m_{e1} - m_{e2} - m_x \\
 m_{dot_{c_{HX3}}} &= m - m_f - m_{e1} - m_x \\
 C_{h_{HX3}} &= m_{h_{HX3}} * cp_{hotfluid_{HX3}} \\
 C_{c_{HX3}} &= m_{c_{HX3}} * cp_{coldfluid_{HX3}} \\
 q_{HX3} &= C_{h_{HX3}} * (T_4 - T_5) \\
 q_{HX3} &= C_{c_{HX3}} * (T_{11} - T_{10}) \\
 q_{max\_HX3} &= C_{min\_HX3} * (T_4 - T_{10}) \\
 \epsilon_{HX3} &= q_{HX3} / q_{max\_HX3} \\
 Ntu_{HX3} &= HX(TypeHX_{3\$}, \epsilon_{HX3}, C_{h_{HX3}}, C_{c_{HX3}}, 'Ntu') \\
 Ntu_{HX3} &= (G_{HX3}) / C_{dot\_min\_HX3} \\
 Ex_{in_{HX3}} &= (m - m_{e1} - m_{e2} - m_x) * ((h_4 - h_5) - (T_0 * (s_4 - s_5))) \\
 Ex_{out_{HX3}} &= (m - m_f - m_{e1} - m_x) * ((h_{10} - h_{11}) - (T_0 * (s_{10} - s_{11}))) \\
 Ed_{HX3} &= ((Ex_{in_{HX3}}) - (Ex_{out_{HX3}}))
 \end{aligned}$$

#### 4.4 Fourth Heat Exchanger( HX\_4) analysis

$$\begin{aligned}
 &TypeHX_{4\$} = 'counterflow' \\
 \epsilon_{HX4} &= 0.85 \\
 c_{pfluid_{hot}} &= 5.192 \left[ \frac{kJ}{kgK} \right] \\
 &First Mixing temperature \\
 T_{10} * (m - m_f - m_{e1}) &= m_{e2} * T_{e2} +
 \end{aligned}$$

$$\begin{aligned}
 &(m - m_f - m_{e1} - m_{e2}) * T_9 \\
 m_{h_{HX4}} &= m - m_{e1} - m_{e2} - m_x \\
 m_{c_{HX4}} &= m - m_{e1} - m_x - m_f - m_{e2} \\
 C_{h_{HX4}} &= m_{h_{HX4}} * cp_{hotfluid_{HX4}} \\
 C_{c_{HX4}} &= m_{c_{HX4}} * cp_{coldfluid_{HX4}} \\
 q_{HX4} &= C_{h_{HX4}} * (T_5 - T_6) \\
 q_{HX4} &= C_{c_{HX4}} * (T_9 - T_g) \\
 q_{max\_HX4} &= C_{min\_HX4} * (T_5 - T_g) \\
 \epsilon_{HX4} &= q_{HX4} / q_{max\_HX4} \\
 Ntu_{HX4} &= HX(TypeHX_{4\$}, \epsilon_{HX4}, C_{h_{HX4}}, C_{c_{HX4}}, 'Ntu') \\
 Ntu_{HX4} &= (G_{HX4}) / C_{dot\_min\_HX4} \\
 Ex_{in_{HX4}} &= (m - m_{e1} - m_{e2} - m_x) * ((h_5 - h_6) - (T_0 * (s_5 - s_6))) \\
 Ex_{out_{HX4}} &= (m - m_{e1} - m_x - m_f - m_{e2}) * ((h_8 - h_9) - (T_0 * (s_8 - s_9))) \\
 Ed_{HX4} &= abs((Ex_{in_{HX4}}) - (Ex_{out_{HX4}})) \\
 h_g &= h_8 \\
 s_g &= s_8
 \end{aligned}$$

#### Heat Exchanger "C"

$$\begin{aligned}
 &m_x * h_2 + m_{LN} * HF_N = m_{LN_{evop}} * h_{vaccin} + m_x * h_x \\
 & \qquad \qquad \qquad m_{LN} = m_{LN_{evop}} \\
 &Enthalpy of Fusion \\
 HF_N &= Enthalpy_{fusion(Nitrogen)} \\
 s_{ex} &= s_x \\
 &Temperature of liquid nitrogen \\
 T_x &= 77
 \end{aligned}$$

#### Separator

$$\begin{aligned}
 &(m - m_{e1} - m_{e2} - m_x) * h_7 = m_f * h_f \\
 &+ (m - m_{e1} - m_{e2} - m_f - m_x) * h_g \\
 Ed_{sep} &= abs \left( T_0 * \left( (m_g * s_g - (m_g + m_f) * s_7) + \left( \frac{m_g * h_g - m_f * h_f}{T_0} \right) \right) \right) \\
 m_g &= (m - m_{e1} - m_{e2} - m_f - m_x) \\
 &J-T Valve \\
 h_6 &= h_7 \\
 x_1 &= 1 \\
 Ex_{in_{val}} &= (m - m_{e1} - m_{e2} - m_x) * ((h_6 - h_0) - T_0 * (s_6 - s_0)) \\
 Ex_{out_{val}} &= (m - m_{e1} - m_{e2} - m_x) * ((h_7 - h_0) - T_0 * (s_7 - s_0)) \\
 Ed_{val} &= abs(Ex_{in_{val}} - Ex_{out_{val}}) \\
 Ed_{comp\%} &= \left( \frac{Ed_{comp}}{Ed_{Heimpsys}} \right) * 100 \\
 Ed_{We1\%} &= \left( \frac{Ed_{We1}}{Ed_{Heimpsys}} \right) * 100
 \end{aligned}$$

$$Ed_{W_{e2}\%} = \left( \frac{Ed_{W_{e2}}}{Ed_{He_{impsys}}} \right) * 100$$

$$Ed_{W_{ex}\%} = \left( \frac{Ed_{W_{ex}}}{Ed_{He_{impsys}}} \right) * 100$$

$$Ed_{HX1}\% = \left( \frac{Ed_{HX1}}{Ed_{He_{impsys}}} \right) * 100$$

$$Ed_{HX2}\% = \left( \frac{Ed_{HX2}}{Ed_{He_{impsys}}} \right) * 100$$

$$Ed_{HX3}\% = \left( \frac{Ed_{HX3}}{Ed_{He_{impsys}}} \right) * 100$$

$$Ed_{HX4}\% = \left( \frac{Ed_{HX4}}{Ed_{He_{impsys}}} \right) * 100$$

$$Ed_{val}\% = \left( \frac{Ed_{val}}{Ed_{He_{impsys}}} \right) * 100$$

$$Ed_{sep}\% = \left( \frac{Ed_{sep}}{Ed_{He_{impsys}}} \right) * 100$$

$$Ed_{He_{impsys}} = Ed_{comp} + Ed_{W_{e1}} + Ed_{W_{e2}} + Ed_{W_{ex}} + Ed_{HX1} + Ed_{HX2} + Ed_{HX3} + Ed_{HX4} + Ed_{val} + Ed_{sep}$$

In Non-ideal gas any variable can be defined by two other dependent variable on them:

$$a_{non-ideal\ gas} = f(x(b, c))$$

Table 1: Variable Table (Collin improved system)

Variable (a)	Gas	Variable (b)	Variable (c)
$h_0$	R\$	$T_0$	$P_1$
$h_1$	R\$	$T_1$	$P_1$
$h_2$	R\$	$T_2$	$P_2$
$s_0$	R\$	$T_0$	$P_1$
$s_1$	R\$	$T_1$	$P_1$
$s_2$	R\$	$h_2$	$P_2$
$s_3$	R\$	$T_3$	$P_2$
$h_3$	R\$	$T_3$	$P_2$
$s_f$	R\$	$x_0$	$P_1$
$h_f$	R\$	$x_0$	$P_1$
$s_g$	R\$	$x_1$	$P_1$
$h_g$	R\$	$x_1$	$P_1$
$T_f$	R\$	$h_f$	$P_1$
$T_{e1}$	R\$	$s_3$	$P_1$
$h_{e1}$	R\$	$T_{e1}$	$P_1$
$s_{e1}$	R\$	$T_{e1}$	$h_{e1}$
$T_{e2}$	R\$	$s_4$	$P_1$
$h_{e2}$	R\$	$T_{e2}$	$P_1$
$s_{e2}$	R\$	$P_1$	$h_{e1}$
$s_x$	R\$	$T_x$	$P_2$
$T_{ex}$	R\$	$s_{ex}$	$P_1$
$h_x$	R\$	$T_x$	$P_2$
$h_{vacc\_in}$	R\$	$T_x$	$P_1$

$cp(hf)_{HX1}$	R\$	$T_2$	$P_2$
$cp(cf)_{HX1}$	R\$	$T_{14}$	$P_1$
$C_{min}$	-	$C_{hot\_HX1}$	$C_{cold\_HX1}$
$cp(hf)_{HX2}$	R\$	$T_3$	$P_2$
$cp(cf)_{HX2}$	R\$	$T_{14}$	$P_1$
$C_{min}$	R\$	$C_{hot\_HX2}$	$C_{cold\_HX2}$
$cp(hf)_{HX3}$	R\$	$T_4$	$P_2$
$cp(cf)_{HX3}$	R\$	$T_{13}$	$P_1$
$C_{min}$	R\$	$C_{hot\_HX3}$	$C_{cold\_HX3}$
$cp(hf)_{HX4}$	R\$	$T_6$	$P_2$
$cp(cf)_{HX4}$	R\$	$T_g$	$P_1$
$C_{min}$	R\$	$C_{hot\_HX4}$	$C_{cold\_HX4}$
$h_6$	R\$	$T_6$	$P_2$
$s_6$	R\$	$T_6$	$P_2$
$s_7$	R\$	$h_6$	$P_2$
$s_4$	R\$	$T_4$	$P_2$
$h_4$	R\$	$T_4$	$P_2$
$s_5$	R\$	$T_5$	$P_2$
$h_5$	R\$	$T_5$	$P_2$
$h_9$	R\$	$T_9$	$P_1$
$s_9$	R\$	$T_9$	$P_1$
$h_{10}$	R\$	$T_{10}$	$P_1$
$s_{10}$	R\$	$T_{10}$	$P_1$
$h_{11}$	R\$	$T_{11}$	$P_1$
$s_{11}$	R\$	$T_{11}$	$P_1$
$h_{12}$	R\$	$T_{12}$	$P_1$
$s_{12}$	R\$	$T_{12}$	$P_1$
$h_{13}$	R\$	$T_{13}$	$P_1$
$s_{13}$	R\$	$T_{13}$	$P_1$
$h_{14}$	R\$	$T_{14}$	$P_2$
$s_{14}$	R\$	$T_{14}$	$P_2$
$h_{15}$	R\$	$T_{15}$	$P_1$
$s_{15}$	R\$	$T_{15}$	$P_1$

### 5. Results and Discussions

In this system, performance of improved Collin system was analyzed on the basis of cycle pressure ratio and expander flow ratio. Fig. 2 shows the variation in COP and second law efficiency with the cycle pressure ratio. It has been seen that cycle second law efficiency first increase and then suddenly starts to decrease up to cycle pressure ratio 25. On the other hand, COP is continuously decreasing as shown in fig.2. Maximum second law efficiency and COP is found to be 54.19% and 0.07558, respectively.

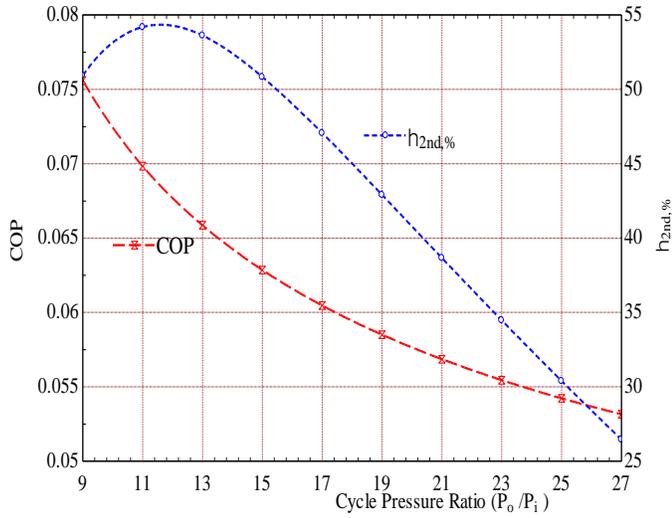


Figure 2: Variation in COP and second law efficiency with the cycle pressure ratio

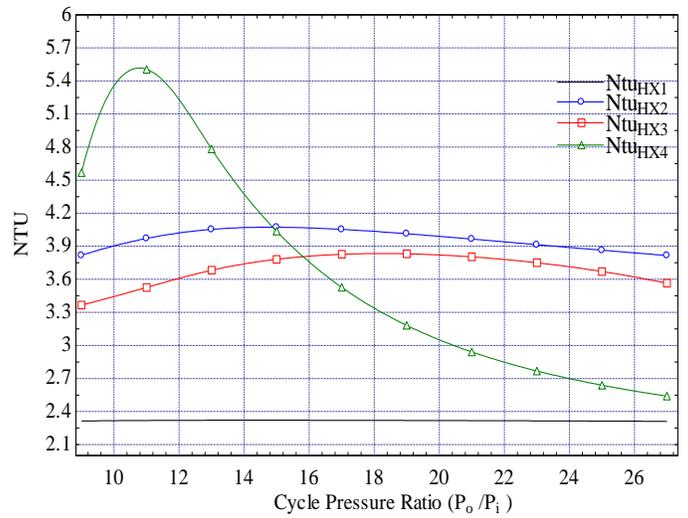


Figure 5: Variation in NTU in HX with cycle pressure ratio

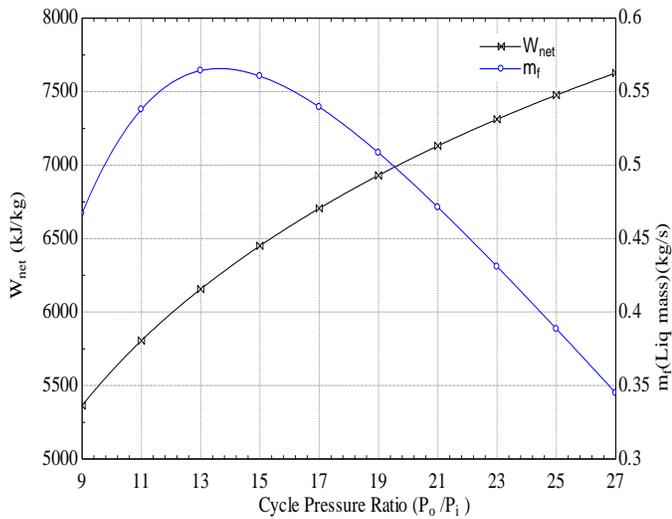


Figure 3: Variation in net work done and liquefaction mass flow with compressor pressure ratio

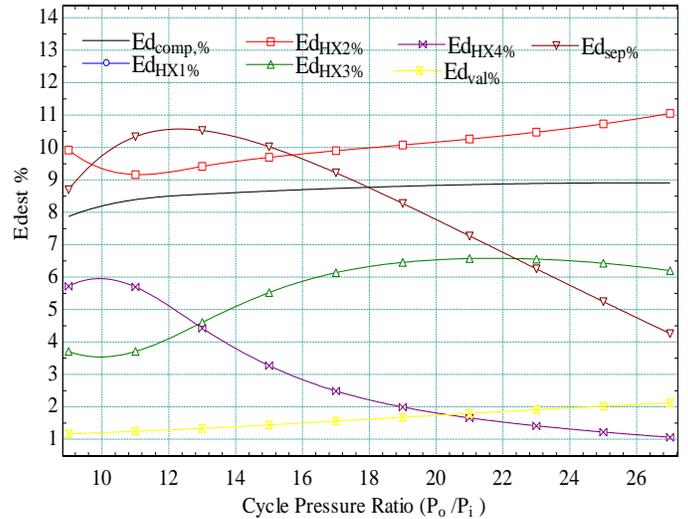


Figure 6: Variation in exergy destruction in HX with cycle pressure ratio

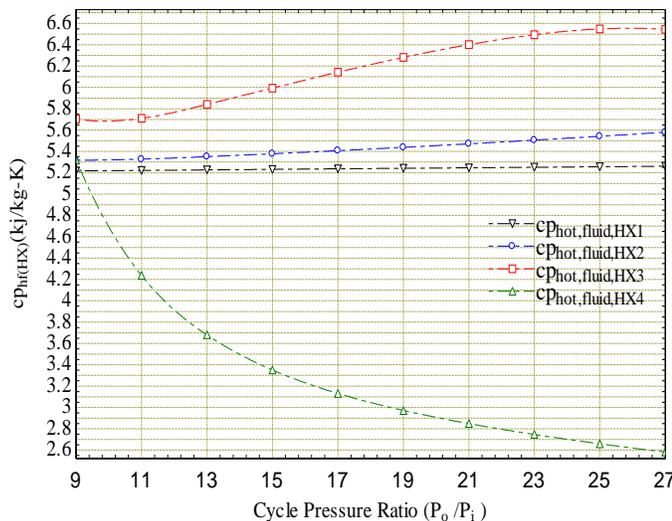


Figure 4: Variation in specific heat of hot fluid in HX with cycle pressure ratio

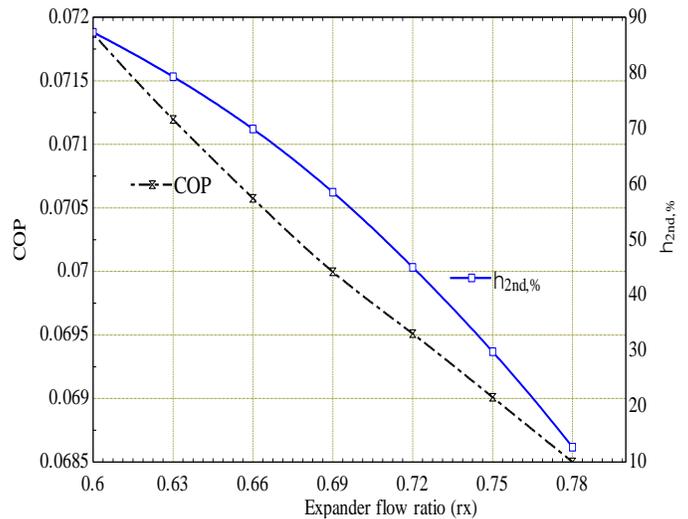


Figure 7: Variation in COP and second law efficiency with expander flow ratio

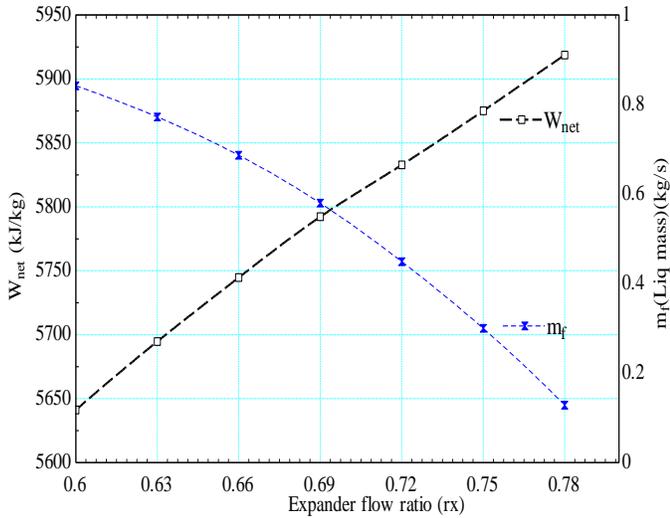


Figure 8: Variation in net work done and liquefaction mass flow with expander flow ratio

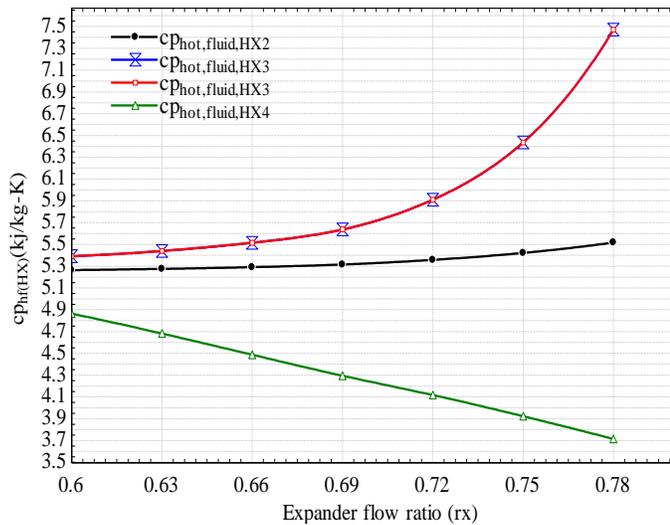


Figure 9: Variation in specific heat of hot fluid in HX with the expander flow ratio

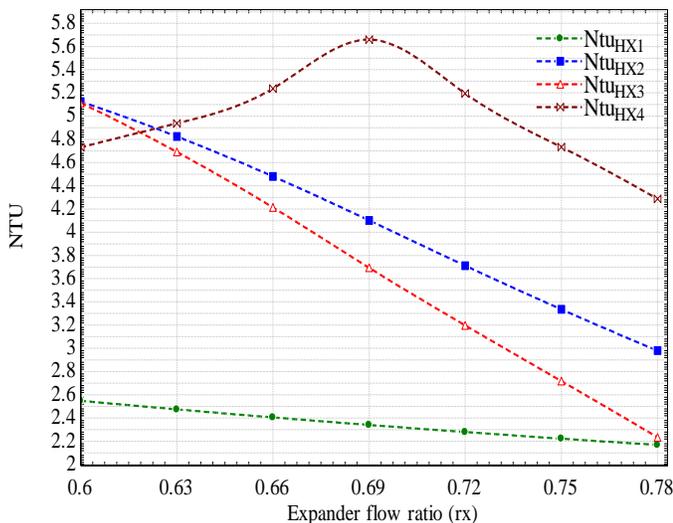


Figure 10: Variation in NTU in HX with the expander flow ratio

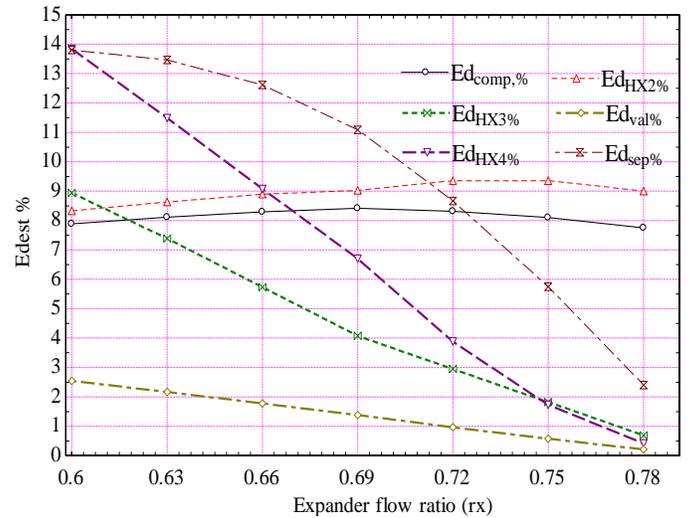


Figure 11: Variation in percentage exergy destruction rate with the expander flow ratio

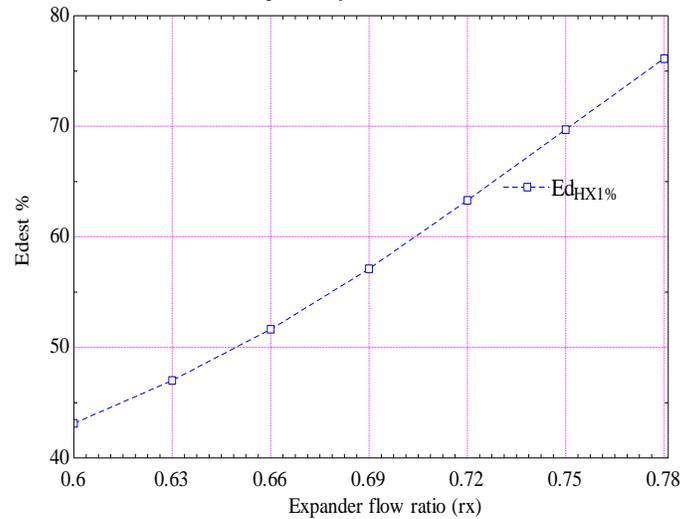


Figure 12: Variation in percentage exergy destruction with the expander flow ratio

Fig.3 indicates net work done and mass liquefaction rate with the cycle pressure ratio. Maximum liquefaction mass flow and net work done is found to be 0.5643kg/s and 7627kJ. Fig.4 illustrates the specific heat of hot fluid in all heat exchanger with the cycle pressure ratio. It has been analyzed that specific heat of hot fluid in HX3 continuously increasing with the cycle pressure ratio of 9 to 27. While the specific heat of hot fluid in HX2 and HX1 slightly increasing. Apart from this, specific heat of hot fluid in HX4 is continuously decreasing for the prescribed cycle pressure ratio limit. Fig. 5 shows the variation in NTU with the cycle pressure ratio. It has been seen that NTU in HX1 remain a constant value and NTU in HX2 first increasing slightly, and then continuously shows the decreasing behavior followed by the graph of NTU in HX2. Finally, the NTU in HX4 increasing sharply first up to cycle pressure ratio 11 and then suddenly decreasing up to minimum value. Fig.6 demonstrates the variation in exergy destruction rate in compressor, HX1, HX2, HX3, HX4, separator and valve, respectively. Exergy destruction rate in compressor, valve, HX2 and HX3 shows continuously increasing behavior.

While separator and HX4 initially illustrates the increasing trend and then continuously decreasing. Fig.7 shows the variations in COP and second law efficiency with the expander flow ratio. It has been observed that both COP and second law efficiency both decreasing continuously and the maximum value of COP and second law efficiency is found to be 0.07187 and 87.29%, respectively. Fig.8 indicates the variation in liquefaction mass flow rate and net work done with the expander flow ratio. It has been seen that liquefaction mass flow rate continuously decreasing and net work done continuously shows an increasing trend between the expander flow ratios from 0.6 to 0.78. Fig.9 illustrates the variation in specific heat of hot fluid in HX with the expander flow ratio. It has been seen that specific heat of hot fluid in HX1 and HX3 shows the same value and it is continuously increasing. On the other hand, specific heat of hot fluid in HX2 shows slightly increasing behavior. While, specific heat of hot fluid shows a decreasing trend with in limit of expander flow ratio. Fig.10 shows the NTU in HX1, HX2, HX3 and HX4 with the expander flow ratio of 0.6 to 0.78. It has been seen that NTU in HX1, HX2 and HX3 shows a decreasing behavior. On the other side, NTU in HX4 continuously increasing first up to 0.69 and then its graph starts decreasing. Fig.11 and fig.12 shows percentage exergy destruction compressor, HX1, HX2, HX3, HX4, valve and separator with the expander flow ratio. It has been notice that percentage exergy destruction in compressor up to 0.69 and then starts to decrease. It has been observed that percentage exergy destruction in HX1 and HX2 continuously shows an increasing trend. While, percentage exergy destruction in HX3, HX4, separator and valve has an decreasing behavior between the prescribed limit of 0.6 to 0.78

## 6. Conclusions

Following conclusions were made from investigation

- (1) Exergy analysis is powerful tool of optimization. of refrigeration systems which showed very low exergy efficiency
- (2) High exergy efficiencies (52% for hydrogen and 58% for methane and nitrogen) are achievable on very general consumptions
- (3) At Different pressure values the system is analysed to find best pressure ration for optimum number of stages for liquefaction process
- (4) More alternate arrangements of Helium cycle can be explore to enhance its thermal efficiency

## References

- [1] Rijo Jacob Thomas, et.al.“Application of exergy analysis in designing helium liquefiers” 7th Biennial International Workshop “Advances in Energy Studies” Volume 37, Issue 1, January 2012, Pages 207–219.
- [2] Ibrahim Dincer and Marc A. Rosen “Exergy Analysis of Cryogenic and Liquefaction Systems” Exergy (Second Edition) Energy, Environment and Sustainable Development, 2013.
- [3] Rijo Jacob Thomas, et.al, (2012) “ Exergy based analysis on different expander arrangements in helium liquefiers” international journal of refrigeration 35.

- [4] W. K. Erdt, P. Frandsen, D. Güsewell, K. Kurtcuoglu, K. Löhlein, A.-E. Senn, N. O. Solheim, U. Wagner, G. Winkler and B. Ziegler, “Performance of an Efficient 6 Kw Helium Refrigerator for the LEP 200 Project at CERN” ,Advances in Cryogenic Engineering, Volume 39, 1994, Pages 553-561.
- [5] Yongliang Li, Xiang Wang and Yulong Ding, (2012) “An optimal design methodology for large-scale gas liquefaction” , Applied Energy 99 (2012) , Pages 484–490.
- [6] Moses Minta, Joseph L. Smith Jr. (,1984) “An Entropy Flow Optimization Technique for Helium Liquefaction Cycles” Advances in Cryogenic Engineering , ,Pages 469-478