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Thermodynamic performance comparison of six cryogenic systems

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Abstract

Cryogenic Technology is used for production of Gases for industrial and commercial applications. In this process liquefaction and purification of Helium, Nitrogen gases. Thermodynamic (Energy-Exergy) analysis of six cryogenic systems for liquefaction of gases are analyze using and comparison is done between six cryogenic systems. It was observed that in all gases methane gas show highest performance in most of systems while argon show lowest thermodynamic performance.
Keywords: Thermodynamic analysis, Energy-Exergy Analysis Cryogenic systems

1. Introduction

To achieve a very low temperature for refrigeration process the gas must be liquefied .To do so mainly two methods are
Isentropic expansion: Gas is expanded isentropically to produce low temperature, basically employed in aircraft refrigeration system.
Joule-Thomson Coefficient (μ) (Free, irreversible expansion): Change in temperature with drop in pressure at constant enthalpy is joule Thompson coefficient

$$\mu = \left(\frac{dT}{dP}\right)_H$$

It measure the the deviation of a gas from perfect gas. For real gasesμ either positive or negative depending upon the thermodynamic state .When μ is zero (inversion temperature for a given pressure) temperature of gas remain constant with throttling or when μ is positive temperature of gas decrease with throttling.

2. Use of exergy method for finding irreversibility in the system

Whole part of heat energy can never be converted completely into work, there some part of energy which used and second which get waste, the useful part of energy that is available to convert into heat is called available energy or exergy and unavailable part which get destroyed is called unavailable energy or exergy. As the first law of thermodynamics state that the energy is always conserved but the content of that energy which is capable of producing useful work is not constant that is exergy.

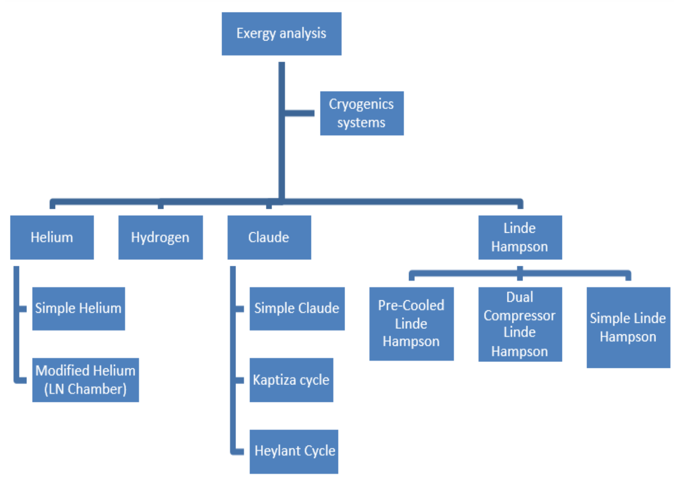

Figure 1 Cryogenic Systems

The maximum useful work or exergy at a particular state is a composite property depending upon the state of system and

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surrounding. A dead state having Zero exergy that is equilibrium state. The exergy analysis allows us to identify and quantify the sites with the losses of exergy, and therefore showing the direction for the minimization of exergy losses to approach the reversible COP. The importance of cryogenics is given below [1].

2.1 Importance of Cryogenics

(i) Cryogenic Technology is used for production of Gases for industrial and commercial applications. In this process liquefaction and purification of Helium, Nitrogen gases are done. Also using this technique production of inert gases is done.
(ii) 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.
(iii) 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.
(v) Cryogenic has got lot of application in medical field. It is wildly used in MRI equipment for diagnosis of diseases.
(vi) Cryogenic has got a great role in chilled water storage system.

2.2 Literature Review

H. Mahabadipour and H. Ghaebi [1], 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 [2] also carried out Exergy analysis of vapor compression refrigeration systems. Gadhiraju Venkatarathnam [3], 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. .

(a) 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.
(b) Heat exchanger and expansion valve, expander and other addition parts should also properly analyze.

2.3 Analysis and comparison of systems

Advanced technologies are used in very limited way and only on some part of system. Therefore following objectives of present studies are

(a) Exergy analysis of considered cryogenics systems and finding exergy destruction in each and there individuals components
(b) Suggestion for reducing exergy destruction losses in whole systems and there components

In part of the analysis, the effects of pressure ratio and gas outlet temperature of compressor on various energy- and exergy-based performance parameters are investigated considering all six gases as the gas being liquefied.

3. Results and Discussions

Initial six systems are individually analyze using one gas methane and comparison is done between systems. Collin system and improved Collin system are also compared on the basis of second law for better understanding of working

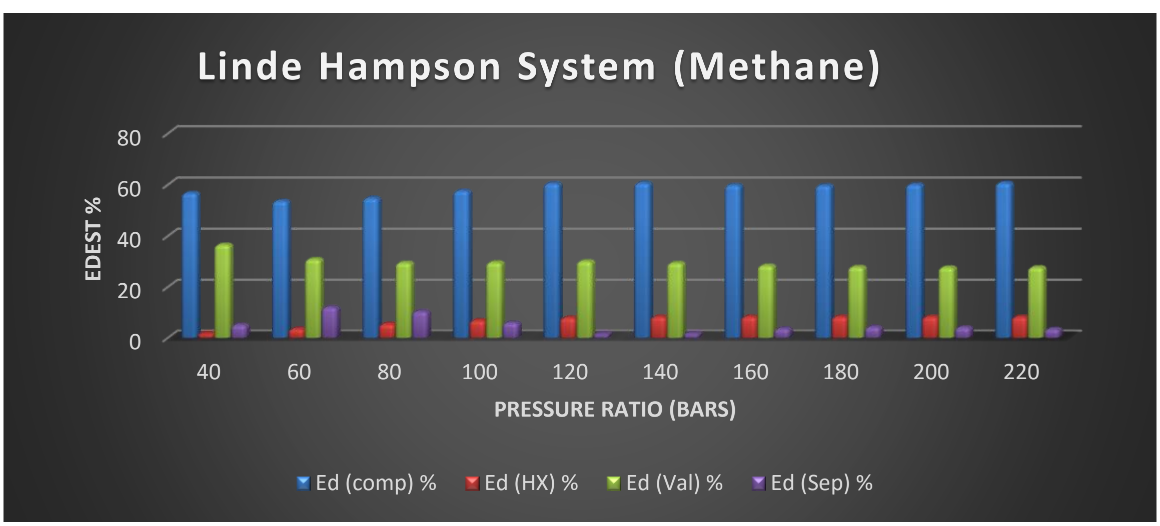

Figure 2: Variation in percentage exergy destruction for methane with the pressure ratio [1]

In the above fig.2 percentage exergy destruction for methane in the component associated with Linde Hampson system was studied. It has been observed that compressor has the highest rate of exergy destruction, which is continuously increasing between the pressure ratios of 40 to 220 bar. While exergy destruction in the HX occupy the very less value among the other components. It has been found that maximum percentage exergy destruction is around 60% in compressor followed by valve, separator, and HX, respectively

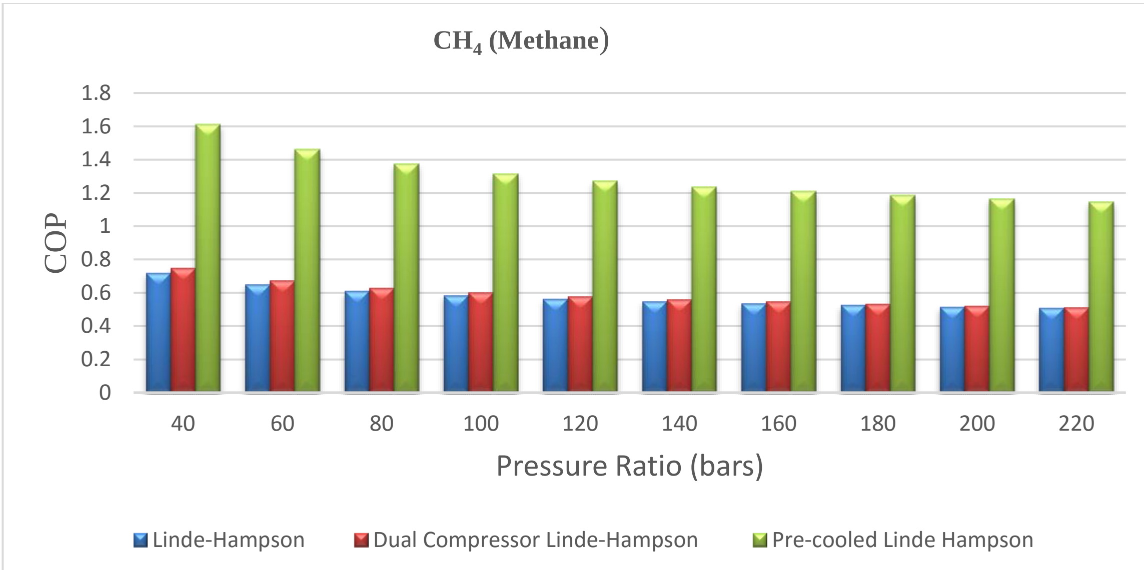

Figure 3: Variation in COP for methane with pressure ratio of three cryogenic systems

From the fig.3 it has been seen that Pre-cooled Linde Hampson has the largest COP among the dual compressor Linde-Hampson and Linde-Hampson. Maximum COP reported in the Pre-cooled Linde Hampson, i.e. around 1.6 and it is continuously decreasing up to pressure ratio 220

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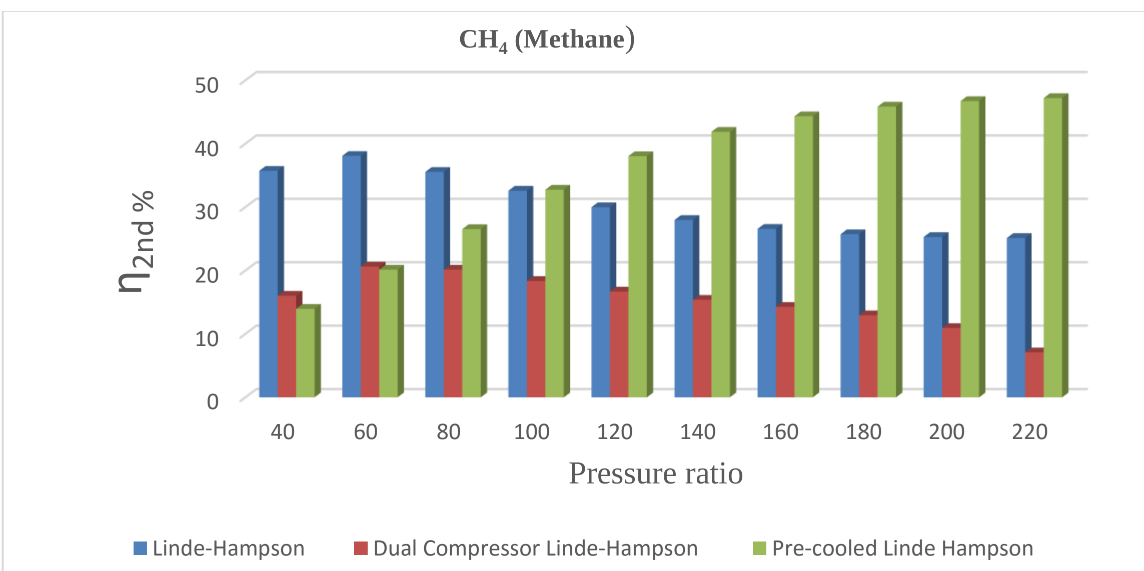

Figure 4: Variation in second law efficiency for methane gas with the pressure ratio in three cryogenic systems

Fig. 4 shows the variation in second law efficiency for methane for the different systems between the pressure ratios of 40 to 220. It has been observed that Pre-cooled Linde Hampson has the highest second law efficiency, i.e. around 47%. On the other hand, second law efficiency of Linde-Hampson and Dual compressor Linde-Hampson first increasing and then decreasing continuously up to pressure ratio 220.

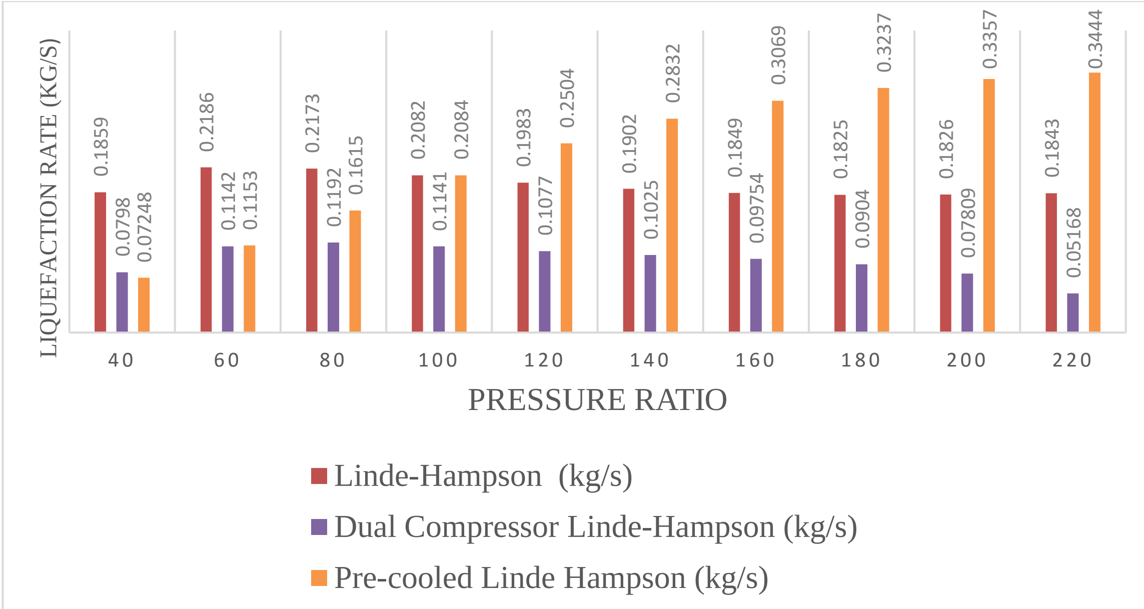

Figure 5: Variation in mass liquefaction rate of different system with pressure ratio in three cryogenic systems

In the above fig.5 mass liquefaction rate was discussed for the different considered systems. It has been seen that mass liquefaction rate for the pre-cooled Linde Hampson system is continuously increasing and the maximum value is 0.3444kg/s at 220bar. On the other side, mass liquefaction rate for Linde-Hampson initially increasing then suddenly starts to decrease followed by Dual Compressor Linde Hampson system.

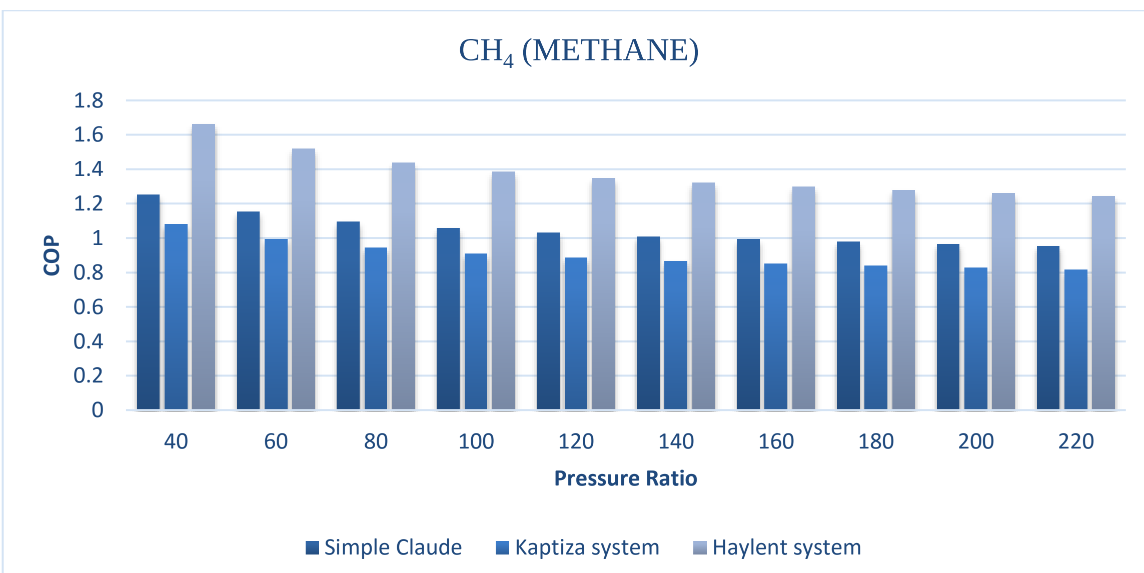

Figure 6: Variation in COP for the different systems with the pressure ratio in three cryogenic systems

In this fig.6, it has been observed that Haylent system for methane gas has the highest value of the COP, i.e. around 1.7 and it is continuously decreasing up to 220 bar, which is followed by simple Claude and Kaptiza system, i.e. COP is around 1.3 and 1.1, respectively

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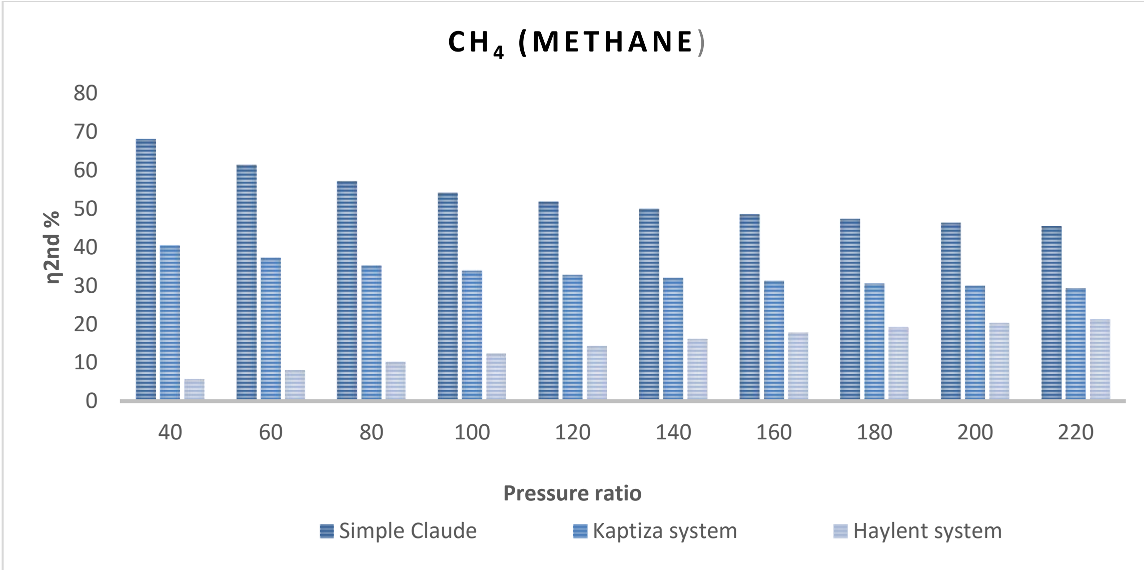

Figure 7: Variation in second law efficiency with the pressure ratio in three cryogenic systems

In the above fig.7 second law efficiency for the different system based on methane gas has been discussed. It has been seen that second law efficiency of simple Claude system is continuously decreasing and the maximum value of second law efficiency, i.e. around 70%, which is followed by Kaptiza system, i.e. around 40%. On the other hand, Haylent system having the increasing trend of second law efficiency and the maximum second law efficiency, i.e. 20%.

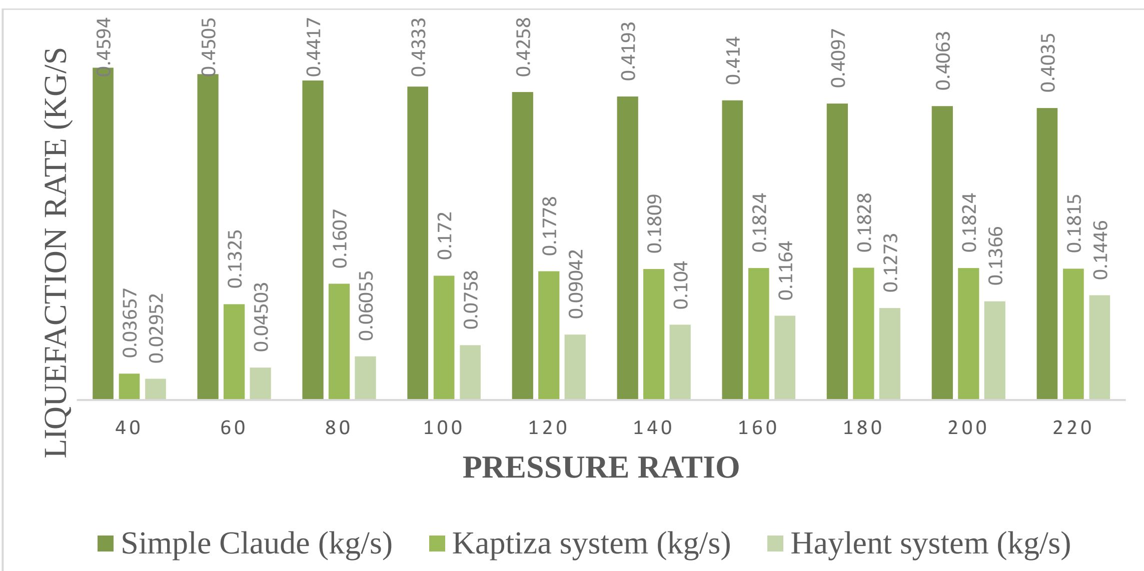

Figure 8: Variation in liquefaction mass flow rate with the pressure ratio in three cryogenic systems

In the above fig. 8 liquefaction mass flow rate for the different system has been discussed. It has been observed that simple Claude has the highest second law efficiency, i.e. 0.4594kg/s at 40 and it is continuously decreasing up to pressure ratio 220 followed by Kaptiza system and Haylent system, respectively. In this figure percentage exergy destruction in the different components for the pressure ratio of 40 to 220bar has been discussed. It has been observed that percentage exergy destruction in compressor has the largest value, i.e around 46% at 220bar pressure ratio among the other components such as separator, HX2, HX3, Valve, and separator, which is around 33% at 40bar, 18% at 40bar, 11% at 40 bar, 8% at 220 bar, and 1% at 40bar, respectively.

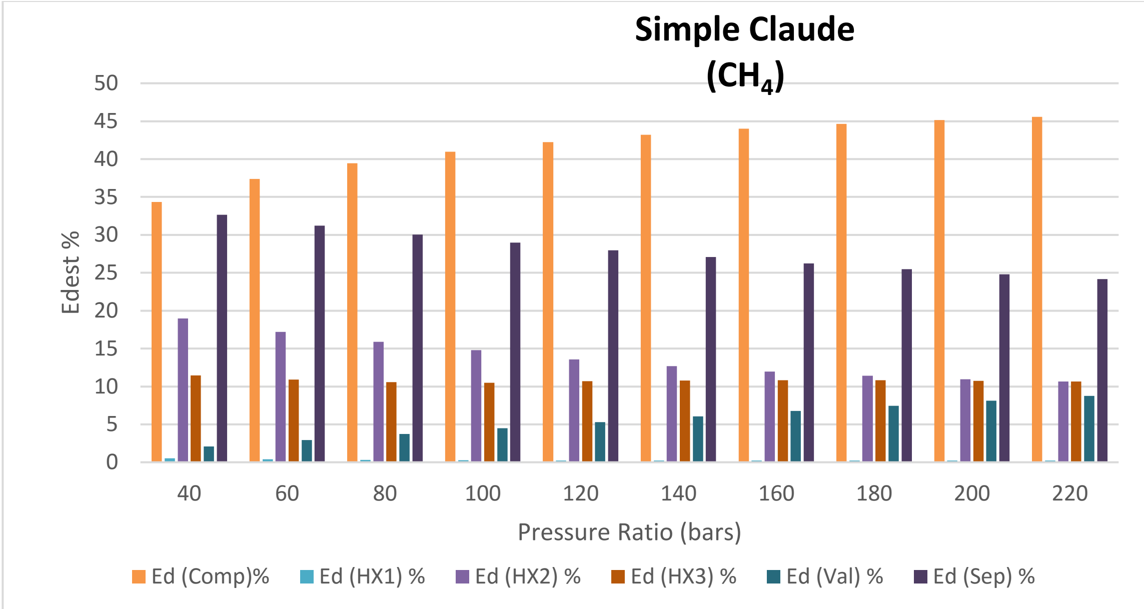

Figure 9: Variation in percentage exergy destruction with the pressure ratio

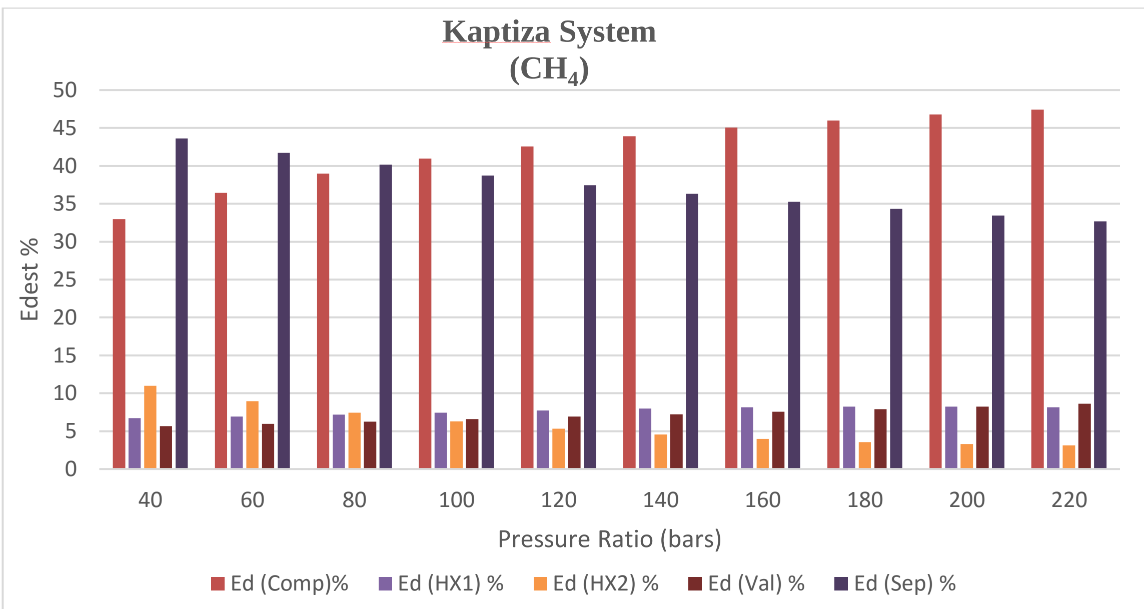

Figure 10: Variation in percentage exergy destruction rate with the pressure ratio

In this fig 10 illustrates the percentage exergy destruction in the different components for methane gas in Kaptiza system has been discussed. It has been seen that exergy destruction rate in compressor is very high, i.e. around 47% at 220bar, which is followed by separator, HX2, HX1, and valve respectively.

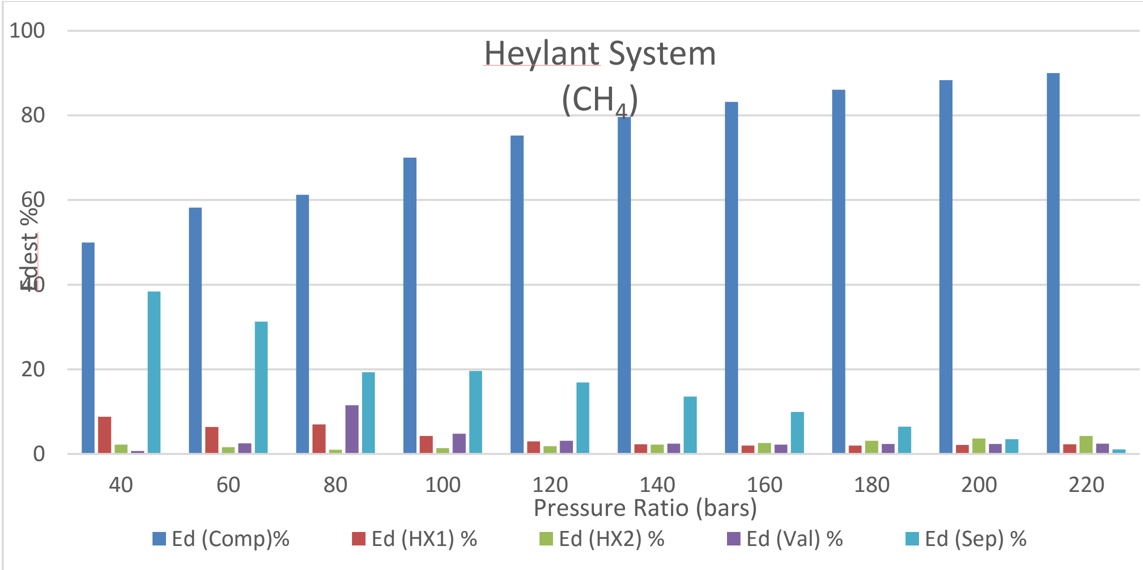

Figure 11 Variation in percentage exergy destruction in different components with the pressure ratio

In the above fig.11 shows the percentage exergy destruction in the different components with the pressure ratio of 40bar to 220bar. It has been seen that percentage exergy destruction is continuously increasing and the maximum value is around 90% at 220bar, which is followed by separator, HX1, valve, HX1 and, HX2 respectively. The maximum liquefaction mass flow rate for the different system Numerical Values of optimize performance parameters For Systems (COP &η2nd %) of various system are given in Table-2&3 respectively.

Table .1 Various Optimize performance parameters For Systems (COP &η2nd %)

Systems	Optimize performance parameters	Oxygen	Argon	Methane	Fluorine	Air	Nitrogen
Linde-Hampson	COP	1.305	1.29	0.6	0.5	0.6	0.62
	η2nd %	4.98	5.261	35.5	26.5	20.38	19.8
	PR	58	49	60	80	60	72
Dual-Comp L-H	COP	0.59	0.43	0.67	0.6	0.67	0.69
	η2nd %	12.4	12.45	20.62	9.6	6.9	8.4
	PR	70	80	64	88	60	60
Pre-cooled L-H	COP	1.057	0.9114		1.007	1.027	1.007
	η2nd %	22.66	23.37		16.54	17.39	16.54
	PR	140	140		100	120	120
Simple Claude	COP	1.13	0.99	1.253	1.114	1.59	1.04
	η2nd %	80.6	82.99	68.11	84.34	81.95	83.88
	PR	40	40	40	40	40	40
Kaptiza system	COP	0.96	0.88	1.08	0.87	0.78	0.74
	η2nd %	36.8	41.32	40.47	30.85	21.6	22.4
	PR	40	40	40	64	60	62
Haylent system	COP	1.225	1.129	1.32	1.129	0.94	1.05
	η2nd %	6.153	6.05	16.31	6.354	9.04	7.7
	PR	94	69	100-140	120	100-220	100-120

Table .2 shows the maximum liquefaction mass flow rate for the different system

Maximum Liquefaction Pressure Range (bars) and (kg/s)						
	Oxygen	Argon	Methane	Fluorine	Air	Nitrogen
Linde-Hampson	100-120 (0.15)	140-160 (0.15)	60-70 (0.21)	80-100 (0.14)	60-80 (0.10)	80-100 (0.10)
Dual Compressor	96-100 (0.066)	94-100 (0.069)	72-80 (0.1192)	96-100 (0.050)	60-64 (0.038)	60-64 (0.032)
Pre-cooled L-H	120-140 (0.148)	100-140 (0.151)	120-140 (0.121)	120-140 (0.1044)	100-120 (0.097)	100-120 (0.09)
Simple Claude	40-60 (0.467)	40-60 (0.47)	40-60 (0.45)	40-60 (0.46)	40-60 (0.44)	40-60 (0.4583)
Kaptiza system	100-120 (0.2605)	80-100 (0.2819)	40-60 (0.3157)	100-120 (0.2328)	80-100 (0.16)	120-140 (0.177)
Haylent system	80-100 (0.04)	100-120 (0.051)	120-140 (0.104)	100-120 (0.03)	200-220 (0.05)	120-140 (0.04)

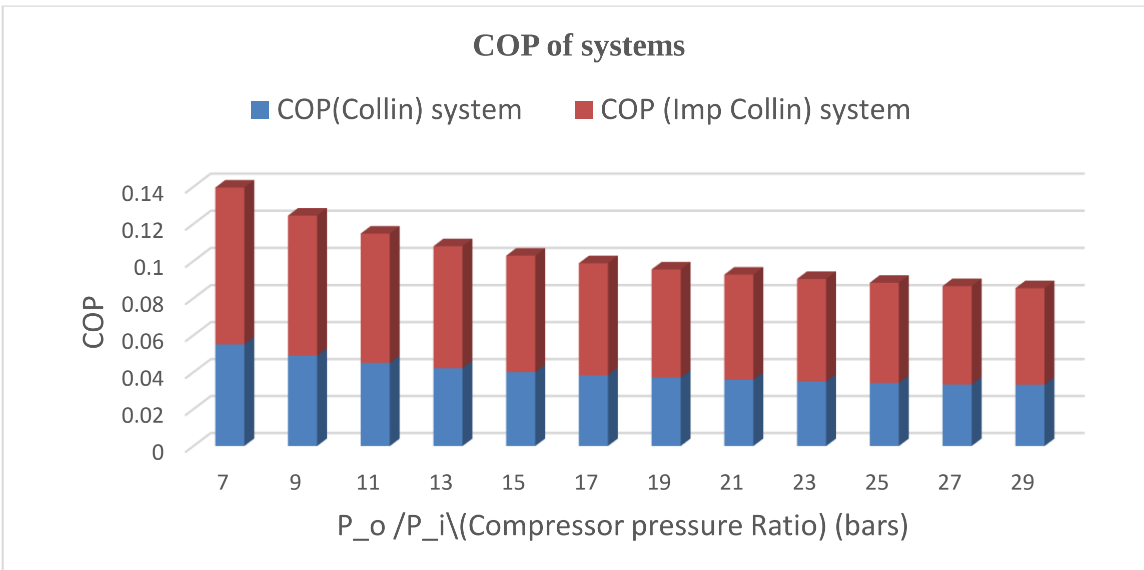

Figure 12: Variations in COP with the compressor pressure ratio in two cryogenic systems

In this fig.12, the COP of Collin and improved Collin system has been studied with the compressor pressure ratio of 7bar to 29bar. It has been seen that improved Collin system has the highest COP i.e. 0.14 at 7bar as compared to the Collin system with the COP of 0.06 at 7bar.

4. Conclusions

Exergy analysis of cryogenics systems in which first six system with different gases and rest systems such as hydrogen, Collin, improved Collin system are evaluated on the basis of pressure ratio, compressor outlet temperature, and expander mass flow ratio.. Following results are concluded from study.

(i) During off design condition, performance of cycle does not hamper within the specific range of cyclic pressure ratio, for particular considered system there is always appropriate operating pressure ratio range for each working gas on which system work better.

(ii) All six system are compared on the basis of performance parameters at different pressure ratio, form the data observation it observed that simple Claude cycle is most suitable system because the three heat exchanger help in achieving more refrigerant effect which is in turn optimize the performance of the system.

(iii) Variation in expander mass flow has highly influence the refrigeration effect of expander and overall performance of system. Optimum range of EXP flow fraction (r) producing refrigeration effect is 0.55 to 0.7. Liquid production rate is highly influenced by refrigeration effect of expander.

(iv) Inlet temperature of expander also plays an important factor to determine the refrigeration effect while other parameters in the system are constant. As the mass flow fraction increases through EXP, the output temperature of expander T_e also decreases which in turn lower the inlet temperature of input temperature of $T_{in\ EXP}$.

(v) In all gases methane gas show highest performance parameters in most of system while argon show lowest.

(vi) The performance of hydrogen liquefaction cycle does not much deteriorate during off design condition when it is operated in selected operated range of PR 20-52 bar (the compressor suction pressure is atmospheric).

(vii) xergetic efficiency of the heat exchanger (HXD) at the lowest temperature of a hydrogen liquefier can be improved by increasing the pressure ratio because the mass imbalance gets compensated by the specific heat imbalance.

(viii) While designing the hydrogen liquefaction cycle, owing to their lower exergetic efficiencies, additional care should be taken for ensuring superior heat transfer performance by the high temperature heat exchanger HXA and the lowest temperature heat exchanger HXD.

(ix) Initial feasible range of pressure ratio in hydrogen liquefaction system is 20 to 87 bar, COP of the system decrease at very rapid rate but after that the rate of reduction in COP with increase PR start becoming constant with very less change while the second law efficiency show a constant reduction with increase in PR.

(x) Design parameter NTU for HX is carefully study for best performance of system. NTU term continuously decrease in hydrogen liquefaction system upto 70 bar for the J-T heat exchanger HXD and minimum at 70 bar while the variation in NTU term for HXA and HXB is quite different due to the different cold stream temperature of exchangers

(xi) Improved Collin system show high efficiency as compared to Collin system, the nitrogen chamber and extra expander gives extra refrigerant effect which enhance liquefaction rate in the system and increasing the performance parameters of systems.

(xii) The improved Collin system at PR 11 bars show highest exergtic efficiency of 54.19% keeping the expander ratio of all three expander is 70%,10%,10% respectively while simple Collin helium liquefaction system show 3.54% exergtic efficiency keeping the both expander flow ratio 35% and 50% respectively

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