Thermodynamic performance of modified collin cryonic system using energy-exergy analysis for liquefaction of helium gas

R. S. Mishra, Devendra Kumar

Department of Mechanical, Production & Industrial and Automobiles Engineering, Delhi Technological University, Delhi, India

Abstract

Cryogenics systems are which are capable of producing temperature below 150. In the Collin cryogenic systems, a detailed thermodynamic second law analysis have not been reported in literature so far , however in the modification of Collin systems , the yields of liquefied mass of gases is very limited available in literature so far. A comprehensive energy and exergy analysis of Collin cryogenic systems for various gases is carried out in this paper by using various properties variables because cycle pressure ratio is very important factor which highly effect the performance parameters of system .Choice of optimum Pressure Ratio PR increases the overall efficiency of Collin cryogenic system. It was observed that the outlet temperature of compressor affect the performance parameters of system. The second law efficiency decreasing with increasing compressor outlet temperature Similarly liquefaction rate is decreasing with increase outlet temperature of compressor and optimum expander flow fraction 0.55 flow ratio and optimum second law efficiency is 3.5 %, while first heat exchanger (HX1) shows highest rate of exergy destruction ranging from 36 % to 24 % with increase in temperature from 200 K to 400 K. The work done requirement is increases up to pressure ratio 13 and then it start decreasing at a very fast rate with increase in pressure ratio of system.   © 2017 ijrei.com. All rights reserved

Keywords: Thermodynamics Analysis, Collin Cryonic System, Energy-Exergy Analysis, First and second Law Analysis

1.   Introduction

Normally cryogenics systems are which are capable of producing temperature below -150. According to National Institute of Standard and Technology Boulder, Colorado the temperature of cryogenics is start below from -180 (93.15 K) ,This Temperature consider as the dividing line because boiling point of permanent gases (helium, hydrogen, oxygen, nitrogen and air like gases).Various process are design and invent to achieve cryo temperature at different level of lower temperature Cryogenics is used in various important process at different level with different naming like cryobiology, cryonics, cryo-electronics, cryotrons, cryosurgery etc. Cryogenics is very crucial for aerospace application. This technology is very critical for wind tunnel testing application. High performance wind tunnel required rapid movement of nitrogen gas around the aerodynamic circuit. Cryogenic is required for Frozen Food Industries for preservation of food item depending upon type of food item and whether they are cooked or not before freezing. Cryogenic has got lot of application in medical field. It is wildly used in MRI

equipment for diagnosis of diseases. Cryogenic has got a great role in chilled water storage system. The liquefy gases are store in special containers called Dewar flask. To transfer this liquid from carrier to tank the pump which used are called cryogenics transfer pumps. Cryogenic Process to liquefy air which is further extent to extract various particular gases like oxygen, nitrogen, etc. In this process liquefaction and purification of Helium, Nitrogen gases are done. Also using this technique production of inert gases is also be done. Today cryogenics industries are a billionaire industry and lots of research is going on to achieve best one improved process. Various analyses is done to identify the loop hole of process and to rectify it to their upper level.

2.   Liquefaction of Helium

Cryogenic Technology is used for production of Gases for industrial and commercial applications. The helium is the most difficult of all gases to liquefy. At atmospheric pressure, it boils at approximately -269oC. Its maximum inversion

Corresponding author: R.S. Mishra
Email Id:rsmishradtu@gmail.com

temperature is about -234oC. The helium was first liquefied by Onnes H.K in the University of Leiden in 1908. It can be liquefied by an arrangement similar to the hydrogen liquefier where both liquid nitrogen and hydrogen are used for pre-cooling. The disadvantages of hydrogen liquefaction system include the higher cost and hazardous nature of liquid hydrogen. Similarly helium may also be liquefied by using Claude principle, where expanders are used for producing refrigeration. Fig-1(a) shows a system developed by Dr. S.C. Collins for liquefaction of helium. In this system, helium at a pressure of approximately 12 atmospheres is supplied to the liquefier by a four stage compressor. The part of helium is pre-cooled by the liquid nitrogen. By using this combination of heat exchangers and expander are shown in Fig-1(a) and T-S-diagram is also shown in Fig-1(b) respectively .The high pressure helium gas may be cooled to about -257⁰C. The helium gas thus obtained is throttled to atmospheric pressure to product liquid helium at -269oC. Dr. Collins is found that for one such plant, a liquefaction rate of 25 to 32 liters per hour may be obtained with a power requirement of 45kW. Various research and different method are employed to increase efficiency of cryo system. Second law efficiency are very low in all system.
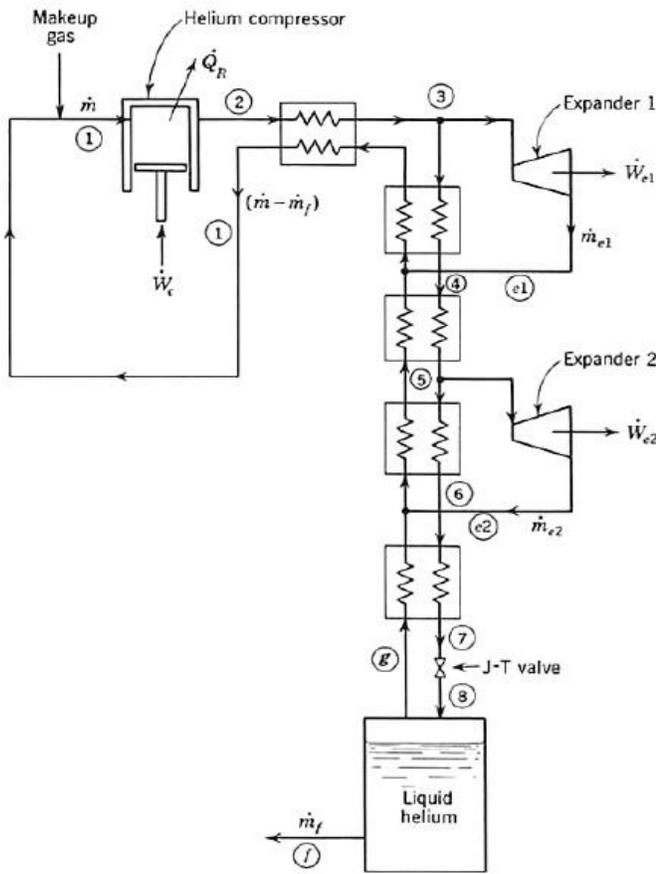
Figure 1(a): Schematic of modified Collin cryonic system

3. Literature Review

Various research and different method are employed to increase efficiency of cryo system. Exergy analysis is a strong method to identified inefficiencies of system and tells which part of system is critical and need to be undertake study. From literature various data collected which help in optimization of cryogenic system.

The Bejan [1] work is basis of all exergetic analysis of heat exchangers. Various problems are studied related to exergy analysis which are mentioning or summarized in [2], from the vast study it noticed that most new methods differ only in the way that entropy generation is non-dimensional [3]. A good exergetic design of a heat exchanger would allow for an increase in the global efficiency of the process, by defining a thermodynamic cycle in which the exergetic losses would be limited [4].

The major cause of exergy loss is the use of compressors and to a lesser extent the use of turbines [5] H. Mahabadipour and H. Ghaebi [6] carried out Thermodynamic (energy –exergy) analysis of and comparison of two expander cycles used in refrigeration system of olefin. Recep Yumrutaş, Mehmet Kunduz, Mehmet Kanoğlu [7] also carried out Exergy analysis of vapor compression refrigeration systems. Gadhiraju Venkatarathnam [8], carried out Simulation of cryogenic processes and compared the performance s of the systems. From literature it noticed that exergy efficiency depend upon mainly upon the inlet condition of the system but which inlet condition best suit for a particular type of the system that is main work of research except to increase the whole system efficiency stress are done on particular parts of system and research are done on that systems. After reviewing literature it conclude that every part of system has its own and equal importance because ones effect on another whether it is small or big create a lot of difference in proper analysis of system. Ignoring one small system due less effect can put gap in complete research analysis of system that why it quite important take all parts of system as one and finding out the every part impact on another to calculate right equation for high output. Air separation unit and compressor, condenser and evaporator of cryo system are the center of research because most of exergy destruction takes place in these parts. Heat exchanger and expansion valve, expander and other addition parts should also properly analyze Advanced technologies are used in very limited way and only on some of system such as Collin cryonic system. Therefore following objectives of present investigation are

(i) energy-exergy analysis of Collin cryogenic systems and to find out optimum exergy destruction in individual component and (ii) Suggestion for reducing exergy destruction losses in whole systems and there components

In this analysis, the effects of pressure ratio and outlet temperature of compressor on various energy- and exergy-based performance parameters are investigated.

4. Mathematical Analysis of Collin system

Fig: 1(b) show the schematic diagram of Collin system along with and T-S diagram in Fig-1(b). The following numerical values have been used for modeling of modified Collins cryogenic system.
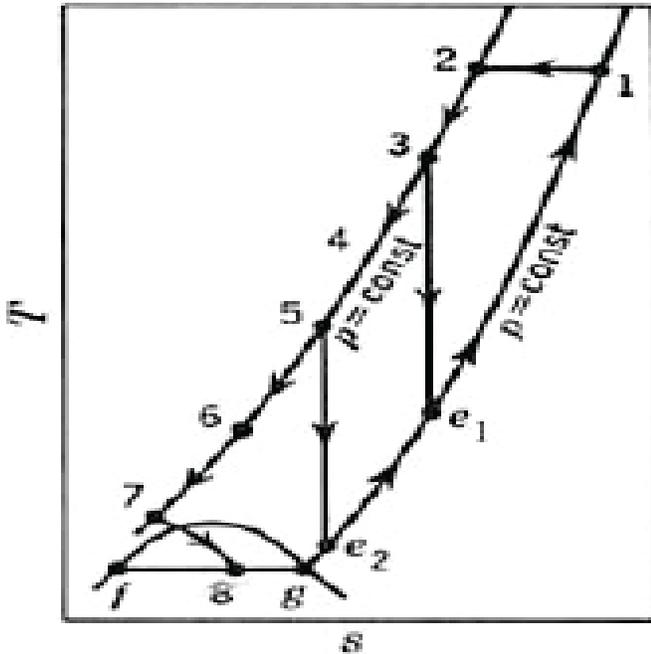

Figure 1(b: T-S Diagram of Collin system

$R\$ =' \, Helium'$
$P_1 = 1.013, T_2 = 300, T_0 = 298, P_2 = 11, T_1 = T_2, r1 = 0.5$
$r2 = \frac{r1}{2}, r1 = \frac{m_{e1}}{m}, r2 = \frac{m_{e2}}{m}, P_2 = P_3, P_2 = P_5, m = 20$
$T_f = T_g, x_0 = 0$

4.1 Control Vol except compressor

$m * h_2 = W_{e1} + W_{e2} + (m - m_f) * h_1 + m_f * h_f$
$W_{e1} = m_{e1} * (h_3 - h_{e1})$
$W_{e2} = m_{e2} * (h_5 - h_{e2})$
$Ed_{W_{e1}} = (m_{e1} * T_0 * (s_3 - s_{e1}))$
$Ed_{W_{e2}} = (m_{e2} * T_0 * (s_5 - s_{e2}))$
$y = \frac{m_f}{m}$
Compressor
$W_c = m * (T_2 * (s_1 - s_2) - (h_1 - h_2))$
$Q = m * (h_2 - h_1)$
$Ed_{comp} = \begin{pmatrix} m * T_1 * (s_1 - s_2) - \\ \left(Q * \left(\frac{T_0}{T_1} \right) \right) \end{pmatrix}$
$W_{net} = W_c + W_{e1} + W_{e2}$
$-\frac{W_{net}}{m} = Z$ Work done per mass of gas

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

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

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

4.2 First Heat Exchanger(HX_1) analysis

$TypeHX_{1\$} =' \, counterflow'$
$epsilon_{HX1} = 0.85, T_{h_i} = T_2, T_{15} = T_{c_o}, m_{h_{HX1}} = m$
$m_{c_{HX1}} = m - m_f, T_{h_o} = T_3, T_{c_i} = T_{14},$
$C_{h_{HX1}} = m_{h_{HX1}} * cp_{hot_{fluid_{HX1}}}$
$C_{c_{HX1}} = m_{c_{HX1}} * cp_{cold_{fluid_{HX1}}}$
$q_{HX1} = C_{h_{HX1}} * (T_{h_i} - T_{h_o})$
$q_{HX1} = C_{c_{HX1}} * (T_{c_o} - T_{c_i})$
$q\_max\_HX1 = C\_min\_HX1 * (T\_h\_i - T\_c\_i)$
$epsilon\_HX1 = q\_HX1/q \max._{HX1}$
$Ntu_{HX1} = HX \begin{pmatrix} TypeHX_{1\$}, \\ epsilon_{HX1}, C_{h_{HX1}}, C_{c_{HX1}}, 'Ntu' \end{pmatrix}$
$Ntu\_HX1 = (G\_HX1)/C \min._{HX1}$
$Ex_{in_{HX1}} = m * \begin{pmatrix} (h_2 - h_3) - \\ (T_0 * (s_2 - s_3)) \end{pmatrix}$
$Ex_{out_{HX1}} = (m - m_f) * \begin{pmatrix} (h_{14} - h_{15}) - \\ (T_0 * (s_{14} - s_{15})) \end{pmatrix}$
$Ed_{HX1} = \left((Ex_{in_{HX1}}) - (Ex_{out_{HX1}}) \right)$

4.3 Second Heat Exchanger(HX_2) analysis

$TypeHX_{2\$} =' \, counterflow'$
$epsilon_{HX2} = 0.85$
$T_{13} * (m - m_f) = m_{e1} * T_{e1} + (m - m\_f - m\_e1) * T\_12 \text{"}$
$m_{h_{HX2}} = m - m_{e1}$
$m_{c_{HX2}} = m - m_f$
$C_{h_{HX2}} = m_{h_{HX2}} * cp_{hot_{fluid_{HX2}}}$
$C_{c_{HX2}} = m_{c_{HX2}} * cp_{cold_{fluid_{HX2}}}$
$q_{HX2} = C_{h_{HX2}} * (T_3 - T_4)$
$q_{HX2} = C_{c_{HX2}} * (T_{14} - T_{13})$
$q\_max\_HX2 = C\_min\_HX2 * (T\_3 - T\_13)$
$epsilon\_HX2 = q\_HX2/q \max._{HX2}$
$Ntu_{HX2} = HX \begin{pmatrix} TypeHX_{2\$}, \\ epsilon_{HX2}, C_{h_{HX2}}, C_{c_{HX2}}, \, 'Ntu' \end{pmatrix}$
$Ntu\_HX2 = (G\_HX2)/C \min._{HX2}$
$Ex_{in_{HX2}} = (m - m_{e1}) * \begin{pmatrix} (h_3 - h_4) - \\ (T_0 * (s_3 - s_4)) \end{pmatrix}$
$Ex_{out_{HX2}} = (m - m_f) * \begin{pmatrix} (h_{13} - h_{14}) - \\ (T_0 * (s_{13} - s_{14})) \end{pmatrix}$

$$Ed_{HX2} = \left(\left(Ex_{in_{HX2}} \right) - \left(Ex_{out_{HX2}} \right) \right)$$

4.4 Third Heat Exchanger (HX_3) analysis

$TypeHX_{3\$} =' \, counterflow'$
$epsilon_{HX3} = 0.85$
$m_{h_{HX3}} = m - m_{e1}$
$m_{c_{HX3}} = m - m_f - m_{e1}$
$C_{h_{HX3}} = m_{h_{HX3}} * cp_{hot_{fluid_{HX3}}}$
$C_{c_{HX3}} = m_{c_{HX3}} * cp_{cold_{fluid_{HX3}}}$
$q_{HX3} = C_{h_{HX3}} * (T_4 - T_5)$
$q_{HX3} = C_{c_{HX3}} * (T_{12} - T_{11})$
$q\_max\_HX3 = C\_min\_HX3 * (T\_4 - T\_11)$
$epsilon\_HX3 = q\_HX3/q \underset{HX3}{\max.}$
$Ntu_{HX3} = HX \left(\begin{matrix} TypeHX_{3\$}, \\ epsilon_{HX3}, C_{h_{HX3}}, C_{c_{HX3}}, 'Ntu' \end{matrix} \right)$
$Ntu\_HX3 = (G\_HX3)/C \underset{HX3}{\min.}$
$Ex_{in_{HX3}} = (m - m_{e1}) * \left(\begin{matrix} (h_4 - h_5) - \\ (T_0 * (s_4 - s_5)) \end{matrix} \right)$
$Ex_{out_{HX3}} = (m - m_f - m_{e1}) * \left(\begin{matrix} (h_{11} - h_{12}) - \\ (T_0 * (s_{11} - s_{12})) \end{matrix} \right)$
$Ed_{HX3} = abs \left(\left(Ex_{in_{HX3}} \right) - \left(Ex_{out_{HX3}} \right) \right)$

4.5 Fourth Heat Exchanger(HX_4) analysis

$TypeHX_{4\$} =' \, counterflow'$
$epsilon_{HX4} = 0.85$
$T_{10} * (m - m_f - m_{e1}) = m_{e2} * T_{e2} + (m - m_f - m_{e1} - m_{e2}) * T_9$
$m_{h_{HX4}} = m - m_{e1} - m_{e2}$
$m_{c_{HX4}} = m - m_f - m_{e1}$
$C_{h_{HX4}} = m_{h_{HX4}} * cp_{hot_{fluid_{HX4}}}$
$C_{c_{HX4}} = m_{c_{HX4}} * cp_{cold_{fluid_{HX4}}}$
$q_{HX4} = C_{h_{HX4}} * (T_5 - T_6)$
$q_{HX4} = C_{c_{HX4}} * (T_{11} - T_{10})$
$q\_max\_HX4 = C\_min\_HX4 * (T\_5 - T\_10)$
$epsilon\_HX4 = q\_HX4/q \underset{HX4}{\max.}$
$Ntu_{HX4} = HX \left(\begin{matrix} TypeHX_{4\$}, \\ epsilon_{HX4}, C_{h_{HX4}}, C_{c_{HX4}}, \, 'NTU' \end{matrix} \right)$
$Ntu\_HX4 = (G\_HX4)/C \underset{HX4}{\min.}$
$Ex_{in_{HX4}} = (m - m_{e1} - m_{e2}) * \left((h_5 - h_6) - (T_0 * (s_5 - s_6)) \right)$
$Ex_{out_{HX4}} = (m - m_f - m_{e1}) * \left((h_{10} - h_{11}) - (T_0 * (s_{10} - s_{11})) \right)$
$Ed_{HX4} = abs \left(\left(Ex_{in_{HX4}} \right) - \left(Ex_{out_{HX4}} \right) \right)$

4.6 Fifth Heat Exchanger(HX_5) analysis

$TypeHX_{5\$} =' \, counterflow'$
$epsilon_{HX5} = 0.90$
$c_{p_{fluid_{hot}}} = 5.192 \left[\dfrac{kj}{kgK} \right]$
$c_{p_{fluid_{cold}}} = 5.146$
$cp_{hot_{fluid_{HX5}}} = Cp(R\$, T = T_6, P = P_2)$
$cp_{cold_{fluid_{HX5}}} = Cp(R\$, T = T_f + 1, P = P_1)$
$m_{dot_{h_{HX5}}} = (m - m_{e1} - m_{e2})$
$m_{dot_{c_{HX5}}} = (m - m_{e1} - m_{e2} - m_f)$
$C_{dot_{h_{HX5}}} = m_{dot_{h_{HX5}}} * c_{p_{fluid_{hot}}}$
$C_{dot_{c_{HX5}}} = m_{dot_{c_{HX5}}} * c_{p_{fluid_{cold}}}$
$q_{HX5} = C_{dot_{h_{HX5}}} * (T_6 - T_7)$
$q_{HX5} = C_{dot_{c_{HX5}}} * (T_9 - T_g)$
$C\_dot\_min\_HX5 = \min(C\_dot\_h\_HX5, C\_dot\_c\_HX5)$
$q\_max\_HX5 = C\_dot\_min\_HX5 * (T\_6 - T\_g)$
$epsilon\_HX5 = q\_HX5/q \underset{HX5}{\max.}$
$Ntu_{HX5} = HX \left(\begin{matrix} TypeHX_{5\$}, epsilon_{HX5}, \\ C_{dot_{h_{HX5}}}, C_{dot_{c_{HX5}}}, 'Ntu' \end{matrix} \right)$
$Ntu\_HX5 = (G\_HX5)/C\_dot \underset{HX5}{\min.}$
$Ex_{in_{HX5}} = (m - m_{e1} - m_{e2}) * \left((h_6 - h_7) - (T_0 * (s_6 - s_7)) \right)$
$Ex_{out_{HX5}} = (m - m_{e1} - m_{e2} - m_f) * \left((h_g - h_9) - (T_0 * (s_g - s_9)) \right)$
$Ed_{HX5} = abs \left(\left(Ex_{in_{HX5}} \right) - \left(Ex_{out_{HX5}} \right) \right)$

"J-T Valve"

$h_7 = h_8$
$x_1 = 1$
$Ex_{in_{Val}} = (m - m_{e1} - m_{e2}) * \left((h_7 - h_0) - T_0 * (s_7 - s_0) \right)$
$Ex_{out_{val}} = (m - m_{e1} - m_{e2}) * \left((h_8 - h_0) - T_0 * (s_8 - s_0) \right)$
$$Ed_{val} = \left(Ex_{in_{Val}} - Ex_{out_{val}} \right)$$
"Separator"
$(m - m_{e1} - m_{e2}) * h_8 = m_f * h_f + (m - m_{e1} - m_{e2} - m_f) * h_g$
$m_g = (m - m_{e1} - m_{e2} - m_f)$
$$Ed_{sep} = abs \left(T_0 * \left(\begin{matrix} m_g * s_g - \\ (m_g + m_f) * s_8) + \\ \dfrac{m_g * h_g - m_f * h_f}{T_0} \end{matrix} \right) \right)$$

$$Ed_{comp_\%} = \left(\frac{Ed_{comp}}{Ed_{He_{sys}}}\right) * 100$$

$$Ed_{W_{e1_\%}} = \left(\frac{Ed_{W_{e1}}}{Ed_{He_{sys}}}\right) * 100$$

$$Ed_{W_{e2_\%}} = \left(\frac{Ed_{W_{e2}}}{Ed_{He_{sys}}}\right) * 100$$

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

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

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

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

$$Ed_{HX5}\% = \left(\frac{Ed_{HX5}}{Ed_{He_{sys}}}\right) * 100$$

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

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

$$Ed_{He_{sys}} = Ed_{comp} + Ed_{W_{e1}} + Ed_{W_{e2}}$$
$$+Ed_{HX1} + Ed_{HX2} + Ed_{HX3} + Ed_{HX4}$$
$$+Ed_{HX5} + Ed_{val} + Ed_{sep}$$

Table 1: Variable Table (Collin 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_5	P_1
h_{e2}	R\$	T_{e1}	P_1
s_{e2}	R\$	P_1	h_{e1}
$cp(hf)_{HX1}$	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_{f+1}	P_1
C_{min}	R\$	C_{hot_HX4}	C_{cold_HX4}
$cp(hf)_{HX5}$	R\$	T_5	P_2
$cp(cf)_{HX5}$	R\$	T_{10}	P_1
C_{min}	R\$	C_{hot_HX4}	C_{cold_HX4}
h_7	R\$	T_6	P_2
s_7	R\$	T_6	P_2
h_7	R\$	T_7	P_2
s_7	R\$	T_7	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
s_8	R\$	h_8	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

A comprehensive exergy analysis and other analysis of Collin system is carried out by using various different gases with variable properties. Numerical computation is carried out to find out mutually dependency and effect of various properties on other properties and their involvement in exergy destruction. In fig.2, the second law efficiency have maximum value at pressure ratio (PR) 11 and beyond this it start decreasing at very fast rate. COP of the system also decrease with increase in PR of cycle but this decrement is marginal .On entire PR range 5 to 29 the decrement in COP of system is 0.065 to 0.03 so the optimum pressure ratio (PR) is chosen on the basis of highest second law efficiency that is pressure ratio (PR) 11. Similarly, the specific heat of fluid in heat exchanger highly influence the performance of system. Due to change in pressure ratio the specific heat of fluid in different heat

exchanger is effected which turn effect the performance of system.
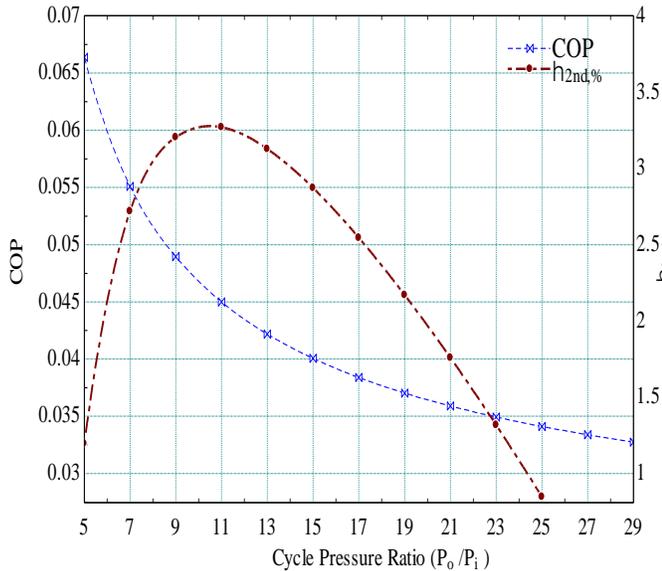

Figure 2: Variation of COP and second law efficiency (%) versus cycle pressure ratio
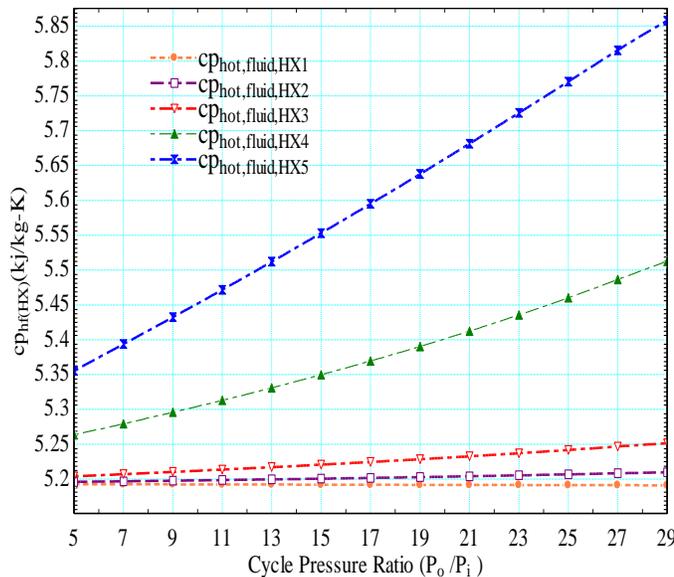

Figure 3: Specific heat of heat exchangers versus cycle pressure ratio

In fig.3, the variation in specific heat of helium gas in different heat exchanger is notice with respect to change in pressure ratio (PR) of the system. From the graph analysis in observed that specific heat in the low temperature heat exchanger (HX4, HX5) are highly influenced by the change in the pressure ratio of system. Lowest heat exchanger five (HX5) show the variation in the specific heat change from 5.35 kJ/kg-K to 5.85 kj/kg-K whereas for fourth heat exchanger (HX4) this change is varies from 5.25 kJ/kg-K to 5.5 kj/kg-K over the cycle pressure ratio range 5 to 29.The high temperature heat

exchanger (HX1, HX2, HX3) show very negligible change in specific heat of helium with variation in cyclic pressure ratio of system. From analysis, it observed that low temperature heat exchangers are very crucial as per design consideration. Number of transfer unit value help in design the heat exchanger.
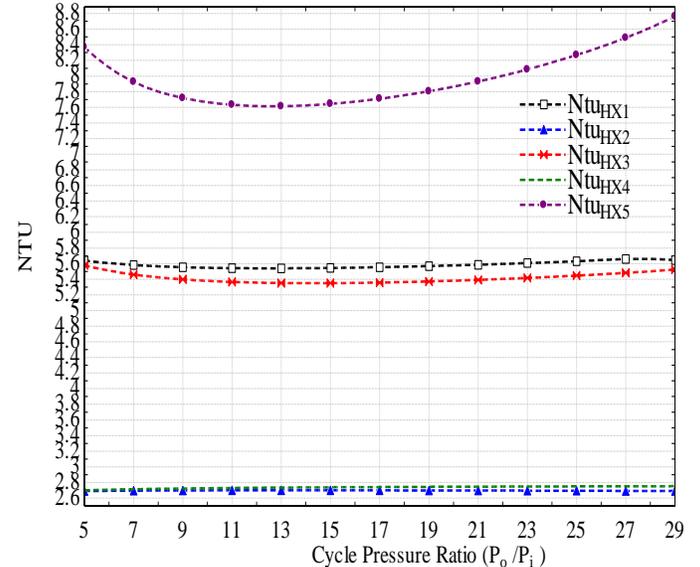
Figure 4: Variation of NTU of heat exchangers versus cycle pressure ratio
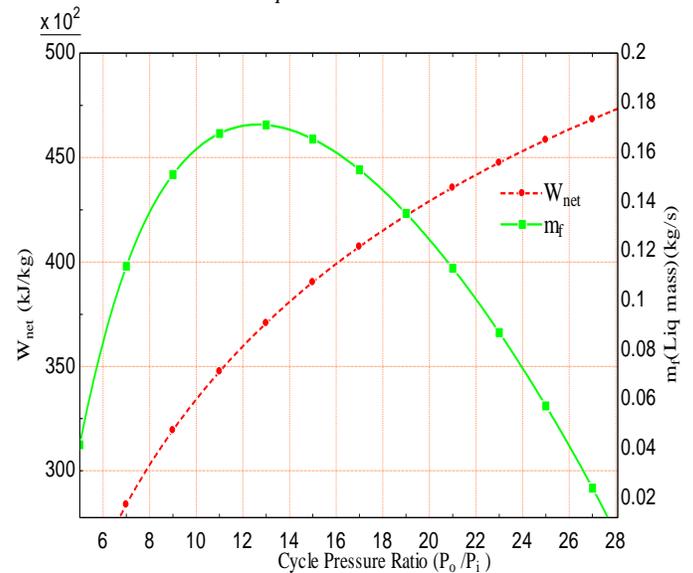
Figure 5: Variation of Net work done and Liquefaction mass rate versus cycle pressure ratio

Fig.4, illustrate the variation in NTU value of heat exchangers with increase in pressure ratio of system. First heat exchanger have the highest value of NTU. Its NTU value first decreases from 8.4 to 7.6 over the PR 5 to 13 .but further increases in PR NTU value of HX1 (First heat exchanger) is increases and it varies from 7.6 to 8.8 up to PR 29.Work done per liquefaction mass and liquefaction rate of system variation with cycle

pressure ratio is shown in fig 5.Liquefaction rate of system is NTU value of HX1 (First heat exchanger) is increases and it varies from 7.6 to 8.8 up to PR 29.Work done per liquefaction mass and liquefaction rate of system variation with cycle pressure ratio is shown in fig 5.Liquefaction rate of system is increases from 0.02 kg/s to 0.18 kg/s over PR range 6 to 28 when input mass flow rate of helium gas is taken as 1 kg/s.

The work done required to liquefy helium gas is very high due to very low liquefaction temperature .The work done requirement is increases up to PR 13 then it start decreasing at a very fast rate with increase in PR of system. Above fig.6 shows exergy destruction (%) in every component of helium liquefaction system with respect to change in pressure ratio. The high temperature heat exchanger show highest rate of destruction in system up 30% while compressor show second highest exergy destruction varies from 15 % to 18 % for pressure ratio range 5 to 29 but at PR 5 and 7 heat exchanger five HX5 show more exergy destruction which gradually decreases over increasing range of PR.

Expansion valve show least exergy destruction among all component followed by separator 3% which gradually decreases with increases in pressure ratio. Exergy destruction in heat exchanger two (HX2) increases with increase in pressure ratio in range of 6 % to 14 % .Heat exchanger four also show decreasing trend of exergy destruction with increase in pressure ratio (PR).

The outlet temperature of compressor affect the performance parameters of system. Fig.7 show the variation in COP and second law efficiency of system with increase in outlet temperature of compressor. COP of system varied from 0.04445 to 0.453 over temperature increasing range of 200 K to 400 K whereas second law efficiency continuously decreasing from 10 % to1 % over this temperature range of compressor. COP of the system is minimum effect of increasing temperature.

Therefore optimum temperature of system is decided by second law efficiency. From graph it is depicted that lowest temperature 200 K is desirable for Collin system and the intersection point of both curve COP and second law efficiency respectively is 270 K.

In fig.8 variation in the total work done required to liquefy helium and liquefaction rate is measured with change in outlet compressor temperature.

Liquefaction rate is varies from 0.35 kg/s to 01 kg/s, a decreasing trend with increase in outlet temperature of compressor.

The net work done is increases with increase in outlet temperature and it varies from 225 kW to 455 kW for overall compressor temperature. Variation in specific heat of helium

from 8.4 to 7.6 over the PR 5 to 13, but further increase in PR in heat exchanger with respect to compressor outlet temperature is shown in fig.9.

Low temperature heat exchanger HX5 and HX4 show decreasing value of specific heat that is 5.6 kJ/kg-K to 5.4 kJ/kg-K (HX5) and 5.4 KJ/kg-k to 5.28 KJ/kg-k for (HX4) for compressor outlet temperature increasing range 220 K to 400 K. Other heat exchanger HX3, HX2 and HX1 specific heat variation is decreasing in nature with increasing compressor temperature. The first heat exchanger (HX1) shows the specific heat variation that 5.1.1 KJ/kg-K. For all heat exchangers NTU value is increases with increase in outlet temperature that is shown in fig.10.

It was observed that HX5 show highest increase in its NTU value from 6.8 to 8.2 while HX1 and HX3 show 5.4 to 5.7 and 5.0 to 5.3 with outlet temperature range 200 K to 400 K. Heat exchanger HX2 and HX4 show least value of NTU 2.7 which almost constant for entire compressor temperature range. The exergy destruction (%) of the system with respect to compressor outlet temperature is depicted in fig.11.

From thermodynamic analysis it observed that first heat exchanger (HX1) show highest rate of destruction ranging from 36 % to 24 % with increase in temperature from 200 K to 400 K. heat exchanger five (HX5) show almost constant exergy destruction 15 % at all considered range of temperature of compressor. In compressor the exergy destruction up to 260 K is lower than the exergy destruction of HX5 and then in start increasing again up to 24 % at 400 K .Valve how lowest and destruction in valve is almost negligible because this valve already work at a very low temperature.HX4 followed by separator exergy destruction 4 % and 1 % respectively and constant over considered pressure range.

The variation in expander flow fraction from compressor effect the performance of the system. In Collin system two expander are employed .Second expander ratio is kept constant in one by three ratio with respect to first expander flow fraction .Figure 12 show the variation in COP and second law efficiency (%) with increase in flow ratio of first expander. From study in concluded that COP of system is decreases 0.0457 to 0.0446 with increase in flow ratio while second law efficiency increases up to 0.55 and then it start decreasing with increases in flow fraction. At 0.55 flow ratio the second law efficiency is 3.5 %, so the optimum expander slow fraction for first expander is 0.55. Variation in liquefaction rate with respect first expander flow fraction is shown in fig. 13.

The liquefaction rate is increases with increase in flow fraction up to 0.55 then it start decreasing further more increase in flow fraction. At flow fraction 0.55 the highest liquefaction rate is 0.18 kg/s

.
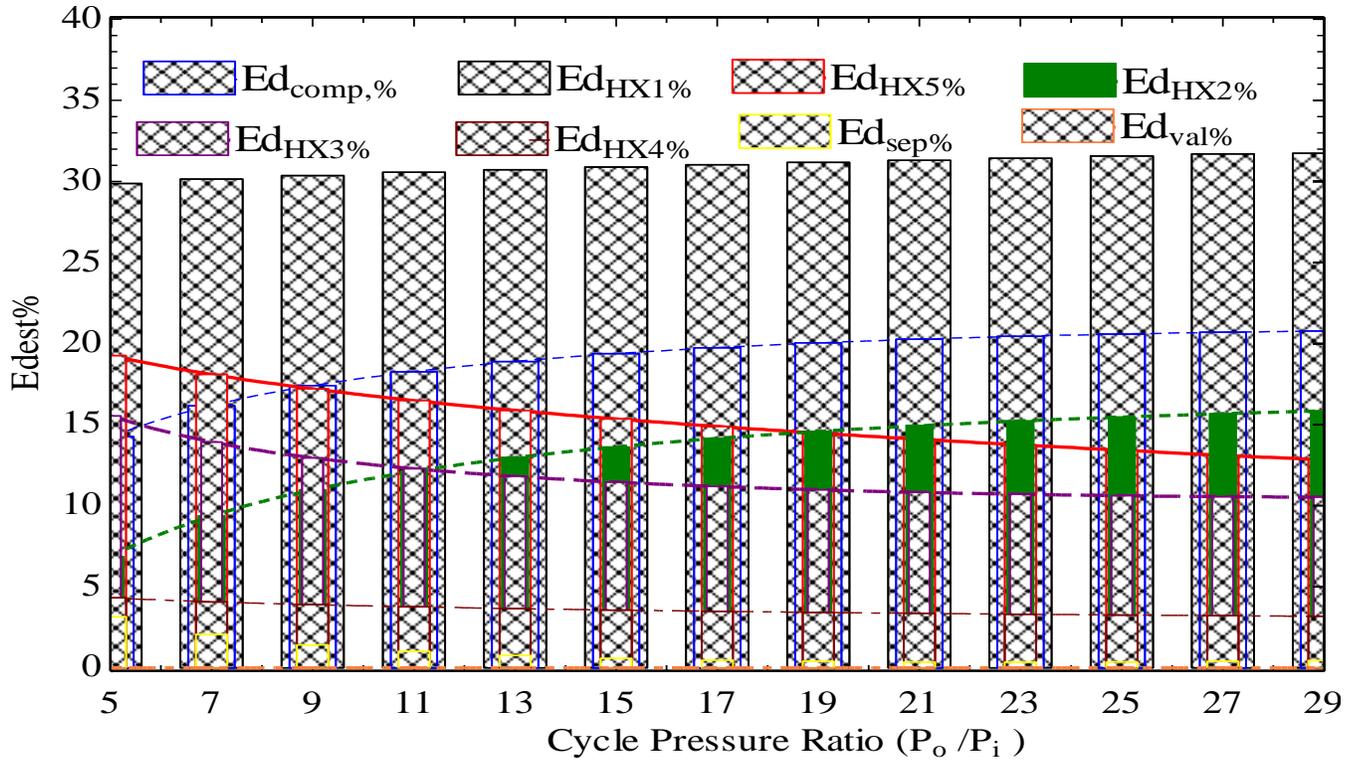
Figure 6: Variation of Exergy destruction (%) versus cycle pressure ratio
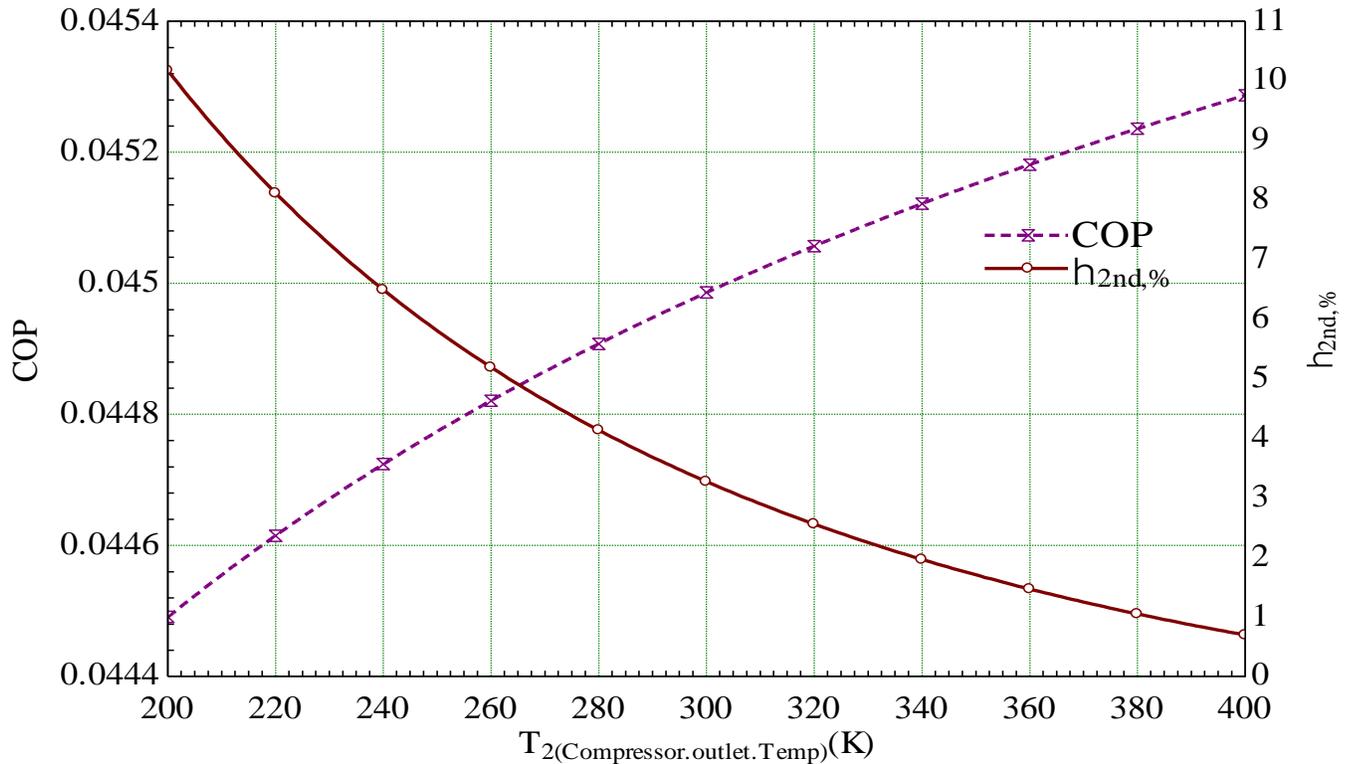

Figure 7: Variation of COP and second law efficiency versus compressor outlet temperature
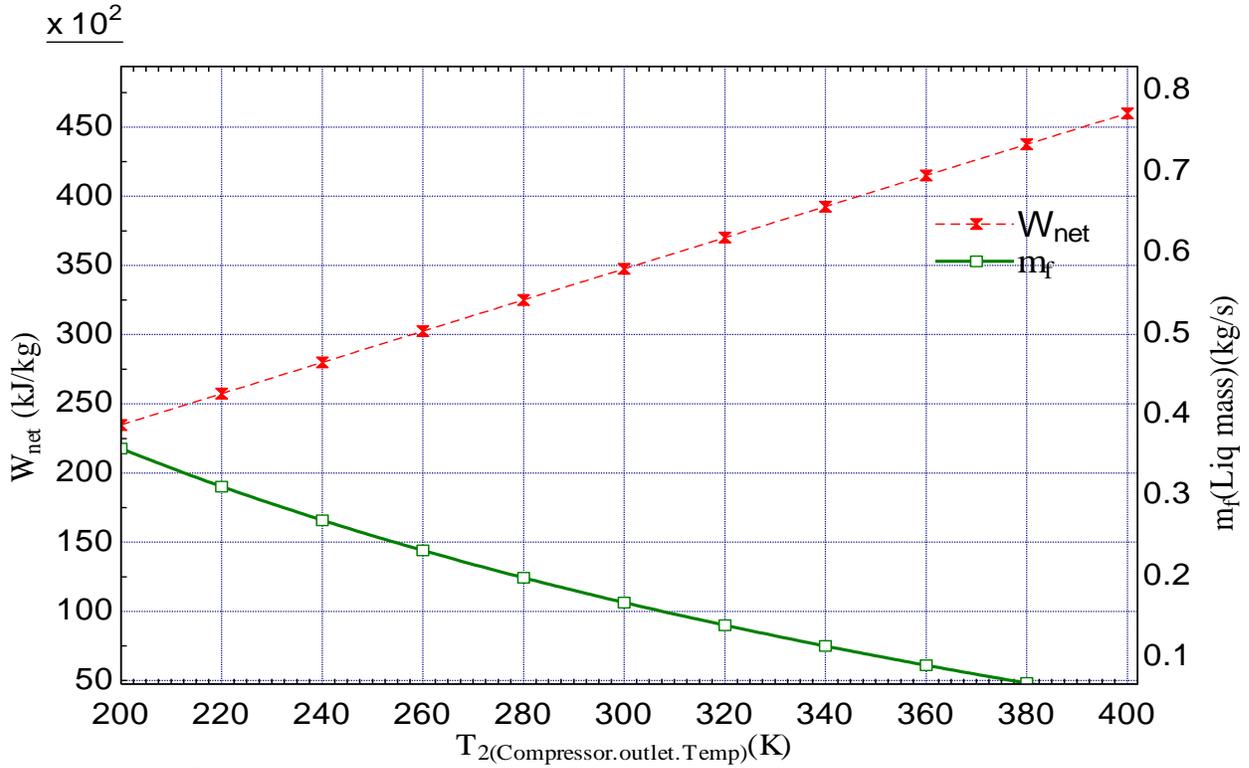
Figure 8: Variation of Net work and liquefaction rate versus compressor outlet temperature
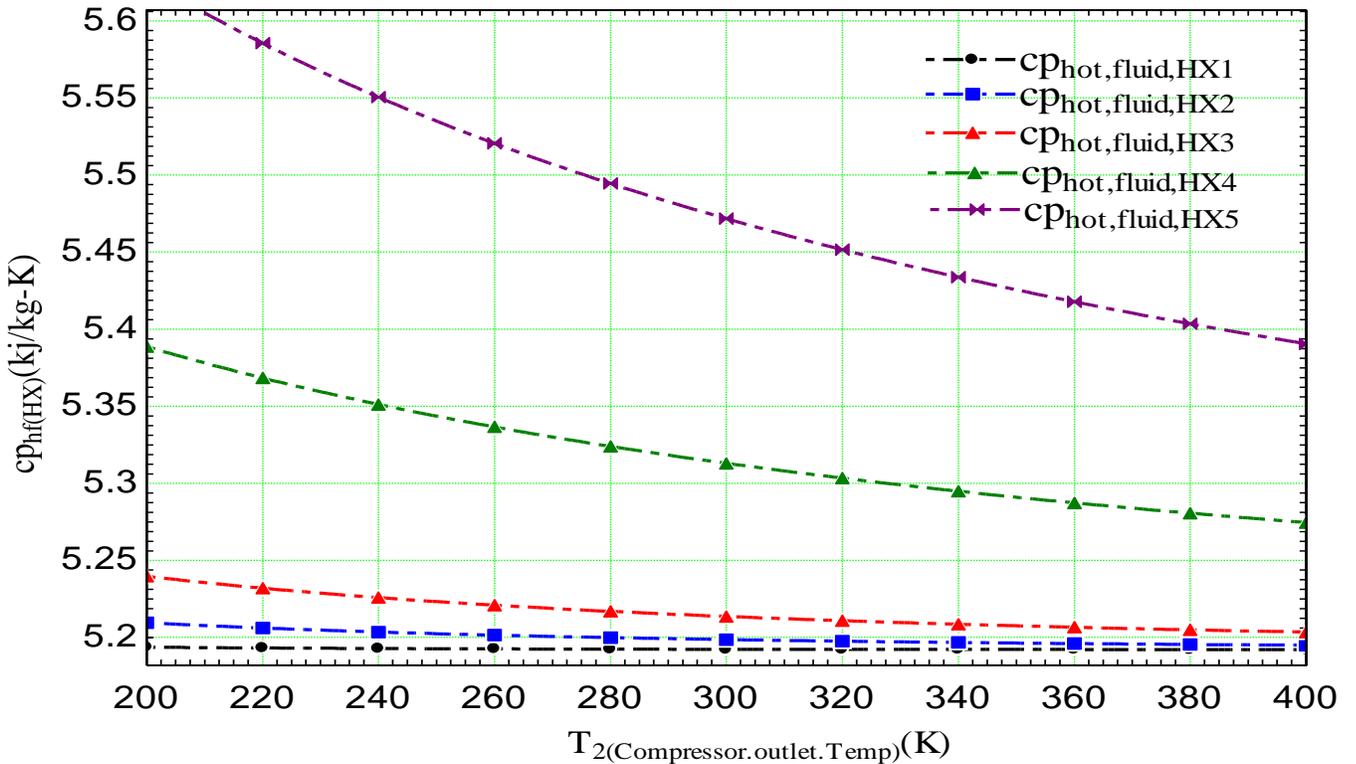

Figure 9: Variation of NTU of heat exchangers versus compressor outlet temperature
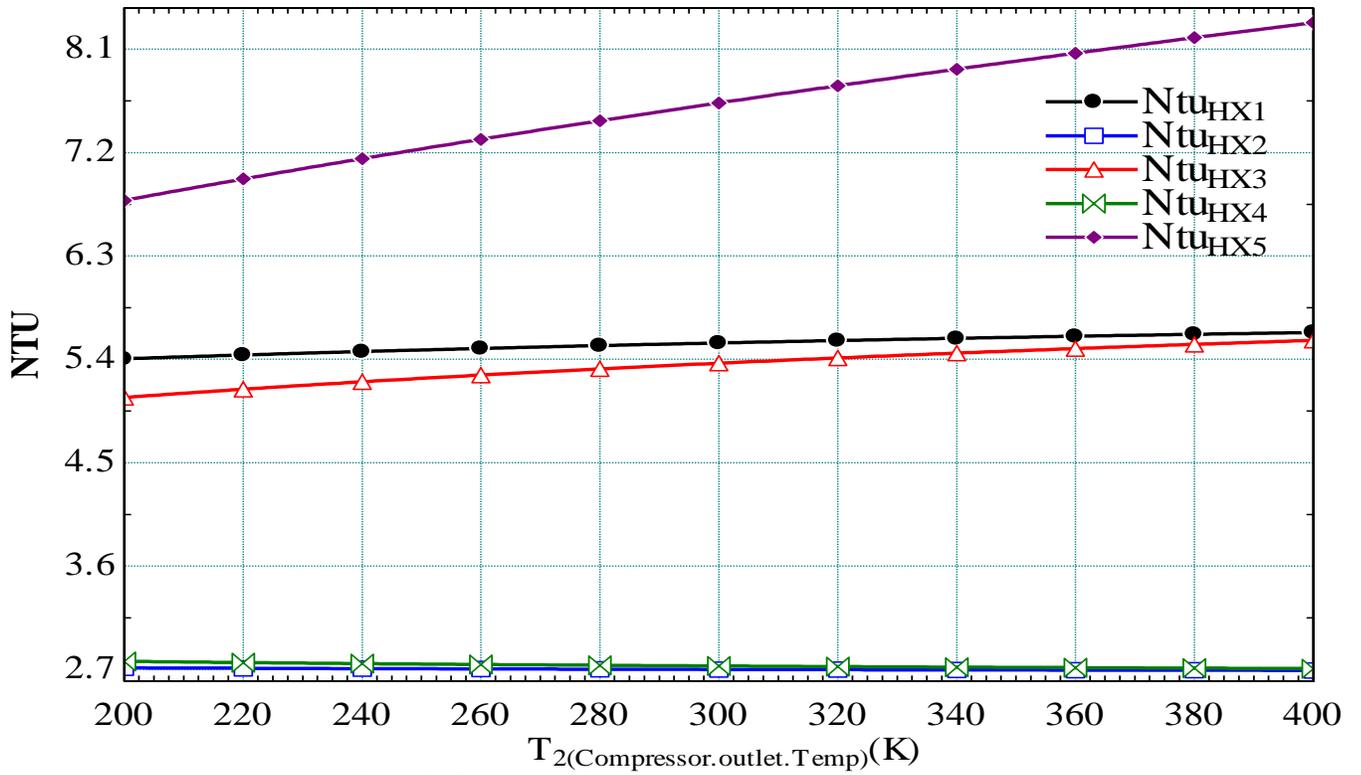
*Figure 10: Variation of NTU versus compressor outlet temperature*
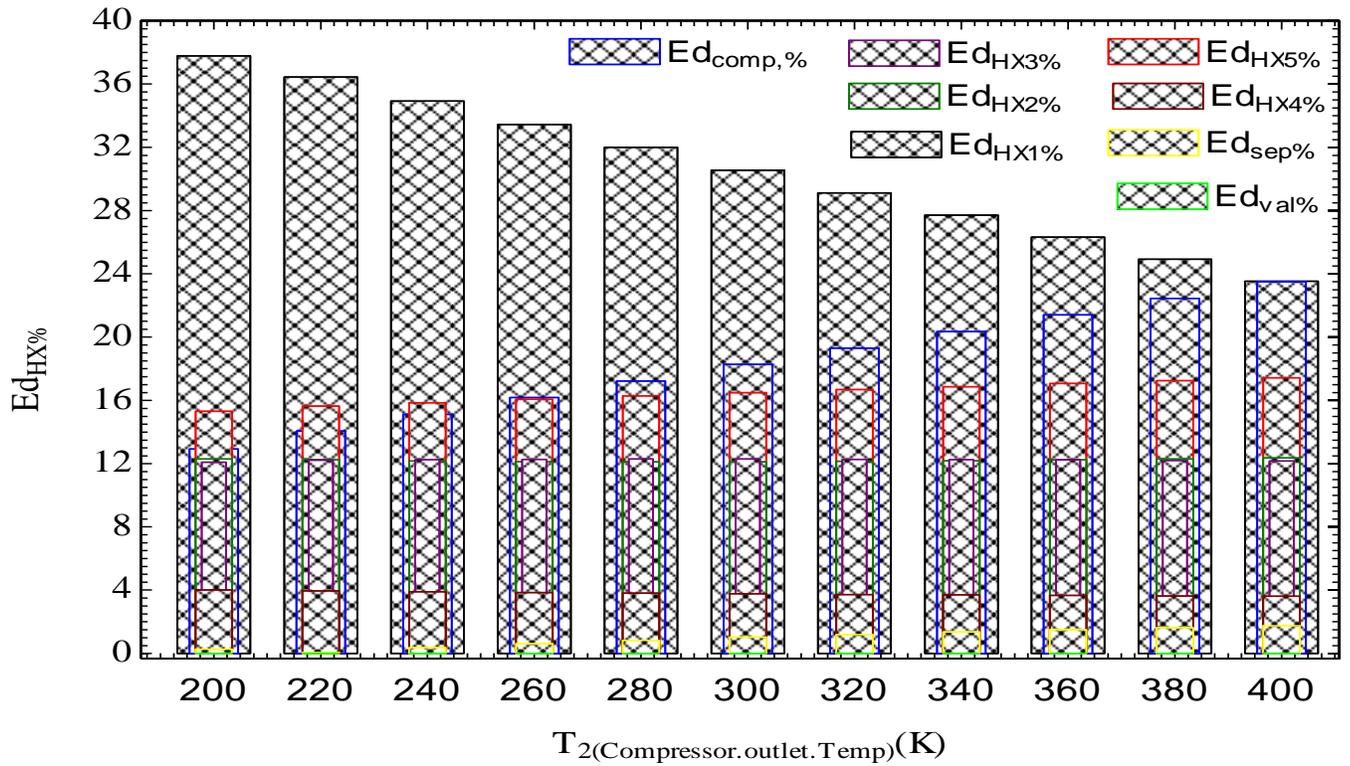

Figure 11: Exergy destruction (%) versus compressor outlet temperature
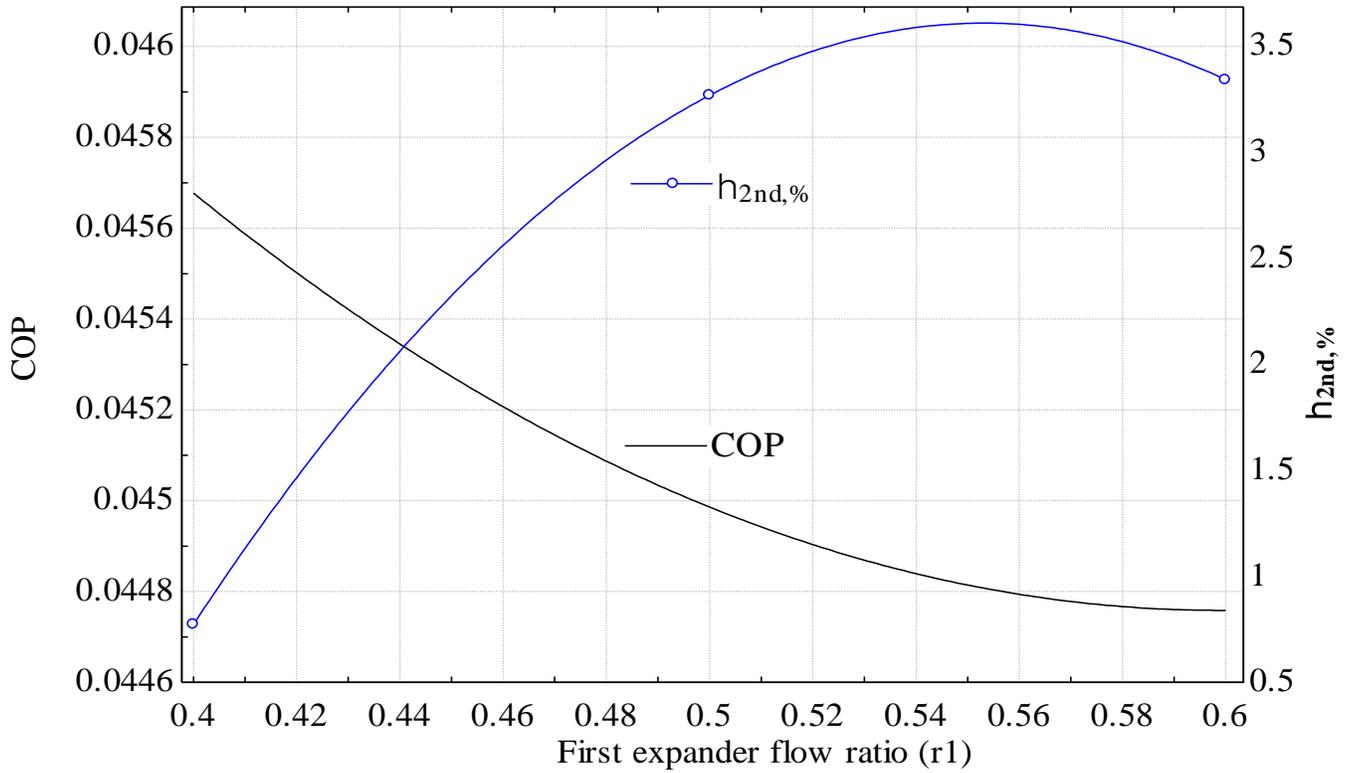
*Figure 12: COP and second law efficiency (%) with respect to first expander flow ratio (r1)*
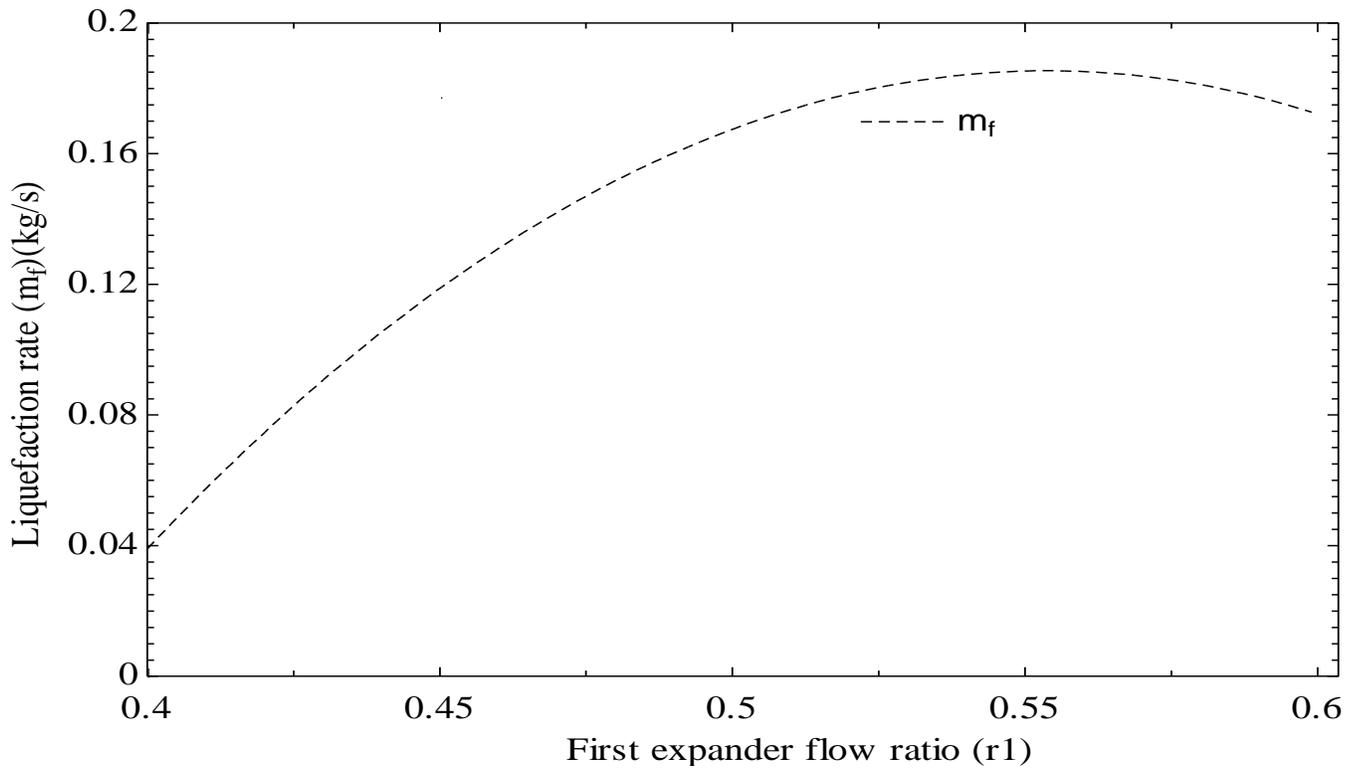
Figure 13: Liquefaction rate versus first expander flow ratio.

6. Conclusions and Recommendations

The following conclusion have been drawn from present investigations.

1. The liquefaction rate is increases with increase in flow fraction to 0.55 then it start decreasing further more increase in flow fraction.
2. At flow fraction0.55 the highest liquefaction rate is 0.18 kg/s.
3. First law efficiency in terms of COP of system is decreases 0.0457 to 0.0446 with increase in flow ratio while second law efficiency increases up to 0.55 and then it start decreasing with increases in flow fraction.
4. First heat exchanger (HX1) shows highest rate of exergy destruction ranging from 36 % to 24 % with increase in temperature from 200 K to 400 K.
5. The specific heat variations in all heat exchangers are decreasing in with increasing compressor temperature.
6. All heat exchangers NTU value is increases with increase in outlet temperature and fifth heat exchanger (HX5) shows highest increase in its NTU value from 6.8 to 8.2 while for other heat exchangers, NTU is remains constant.
7. Liquefaction rate is decreasing with increase outlet temperature of compressor.
8. The high temperature heat exchanger show highest rate of destruction in system up 30% while compressor shows second highest exergy destruction varies from 15 % to 18 % for pressure ratio range 5 to 29 while exergy destruction in the second heat exchanger (HX2) increases with increase in pressure ratio.

References

[1] A. Bejan, General criterion for rating heat-exchanger performance. Int. J. Heat Mass Transf. 1978, 21,pp 655– 658
[2] M. Yilmaz, O. N. Sara, S. Karsli, Performance evaluation criteria for heat exchangers based on second law analysis. Exergy Int. J. 2001, 4,pp 278–294
[3] S. T. Wu, X. F. Yuan, Y. R. Li, L. Xiao, Exergy transfer effectiveness on heat exchanger for finite pressure drop. Energy 2006, 32, pp 2110–2120.
[4] T. J. Kotas, The Exergy Method of Thermal Plant Analysis; 1995 Ed.; Krieger Publishing Company London, UK, 1985
[5] R. L. Cornelissen, G. G. Hirs, Exergy analysis of cryogenic air separation, Energy Conversion and Management, 39, 16–18, 1998, pp 1821-1826.
[6] H. Mahabadipour and H. Ghaebi, "Development and comparison of two expander cycles used in refrigeration system of olefin plant based on exergy analysis", Applied Thermal Engineering 50 (2013), pp 771-780.
[7] Recep Yumrutaş, Mehmet Kunduz, Mehmet Kanoğlu, Exergy analysis of vapor compression refrigeration systems, Exergy, An International Journal, Volume 2, Issue 4, 2002, pp 266-272.
[8] Gadhiraju Venkatarathnam , "Simulation of cryogenic processes", Cryogenic Mixed Refrigerant Processes, International Cryogenics Monograph Series 2008, pp 51-63.