



## Thermodynamic analysis of kaptiza cryogetic system

**Mishra. R. S, Devendra Kumar**

*Department of Mechanical, Production Industrial and Automobiles Engineering, Delhi Technological University Delhi-110042*

*Corresponding author: [rsmishra@dce.ac.in](mailto:rsmishra@dce.ac.in)*

### Abstract

The present studies concern on energy and exergy analyses of various cryogenics system up to their sub component level. A parametric study is conducted to investigate the effects of variation of various system input parameters such as pressure ratio, expander mass flow ratio, compressor output temperature on different performance parameters like COP , work input ,liquefaction rate ,specific heat and exergy. The numerical computations have been carried out for Kaptiza Cryogetic system are study with six different gases for liquefaction like oxygen, argon, methane, fluorine, air and nitrogen respectively. Effect of different input gas also studies carefully and behavior of different gases in different system is concluded (i.e. Argon has the highest value of second law efficiency (i.e. exergetic efficiency) and fluorine has the maximum value of first law efficiency (COP) among the other gases.

Methane has the highest value of liquefaction value of mass flow rate and methane has the highest net work done, and it is continuously increasing with cycle pressure ratio .The variations in specific heat of hot fluid in second heat exchanger (HX2) is increasing and methane having the decreasing trend of NTU, while all other gases shows the increasing trend of NTU between the prescribed range of cycle pressure ratio however, methane has the highest NTU in second heat exchanger ( HX2) among the other gases.

© 2017 ijrei.com. All rights reserved

*Keywords* Thermodynamic Analysis, Kaptiza system, Energy-Exergy Analysis

### 1. Introduction

The term “cryogenic” is derived from the Greek word Kryos which means cold or frost. It is frequently applied to very low temperature refrigeration applications such as in the liquefaction of gases and in the study of physical phenomenon at temperature approaching absolute zero. The first low temperature refrigeration system was primarily developed for the solidification of carbon dioxide and the liquefaction and subsequent fractional distillation of gases such as air, oxygen, nitrogen, hydrogen and helium.

Cryogenic process to liquefy air which is further extent to extract various particular gas like oxygen, nitrogen, feron etc. Always various analyses is done to identify the loop hole of process and to rectify it to their upper level. electro caloric cooling is a transiting to new cooling principle’s is critical and one of the most promising alternatives may be <sup>[3]</sup>. Various particular part are taken under study to increase overall performance of cryogenic system e.g 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 <sup>[4]</sup> apart from this other parts like expander, mass ratio and input variables are considered to improve cryosystems.

#### 1.1 Modified Claude system (Kapitza System)

Kapitza (1939) modified the basic Claude system by eliminating the third heat exchanger or low temperature heat exchanger. Several notable practical modifications were also introduced in this system a rotary expansion engine was instead of reciprocating expander.

The first or high temperature heat exchanger in the Kapitza system was actually a set of valve regenerators, which combined the cooling process with the purification process. The incoming warm gas was cooled in one unit and impurities were deposited there, while the outgoing stream warmed up in the other unit and flushed out the frozen impurities deposited in it. Compressor reduce the volume of fed gas and increase the pressure. In cryogenic mostly compressor with high compression ratio are used. An isothermal compression

process is used to compress the gas. A fraction of part of compress gas fed into expander. In Kaptiza a rotary expansion engine was used have high efficiency than reciprocating engine and the loss also less in rotary expander. Remaining fraction part of compress gas is passed through two heat exchangers which transfer heat from hot fluid stream to cold fluid stream. In heat exchanger hot fluid temperature decreases and there is increase in temperature of cold fluid. By losing heat hot fluid is prepared for throttling process and similarly by gaining heat cold fluid heated up for compression process. A throttling valve is used to reduce the pressure of the compressed air so that liquefied gas can be produced and stored. The process is assumed to be isenthalpic expansion. In separator liquefied gas separated from its gaseous part and this gaseous part is again recirculated in the system through mixer. Mixer is a device helps to maintain a constant flow rate of air into the compressor. The extra amount of air is added into incoming stream from separator. The process is assumed to be isobaric.

### 1.2 Modifications

1. A rotary expansion engine of high isentropic efficiency is used instead of reciprocating engine as in Claude cycle.
2. First heat exchanger replaced by a set of valve regenerators which combined the cooling process with purification process.
3. Kapitza cycle can be operate at relatively low pressure is lower than critical pressure of gas.

### 1.3 Assumptions

1. The system is at steady state condition. All processes are steady flow processes.
2. Neglecting the effects of kinetic and potential energy in analysis of all the components of system.
3. There is no heat in-leak to the system.

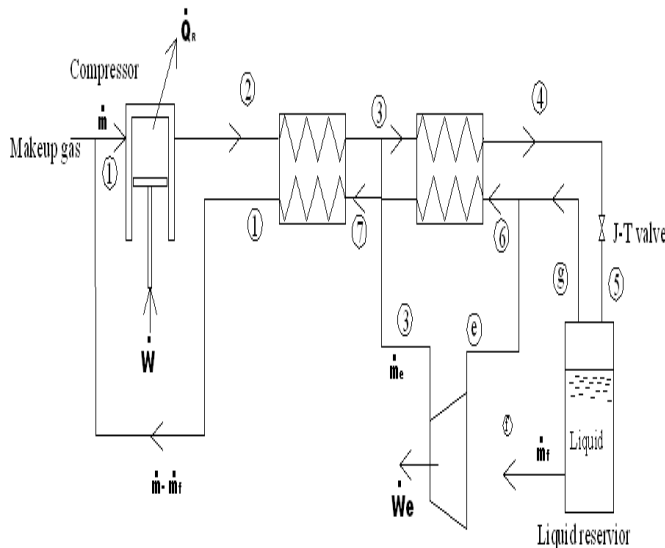


Figure 1: Schematic and T-S diagram of Kaptiza system

### 1.4 Mathematical analysis of Kaptiza Claude system

#### Assumptions

$$R\$ = Gas, m_2 = 1 = m = m_2, r = 0.5, T_0 = 298, T_1 = 300$$

$$T_2 = T_1, P_1 = 1, P_2 = 60, \frac{m_f}{m} = y, \frac{m_e}{m} = r$$

#### 1.4.1 Analysis of Compressor

$$W_c = \left( m_2 * ((h_2 - h_1)) - \right. \\ \left. T_2 * (s_2 - s_1) \right)$$

$$Q_c = m_2 * (h_2 - h_1)$$

$$Ed_{comp} = abs \left( \begin{matrix} m_2 * T_1 * (s_1 - s_2) - \\ \left( Q_c * \left( \frac{T_0}{T_1} \right) \right) \end{matrix} \right)$$

$$Ed_{comp\%} = \left( \frac{Ed_{comp}}{Ed_{Kaptiza}} \right) * 100$$

$$COP = \frac{(h_1 - h_f)}{W_c + W_e}$$

$$W_{net} = (W_c + W_e)$$

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

"Expander"

$$W_e = m_e * ((h_3 - h_e) - T_0 * (s_3 - s_e))$$

"Heat Exchanger HX1"

TypeHX1\$ = ' counterflow'

$$m_h = m$$

$$m_c = m - m_f$$

$$C_{hHX1} = m_h * c_{p_{hotHX1}}$$

$$C_{cHX1} = m_c * c_{p_{coldHX1}}$$

$$q_{HX1} = C_{hHX1} * (T_2 - T_3)$$

$$q_{HX1} = C_{cHX1} * (T_{11} - T_{10})$$

$$q_{max\_HX1} = C_{min\_HX1} * (T_2 - T_{10})$$

$$epsilon_{HX1} = q_{HX1} / q_{max\_HX1}$$

$$epsilon_{HX1} = 0.85$$

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

$$Ex_{inHX1} = m * \left( (h_2 - h_3) - \right. \\ \left. (T_0 * (s_2 - s_3)) \right)$$

$$Ex_{outHX1} = (m - m_f) * \left( (h_{10} - h_{11}) - \right. \\ \left. (T_0 * (s_{10} - s_{11})) \right)$$

$$Ed_{HX1} = ((Ex_{inHX1}) - (Ex_{outHX1}))$$

"Heat Exchanger HX2"

TypeHX2\$ = ' counterflow'

$$epsilon_{HX2} = 0.85$$

$$\begin{aligned}
 m_{h_{HX2}} &= m - m_e \\
 m_{c_{HX2}} &= m - m_f \\
 C_{h_{HX2}} &= m_{h_{HX2}} * cp_{hotfluid_{HX2}} \\
 C_{c_{HX2}} &= m_{c_{HX2}} * cp_{coldfluid_{HX2}} \\
 q_{HX2} &= C_{h_{HX2}} * (T_3 - T_4) \\
 q_{HX2} &= C_{c_{HX2}} * (T_{10} - T_{11}) \\
 q_{max\_HX2} &= C_{min\_HX2} * (T_3 - T_9) \\
 \epsilon_{HX2} &= q_{HX2} / q_{max\_HX2} \\
 Ntu_{HX2} &= (G_{HX2}) / C_{min\_HX2} \\
 T_g &= T_9 \\
 Ex_{in_{HX2}} &= (m - m_e) * \left( \frac{(h_3 - h_4) - (T_0 * (s_3 - s_4))}{T_0} \right) \\
 Ex_{out_{HX2}} &= (m - m_f) * \left( \frac{(h_9 - h_{10}) - (T_0 * (s_9 - s_{10}))}{T_0} \right) \\
 Ed_{HX2} &= (Ex_{in_{HX2}}) - (Ex_{out_{HX2}})
 \end{aligned}$$

1.4.2 Analysis of Valve

$$\begin{aligned}
 h_4 &= h_5 \\
 Ex_{in_{val}} &= (h_4 - h_0) - T_0 * (s_4 - s_0) \\
 Ex_{out_{val}} &= (h_5 - h_0) - T_0 * (s_5 - s_0) \\
 Ed_{val} &= (Ex_{in_{val}} - Ex_{out_{val}})
 \end{aligned}$$

1.4.3 Analysis of separator

$$\begin{aligned}
 (m - m_e) * h_5 &= ((m_f * h_f) + (m_g * h_g)) \\
 m_g &= (m - m_e - m_f) \\
 h_f &= \\
 h_6 &= \\
 h_g &= h_7 \\
 Ed_{sep} &= abs \left( T_0 * \left( \frac{m_g * s_g - ((m_g + m_f) * s_5) + (m_g * h_g - m_f * h_f)}{T_0} \right) \right)
 \end{aligned}$$

$$\begin{aligned}
 Ed_{sep\%} &= \left( \frac{Ed_{sep}}{Ed_{Kaptiza}} \right) * 100 \\
 Ed_{Kaptiza} &= Ed_{comp} + Ed_{HX1} + Ed_{HX2} \\
 &+ Ed_{val} + Ed_{sep} \\
 Ed_{HX1\%} &= \left( \frac{Ed_{HX1}}{Ed_{Kaptiza}} \right) * 100 \\
 Ed_{HX2\%} &= \left( \frac{Ed_{HX2}}{Ed_{Kaptiza}} \right) * 100 \\
 Ed_{val\%} &= \left( \frac{Ed_{val}}{Ed_{Kaptiza}} \right) * 100
 \end{aligned}$$

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

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

Table 1: Variable Table (Kaptiza 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\$	$h_2$	$P_2$
$T_e$	R\$	$h_e$	$P_1$
$h_e$	R\$	$s_3$	$P_1$
$s_e$	R\$	$h_e$	$P_1$
$s_f$	R\$	$x_f$	$P_1$
$T_f$	R\$	$x_0$	$P_1$
$h_f$	R\$	$x_f$	$P_1$
$T_g$	R\$	$x_1$	$P_1$
$s_g$	R\$	$x_1$	$T_g$
$s_3$	R\$	$T_3$	$P_2$
$h_3$	R\$	$T_3$	$P_2$
$s_4$	R\$	$T_4$	$P_2$
$h_4$	R\$	$T_4$	$P_2$
$s_9$	R\$	$T_9 + 1$	$P_1$
$h_9$	R\$	$T_9 + 1$	$P_1$
$s_{10}$	R\$	$T_{10}$	$P_1$
$h_{10}$	R\$	$T_{10}$	$P_1$
$s_{11}$	R\$	$T_{11}$	$P_1$
$h_{11}$	R\$	$T_{11}$	$P_1$
$cp(hf)_{HX1}$	R\$	$T_2$	$P_2$
$cp(cf)_{HX1}$	R\$	$T_7$	$P_1$
$C_{min}$	-	$C_{hot\ HX1}$	$C_{cold\ HX1}$
$cp(hf)_{HX2}$	R\$	$T_2$	$P_2$
$cp(cf)_{HX2}$	R\$	$T_9 - 1$	$P_1$
$C_{min}$	-	$C_{hot\ HX2}$	$C_{cold\ HX2}$
$h_7$	R\$	$T_7$	$P_1$
$s_7$	R\$	$T_7$	$P_1$
$X_5$	R\$	$h_5$	$P_1$
$s_6$	R\$	$h_6$	$P_1$
$s_5$	R\$	$h_5$	$P_1$

In this system, Fig.2 shows the variations in COP and second law efficiency with respect to cycle pressure ratio of 40 to 220. It has been observed that argon has the highest value of second law efficiency, i.e. 41.32% and fluorine has the maximum value of COP, i.e. 0.9595 among the other gases. Fig.3 illustrates the variations in liquefaction mass flow rate with respect to cycle pressure ratio and it has been observed that methane has the highest value of liquefaction value of mass flow rate, which is around 0.3167 at cycle pressure ratio of 40. Fig.4 demonstrates the variations in net work done with respect to cycle pressure ratio. It was observed that methane has the highest net work done, i.e. 1120kJ and it is continuously increasing up to cycle pressure ratio of 220. Fig. 5 indicates the variations in specific heat of hot fluid in HX2, i.e. increasing from 2.493kJ/kg-K to 3.561kJ/kg-K. Fig.7

demonstrates the variations in NTU in HX1 with respect to cycle pressure ratio of 40 to 220. It has been observed that methane having the decreasing trend of NTU, while all other gases shows the increasing trend of NTU between the prescribed ranges of cycle pressure ratio. Fig.8 shows the methane has the highest NTU in HX2 among the other gases, i.e. 3.471 at cycle pressure ratio of 220.

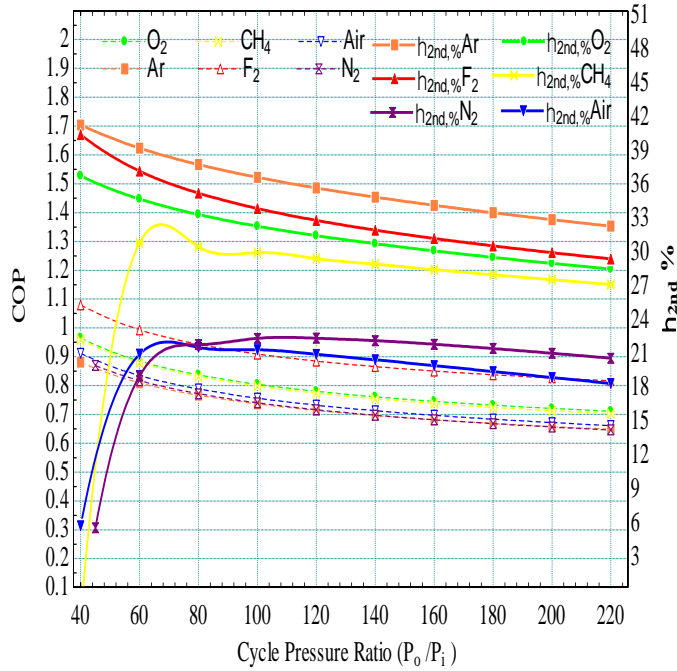


Figure 2: Variations in COP and second law efficiency with cycle pressure ratio

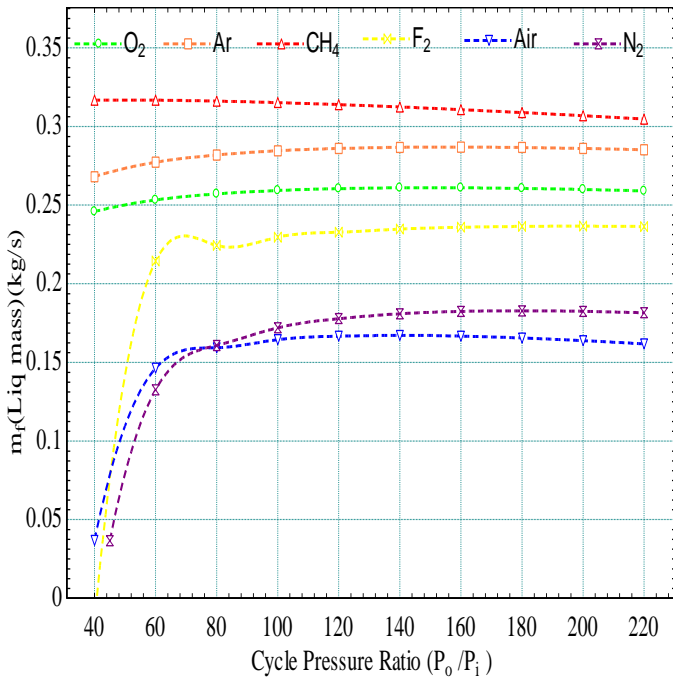


Figure 3: Variations in liquefaction mass flow rate with cycle pressure ratio

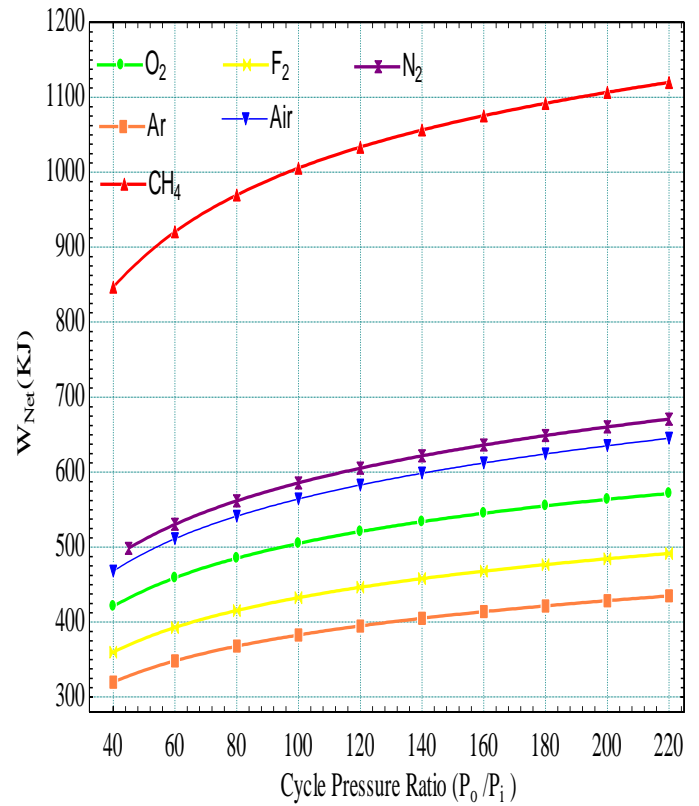


Figure 4: Variation in net work done with cycle pressure ratio

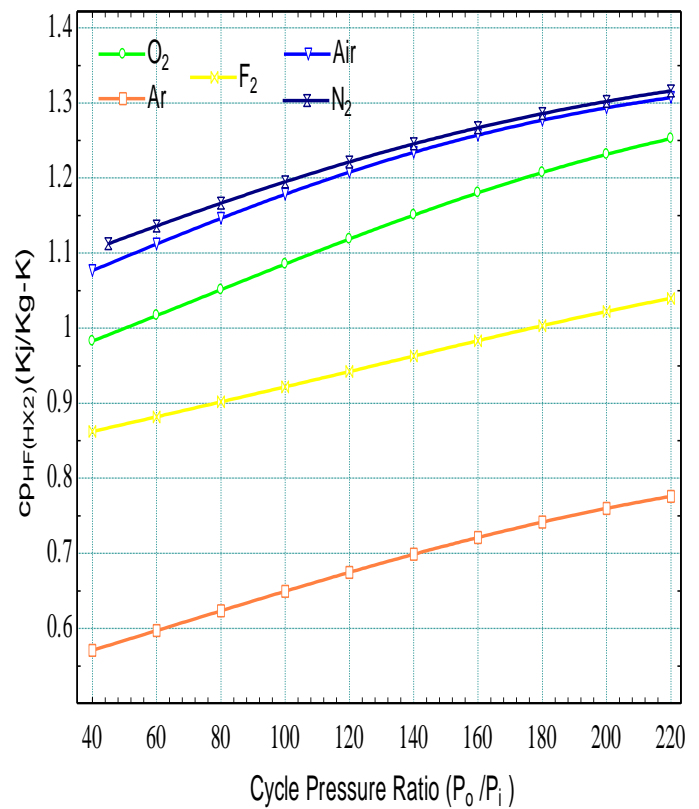


Figure 5: Variation in specific heat of hot fluid in HX2 with cycle pressure ratio

Fig.9 illustrates the variations in temperature at the outlet of the expander with the cycle pressure ratio and it has been seen that methane has the highest temperature at the outlet of expander, which is decreases from 186.1K to 115K. Fig. 10 shows the variations in percentage exergy destruction rate in compressor with respect to the cycle pressure ratio of 40 to 220. It has been analyzed that air has the highest percentage of exergy destruction rate among the other available gases, i.e. 50.21% at cycle pressure ratio of 220. Fig.11 illustrates the variation in percentage exergy destruction rate in HX1 with respect to cycle pressure ratio of 40 to 220. It has been analyzed that nitrogen has the highest value of percentage exergy destruction, i.e. 8.008% at 220. Furthermore, fig.12 indicates the variation in percentage exergy destruction in HX2 with respect to cycle pressure ratio of 40 to 220. It has been seen that air has the highest percentage value of exergy destruction rate i.e., 20.9% at 40. Fig.13 demonstrates the variations in percentage exergy destruction in valve with respect to cycle high pressure of 40 to 220. It has been seen that air has the comparatively highest percentage of exergy destruction rate, i.e. 28.02% at cycle pressure ratio of 40. Fig.14 illustrates the variations in percentage exergy destruction in separator with respect to cycle pressure ratio of 40 to 220. It has been demonstrating that air has the highest percentage of exergy destruction rate with the cycle pressure ratio and it is continuously decreasing. Fig.15 shows the variations in COP and second law efficiency with respect to ratio of compressor flow through expander i.e. 0.1 to 0.8. It has been seen that methane has the highest value of COP and nitrogen has the highest second law efficiency among the other gases. Fig.16 illustrates that methane has the highest value of net work done and it is continuously increasing with ratio of compressor flow through expander. On the other hand, methane also has the highest value of liquefaction mass flow rate and it is first increasing and then decreasing continuously up to 0.8 as show in fig.17

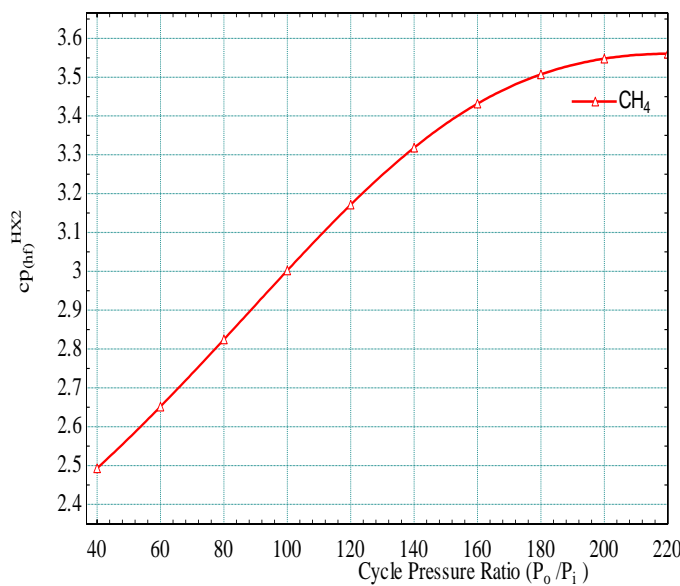


Figure 6: Variations in specific heat of hot fluid in HX2 with cycle pressure ratio

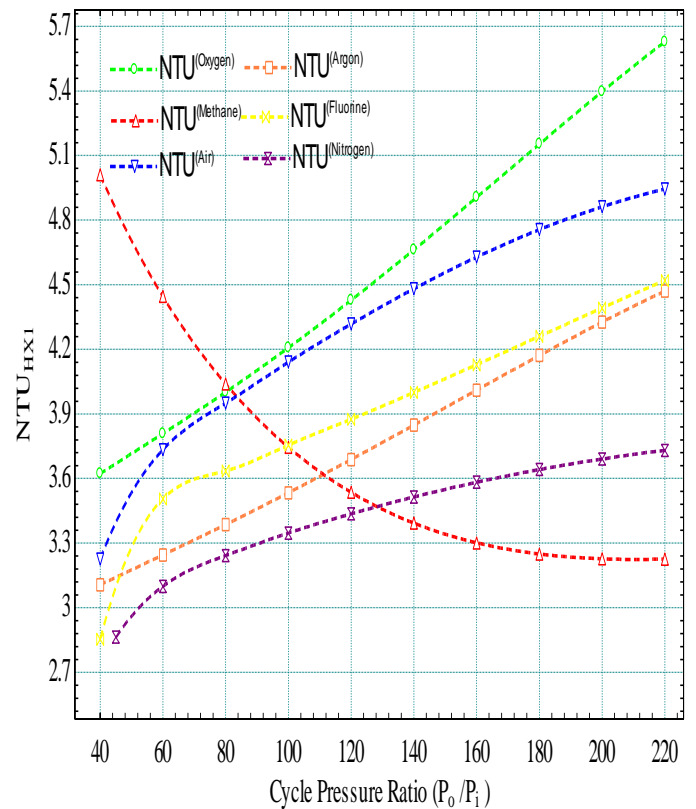


Figure 7: Variations in NTU in HX1 with cycle pressure ratio

Also, fig.18 shows the temperature variations at the outlet of expander with the ratio of compressor flow through expander of 0.1 to 0.8. it has been observed that again methane has the highest value of temperature at the outlet of expander and it is continuously decreasing up to 0.8. Fig.19 illustrates that methane has the highest value of COP and second law efficiency with respect to compressor temperature, i.e. 1.117 at 280K and 46.83% at 280K. Fig.20 indicates the variation in mass liquefaction rate with respect to compressor temperature and it has been analyzed that methane has the highest value of mass liquefaction rate among the other gases i.e. 0.3376kg/s at 280K. Fig.22 shows that methane has the highest net work done among the other gases i.e. 1397 at 460K. Fig.21 indicates the variations in temperature at the outlet of expander with the compressor temperature of 280K to 460K and it has been seen that fluorine has the highest value of temperature at the outlet of expander among the other gases and it continuously increasing up to 460K. Fig.23 shows the variations in specific heat of hot fluid in HX1 with the compressor temperature. It has been noticed that methane has the maximum value of specific heat in hot fluid in HX1 and its value firstly decreases and then continuously increasing up to 460K. While all other gases show the decreasing trend of specific heat. Fig.25 illustrates the variations in NTU in HX1 with compressor temperature. Methane shows the maximum NTU overall, while argon has the minimum NTU. Fig.26 indicates the variations NTU in HX2 with compressor temperature and it has been seen that methane has the highest NTU and its value continuously decreasing with compressor temperature up to

460K. Fig.27 indicates the variations in exergy destruction in compressor with respect to compressor temperature of 280K to 460K. It has been seen that methane has the highest value of exergy destruction and it is increasing continuously from 614.6kJ to 904.8kJ. Fig.28 shows the variations in exergy destruction in HX1 with respect to compressor temperature and it has seen that methane has the highest value of exergy destruction, i.e. 820.2kJ at 460K among the other gases. Fig. 29 demonstrates the variations in exergy destruction in HX2 with respect to compressor temperature and it has been noticed that methane again has the highest rate of exergy destruction, and its trend first decreasing and then increasing suddenly followed by other considered gases

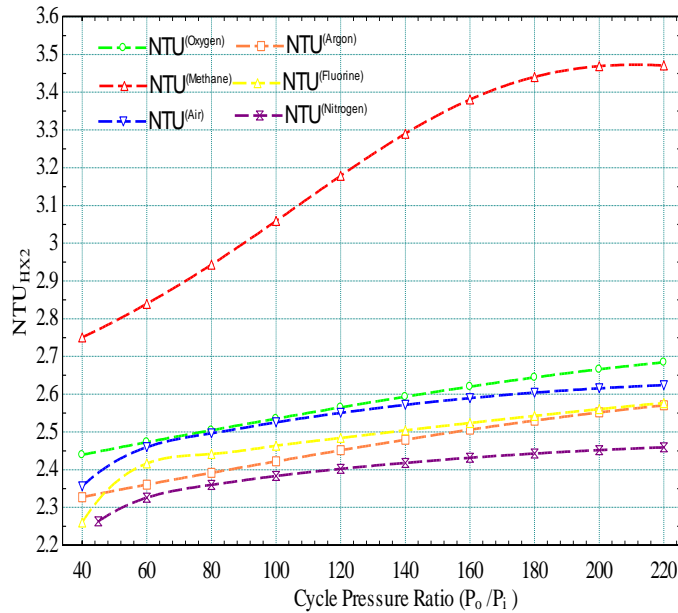


Figure 8: Variations in NTU in HX2 with cycle pressure ratio

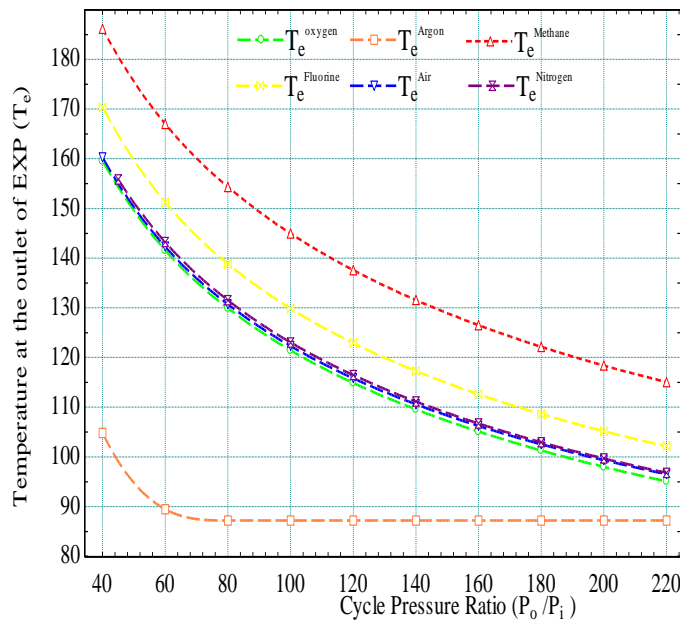


Figure 9: Variations in temperature at the outlet of expander with cycle pressure ratio

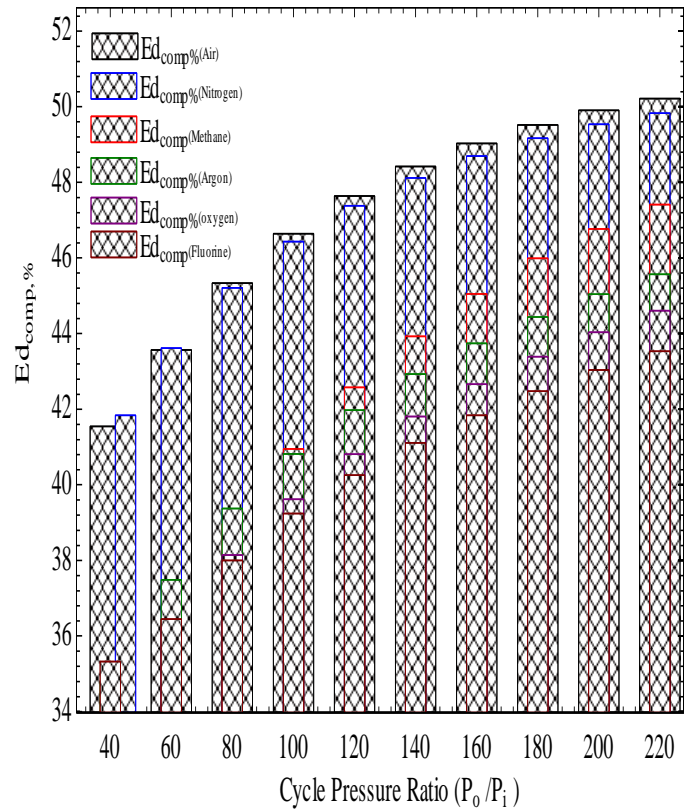


Figure 10: Variations in percentage exergy destruction with cycle pressure ratio

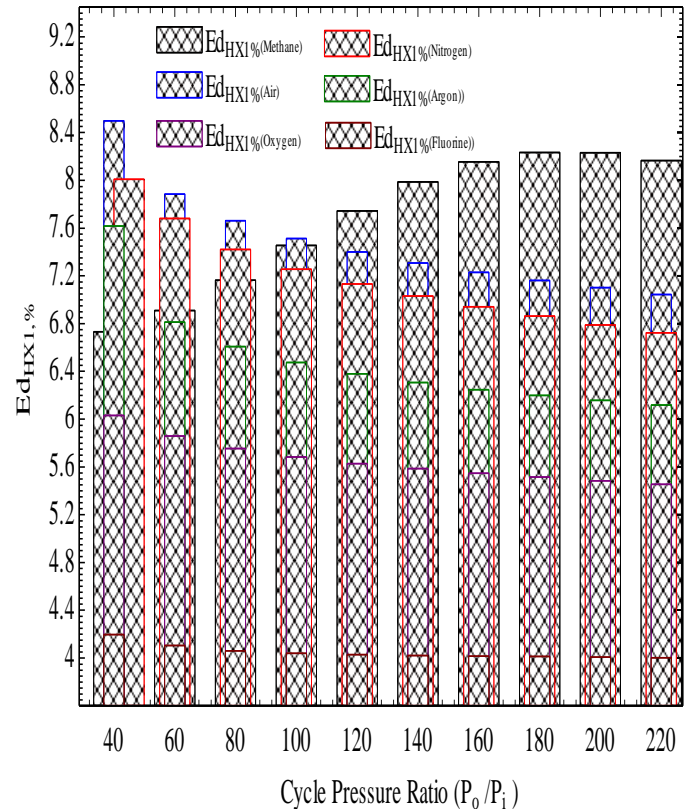


Figure 11: Variations in percentage exergy destruction in HX1 with cycle pressure ratio

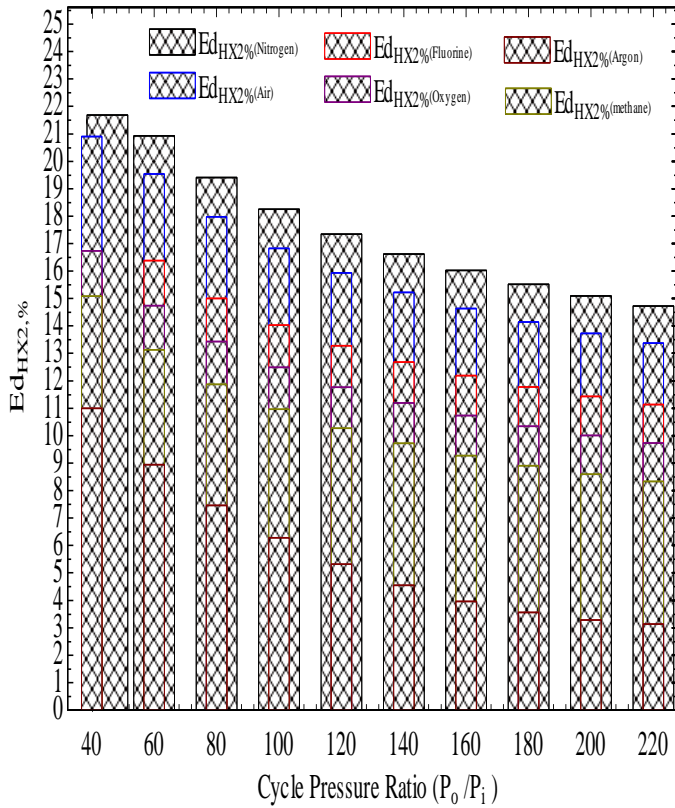


Figure 12: Variations in percentage exergy destruction in HX2 with cycle pressure ratio

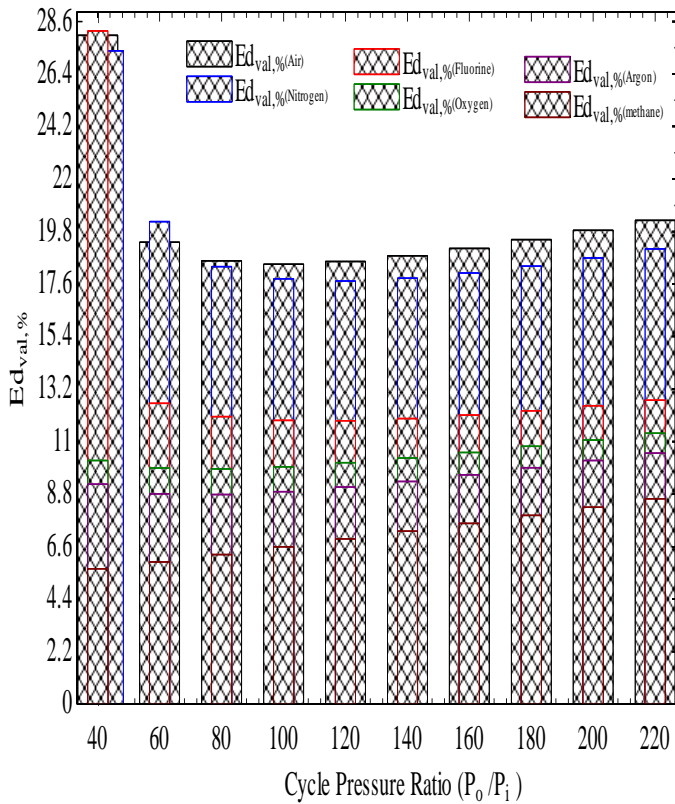


Figure 13: Variations in percentage exergy destruction in valve with cycle pressure ratio

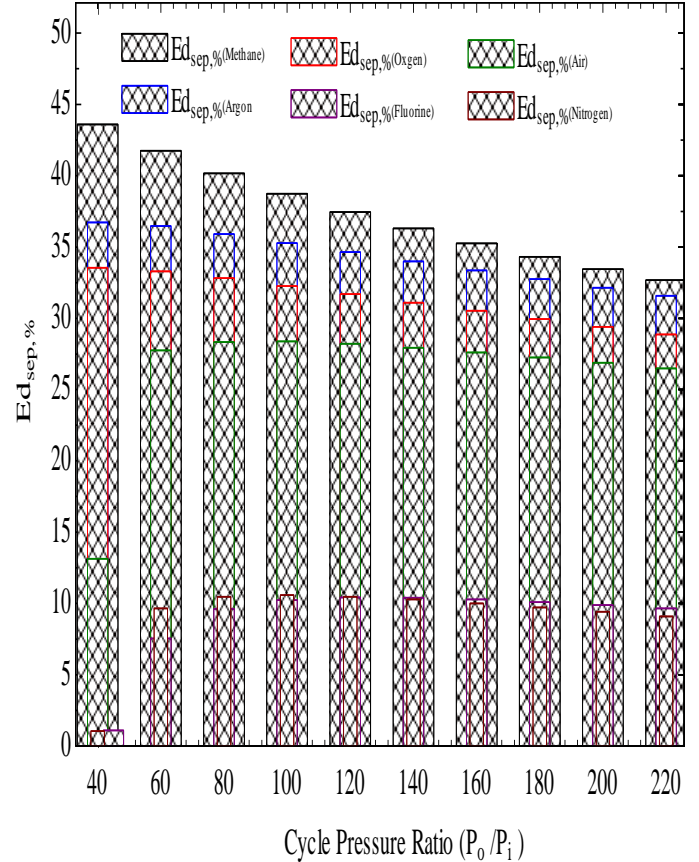


Figure 14: Variations in percentage exergy destruction in separator with cycle pressure ratio

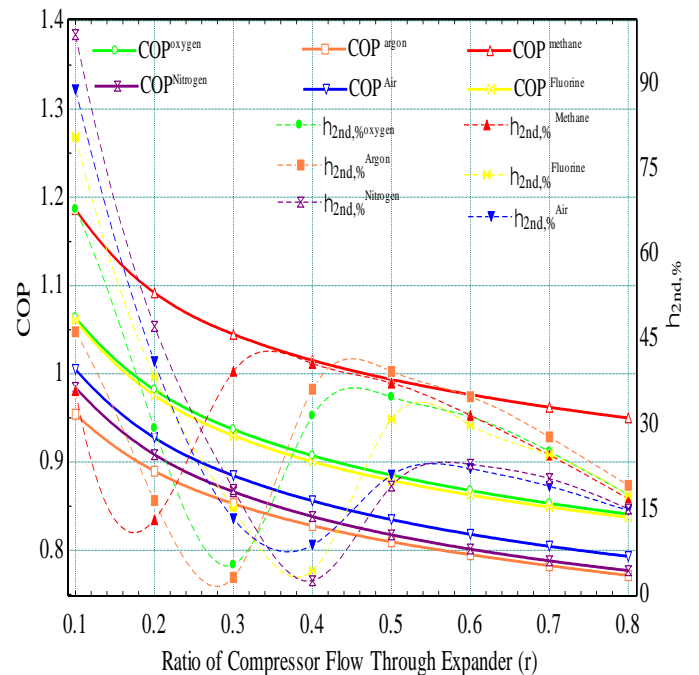


Figure 15: Variations in COP and second law efficiency with the ratio of compressor flow through expander

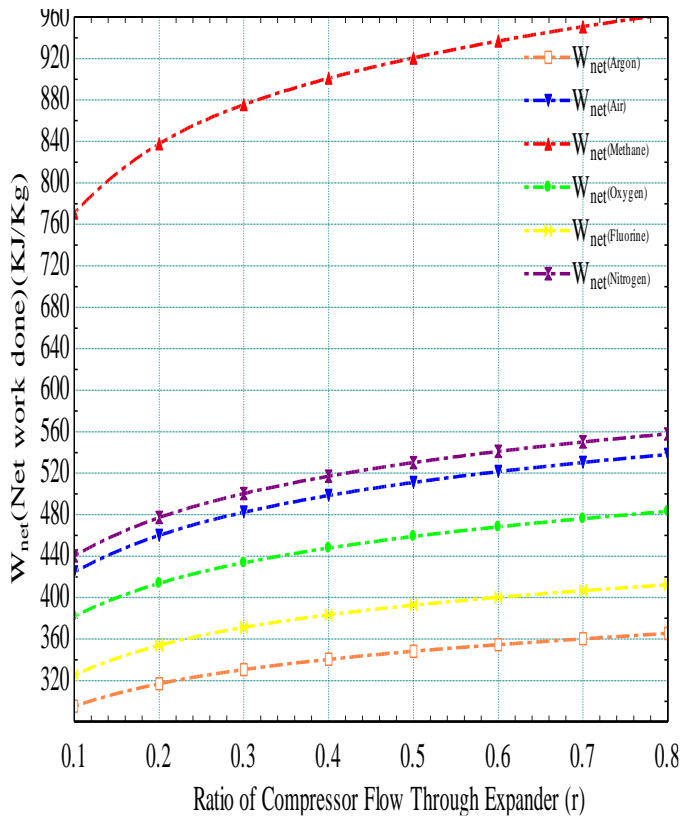


Figure 16: Variations in net work done with the ratio of compressor flow through expander

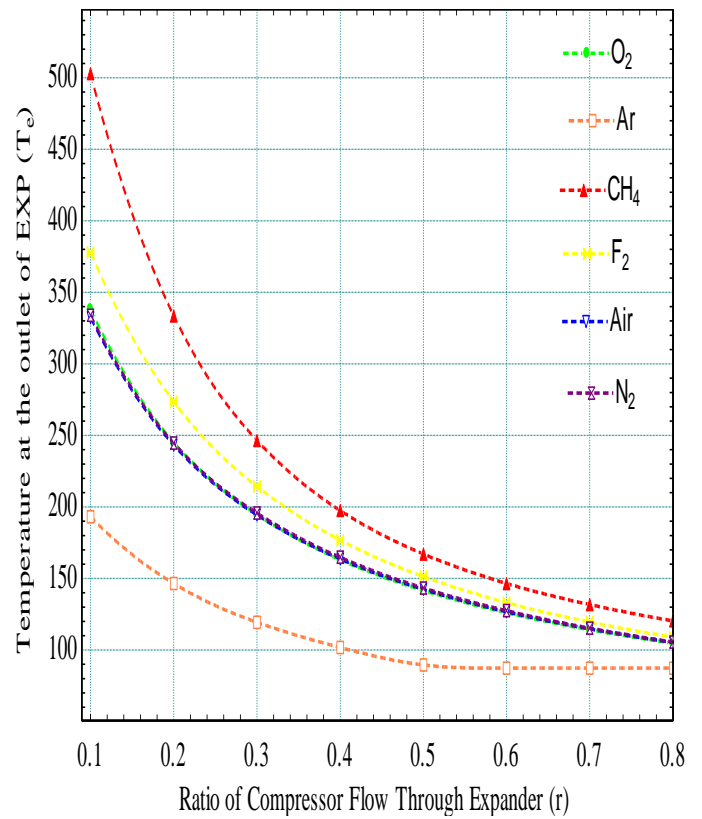


Figure 18: Variations in temperature at the outlet of expander with ratio of compressor flow through expander

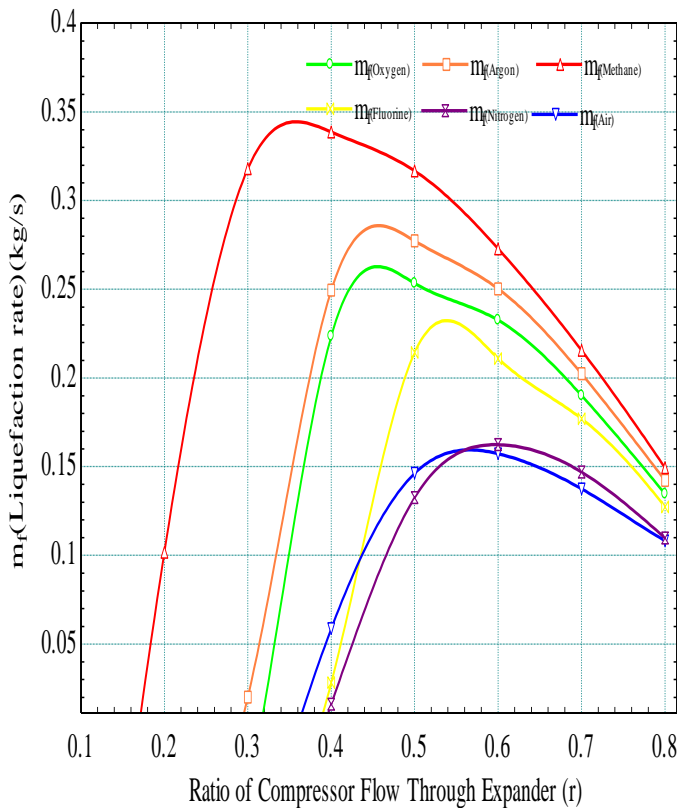


Figure 17: Variations in liquefaction mass flow rate with the ratio of compressor flow through expander

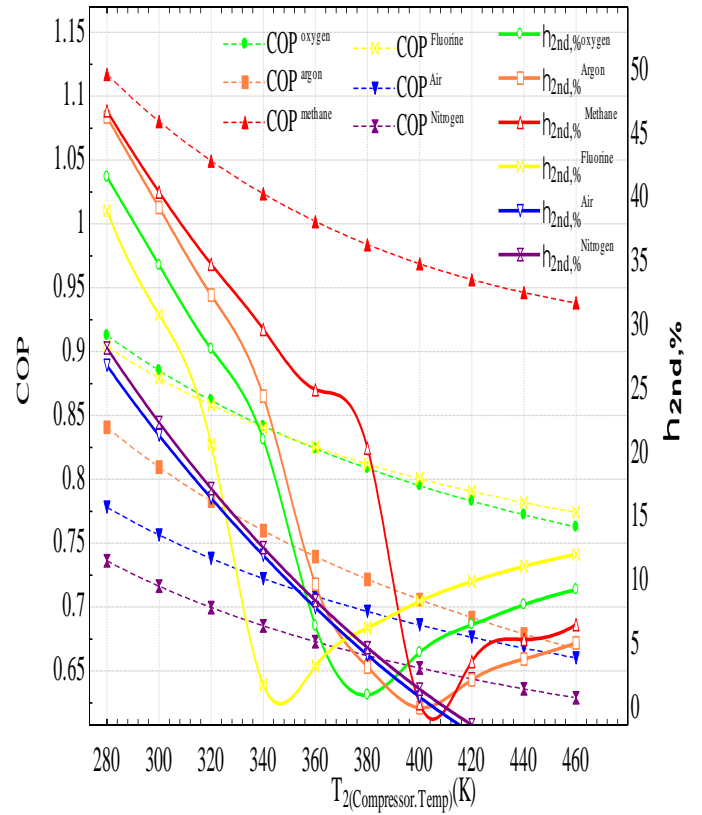


Figure 19: Variations in COP and second law efficiency with compressor temperature



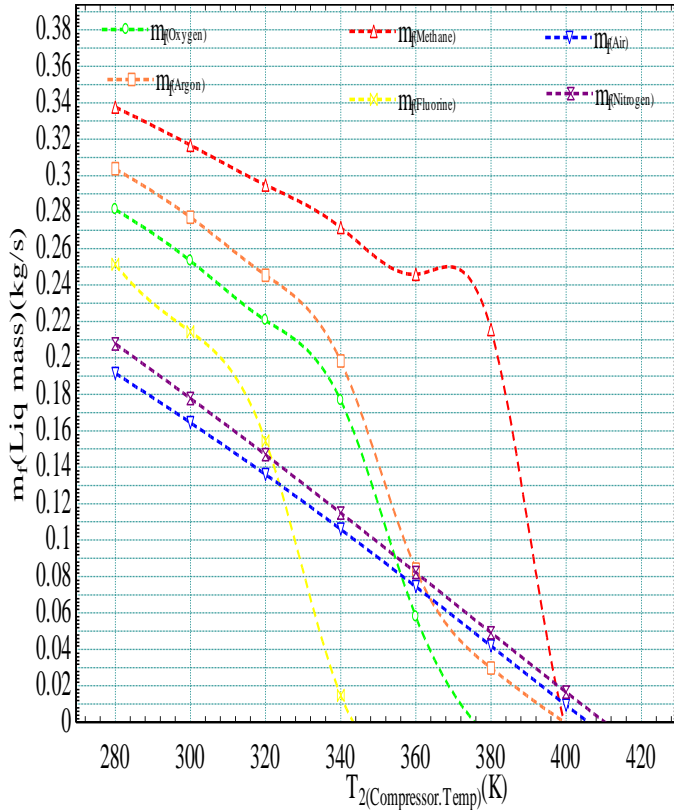


Figure 20: Variations in liquefaction mass flow rate with compressor temperature

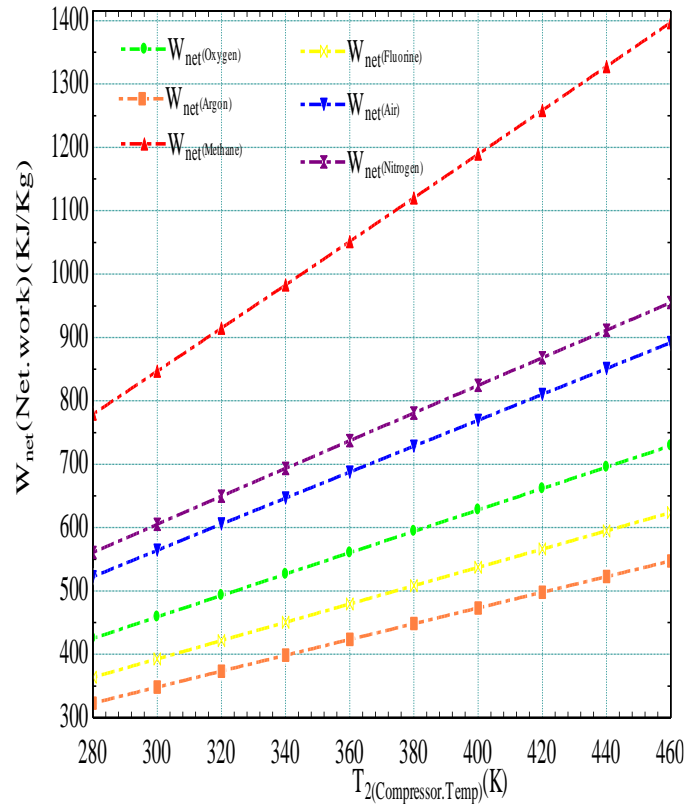


Figure 22: Variations in net work done with compressor temperature

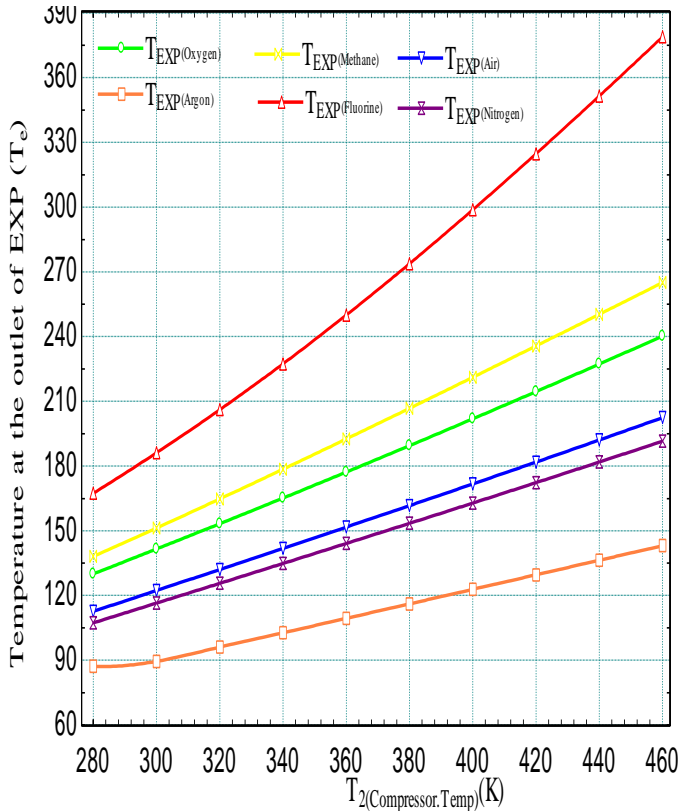


Figure 21: Variations in temperature at the outlet of the expander with compressor temperature

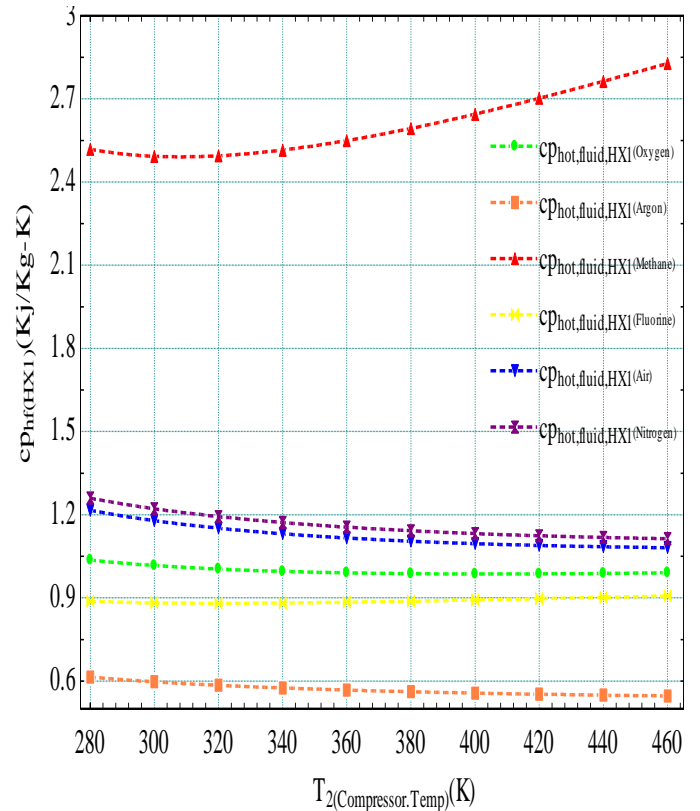


Figure 23: Variations in specific heat of hot fluid in HX1 with compressor temperature

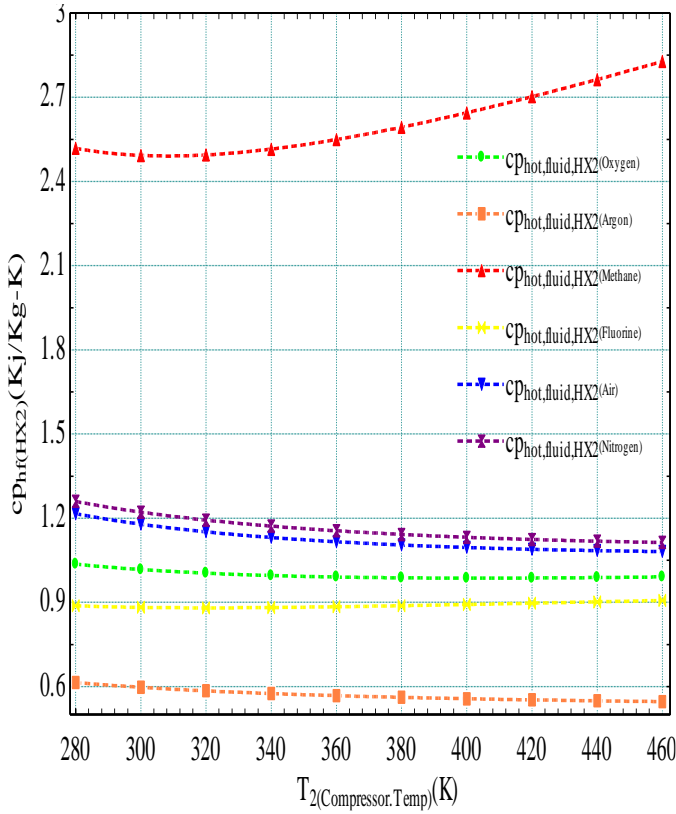


Figure 24: Variations in specific heat of hot fluid in HX2 with compressor temperature

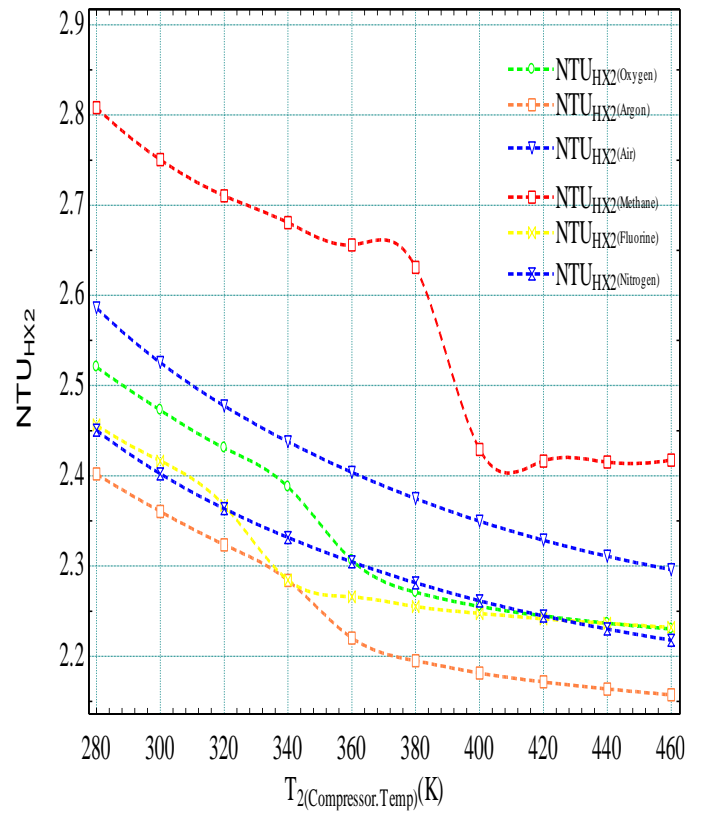


Figure 26: Variations in NTU in HX2 with compressor temperature

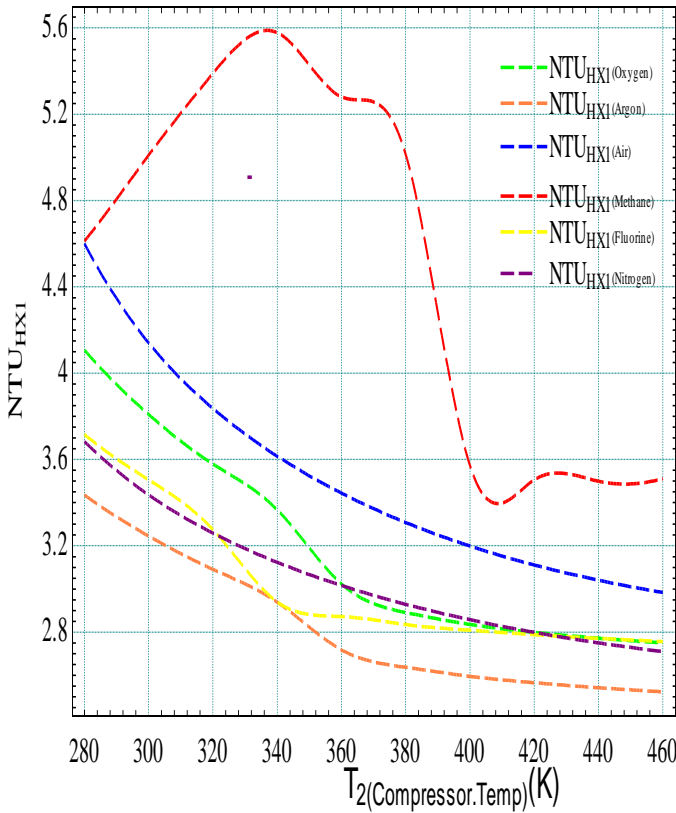


Figure 25: Variations in NTU in HX1 with compressor temperature

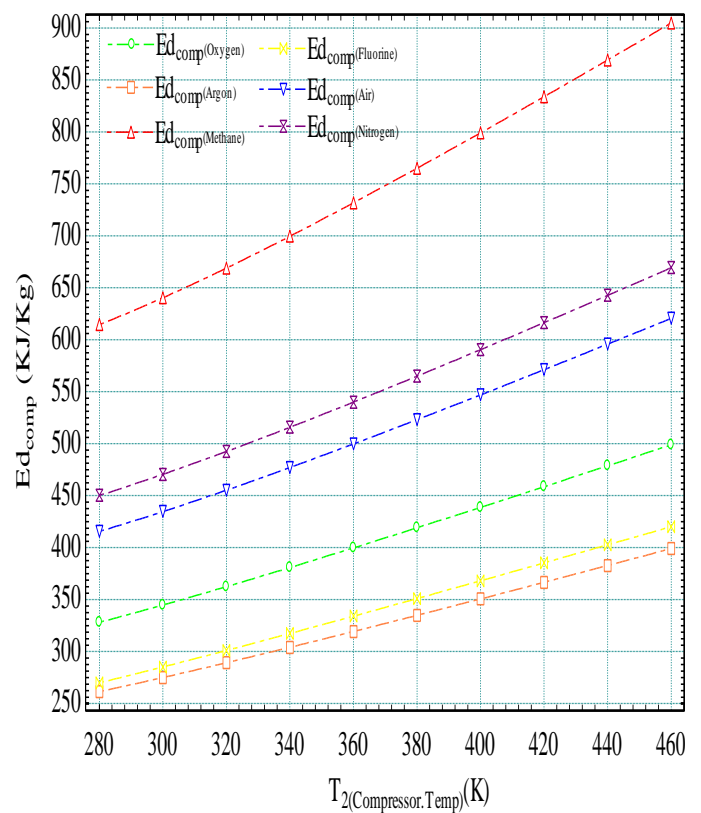


Figure 27: Variations in exergy destruction rate in compressor with compressor temperature

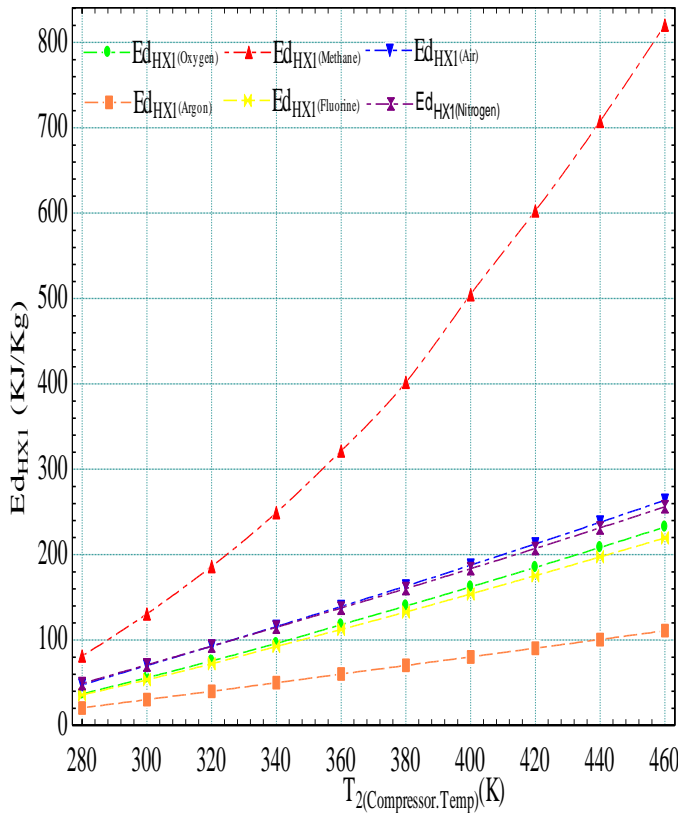


Figure 28: Variations in exergy destruction rate in HX1 with compressor temperature

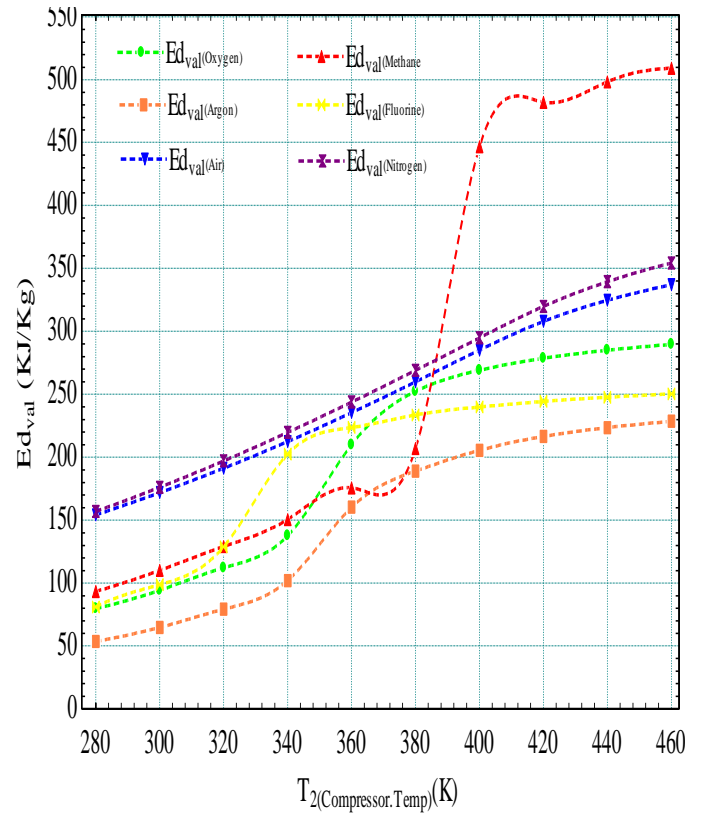


Figure 30: Variations in exergy destruction in valve with compressor temperature

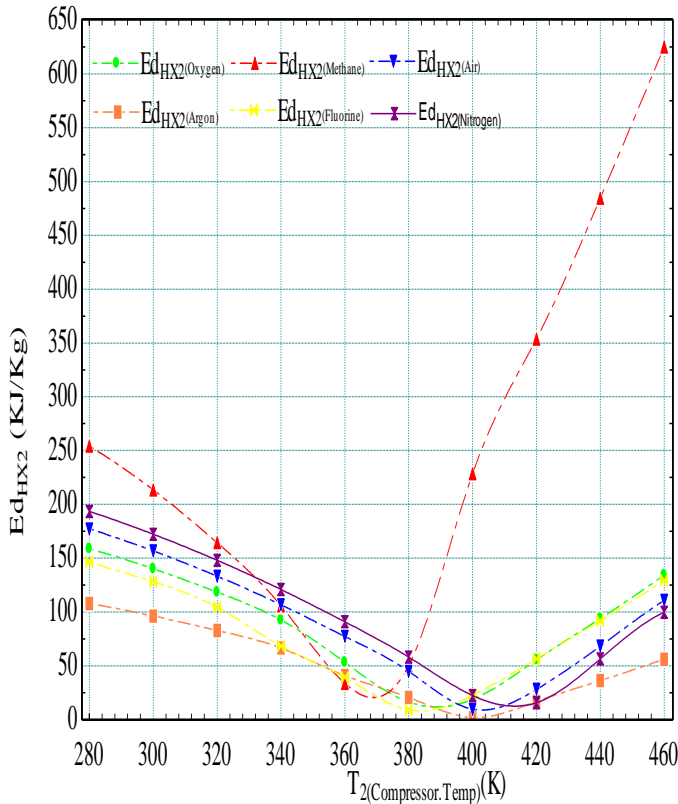


Figure 29: Variations in exergy destruction in HX2 with compressor temperature

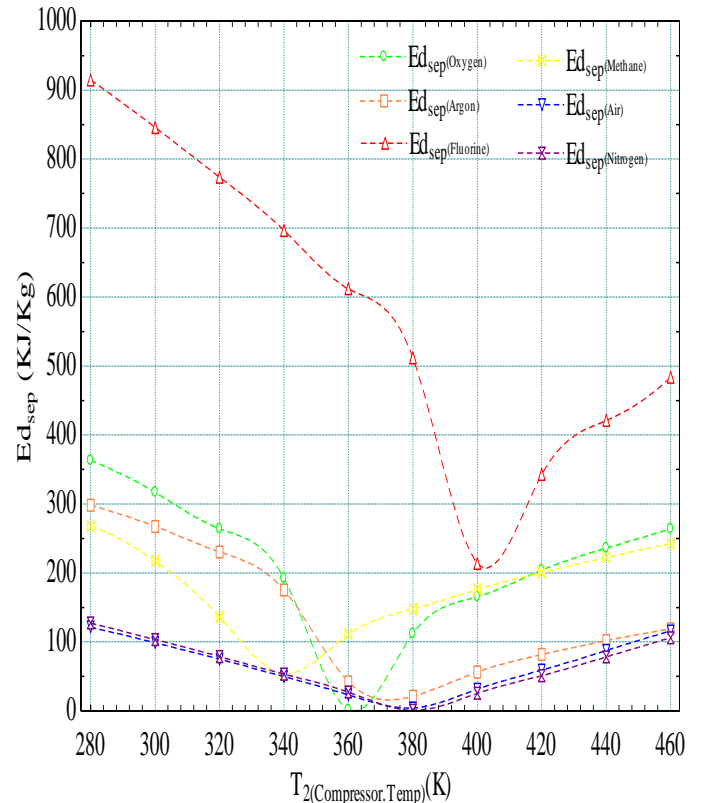


Figure 31: Variations in exergy destruction in separator with compressor temperature

Fig. 30 shows the exergy destruction in valve with respect to compressor temperature of 280K to 460K. It has been seen that nitrogen has the highest rate of exergy destruction up to certain limit of temperature and after that nitrogen is exceeded by methane. Fig.31 shows the exergy destruction in separator with respect to compressor temperature of 280K to 460K. Finally, it has been noticed that fluorine has the highest value of exergy destruction rate in separator and its graph first decreasing up to 400K and then it starts increasing. The maximum exergy destruction rate in case of fluorine is found to be 267.3kJ at 280K followed by other considered gases.

#### 4. Conclusions and Recommendations

Following conclusions have been drawn from present investigation

- (1) Argon has the highest value of second law efficiency (i.e. exergetic efficiency = 41.32%) and fluorine has the maximum value of first law efficiency (i.e. COP=0.9595) among the other gases.
- (2) Methane has the highest value of liquefaction value of mass flow rate, which is around 0.3167 at cycle pressure ratio of 40.
- (3) Methane has the highest net work done, i.e. 1120kJ and it is continuously increasing up to cycle pressure ratio of 220.
- (4) Variations in specific heat of hot fluid in second heat exchanger (HX2,) is increasing from 2.493kJ/kg-K to 3.561kJ/kg-K.
- (5) Methane having the decreasing trend of NTU, while all other gases shows the increasing trend of NTU between the prescribed range of cycle pressure ratio however, methane has the highest NTU in HX2 among the other gases.
- (6) Air has the highest percentage of exergy destruction rate with the cycle pressure ratio and it is continuously decreasing in separator.
- (7) Fluorine has the highest value of exergy destruction rate in separator and it first decreasing up to 400K and then it starts increasing order.
- (8) In compressor, the methane again has the highest rate of exergy destruction, and its trend first decreasing and then increasing suddenly followed by other considered gases.
- (9) Air has the highest percentage value of exergy destruction rate in second heat exchanger.
- (10) Methane shows the maximum NTU overall, while argon has the minimum NTU in first heat exchanger

#### References

- [1] Yu. V. Sinyavskii, Electrocaloric refrigerators: A promising alternative to current low-temperature Apparatus, Chemical and Petroleum Engineering, 31(6), 1995, 295-306.
- [2] R. Agrawal, D. W. Woodward, Efficient cryogenic nitrogen generators: An exergy analysis, Gas Separation & Purification, 5(3), 1991, 139-150.