IJIREEICE

ISSN (Online) 2278-1021
ISSN (Print) 2319-5940

International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering

NCIET- 2020

National Conference on Innovations in Engineering & Technology

Govt., Polytechnic College, Palakkad, Kerala

Vol. 8, Special Issue 1, February 2020

# Exergy Based Analysis of Gas Liquefaction Cycles

**Sijo K K[1], Rijo Jacob Thomas [2]**

Lecturer, Mechanical Engineering, Govt. Polytechnic College, Chelakkara, Thrissur, India[1]

Assistant Professor, Mechanical Engineering, TKM College of Engineering, Kollam, India[2]

**Abstract:** Cryogenic liquefaction systems has greater importance in recent years due to the application of cryogenic fluids in engineering and other scientific researches on different parts of worlds. The main scope of this systems includes the design, development and improvement of various components in order to provide the best working conditions. A designer has to fix parameters such as number of heat exchangers, working pressures and flow diversions etc. as they play important role in heat transfer. Exergy analysis considered as a useful method to analyse and optimize the design and operation of these liquefaction systems. This study concentrates on exergy analysis of cycles commonly used for the liquefaction of gases in order to evaluate and compare their performance under given working conditions and system component efficiencies. The cycles considered are simple Linde-Hampson cycle, Claude cycle and Collins cycle respectively. Systematic evaluation of important operating parameters has been done to determine the exergy destructions in components as well as in the entire cycles. Compressor pressure, expander flow rates are some of the parameters considered during the analysis. The process flow diagrams, simulations of these cryogenic cycles are done with the help of the simulation tool Aspen HYSYS™. All calculations are done at steady state and the results hence obtained. Detailed exergy-based analyses are performed upon the various processes and the exergy destruction in each component also found.

**Keywords:** Exergy, Liquefaction, Heat Exchanger, Expander, Compressor, Pressure.

## I. INTRODUCTION

Cryogenics is the science that involves study of very low temperatures. Low temperatures usually obtained by using liquefied gases such as liquid nitrogen or liquid Helium. Therefore, liquefaction of gases is an important area for cryogenic technologies. There are two main methods for producing low temperature refrigeration namely Joule-Thomson expansion and expansion engine. The first method is the Joule-Thomson expansion and utilizes the Joule-Thomson effect to produce low temperatures. The second method employs an expander to produce low temperature. In most of the liquefaction systems the gas is compressed to a high pressure, cooled in the counter-current heat exchanger, and expanded through a J-T valve. Exergy analysis considered as one of the important tools for predicting the performance of liquefaction cycles. Thermodynamic irreversibility of the cycle, which is defined by the second law of thermodynamics as entropy generation and loss of exergy, provide a direct measure of the rate of liquefaction or capacity of refrigeration of a cycle. The major factors that contribute to the thermodynamic irreversibility are: heat transfer in heat exchanger across a finite temperature difference, other thermal irreversibility such as flow mal distribution, heat inleak and axial conduction in heat exchangers, pressure drop in piping and heat exchangers, isenthalpic expansion in Joule-Thomson valve, finite stages of compression, inefficiencies in expanders, inappropriate flow rates and operating pressures etc. In case of liquefaction cycles, the losses are distributed among different components throughout its operating temperature range. The irreversibility's can be avoided by expander-based systems rather than different precooling systems.

## II. LITERATURE REVIEW

Atrey, M. D [1]. (1998) presented a cycle simulation for the Collins helium liquefaction cycle with six heat exchangers and two reciprocating expanders. It highlights the concept of an optimum mass flow rate through expanders for the liquefier. Wagner, U [12]. (2000) reviews the possible process solutions for liquid nitrogen pre-cooling and their particularities. Five principle solutions with their main characteristics for the process arrangement of the precooling with liquid nitrogen have been presented. Kanoglu, M [6]. et al., (2008) states that Cryogenic temperatures can be obtained by liquid expansion, Joule-Thompson expansion, and expansion engine. This paper presents an analysis of the thermodynamic cycles commonly used for the liquefaction of gases in order to evaluate and compare their performance under various conditions and system component efficiencies. The cycles considered are simple Linde cycle, precooled Linde cycle, Claude cycle, and Kapitza cycle. Devender, K. Mishra, R. S [2]. (2014) deal with energy exergy comparative analysis of two cryogenics systems (i.e Linde Hampson and Claude) in terms of second law efficiency and the output ( which in form of liquefaction mass ) of gases, The numerical computation was carried out for above systems and it was conclude that by joining extra accessories in system make a system efficient in output result but in other hand making system large , its cost and as well as useful energy destruction of overall system are degraded which seen in from of low second law efficiency. According to Rahul [9], et al. (2015) Liquid nitrogen precooling is widely used in helium liquefier/refrigerator for increased liquefaction as well as providing initial cool-down up to 80 K. The advantages are reduction in

IJIREEICE

ISSN (Online) 2278-1021
ISSN (Print) 2319-5940

International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering

NCIET- 2020

National Conference on Innovations in Engineering & Technology

Govt., Polytechnic College, Palakkad, Kerala

Vol. 8, Special Issue 1, February 2020

plant size and in number of equipment. In this paper, through parametric analysis of some reported configurations using Aspen HYSYS® V7.3, design decisions for adopting a precooling scheme for given helium plant has been presented. Results have been analysed for the adopted plant configuration to arrive at conclusion regarding optimum configuration for precooling in the helium plant. Devender, K [3] et al., (2017) conducted complete thermo analysis of pre-cooled Linde system is carried out and various results are predicted. The effect of some various parameters like refrigerant mass flow ratio and compressor pressure on system with six different gases is studied by applying computational numerical technique. Effect of these parameters on system conclude that the system works good near 200 bar pressure and refrigerant mass flow ratio of 0.03 is suitable for system showing high second law efficiency and Liquefaction mass ratio and low work done per liquefaction mass ratio. Mishra, R. S [8] et al., (2018) presents, the validation of Linde system, Pre-cooled Linde system, Claude, Kapitza, Haylandt and Collins system in terms of system performances. In this paper exergy analysis of cryogenics systems with different gases, Collins system is evaluated on the basis of pressure ratio, compressor outlet temperature, and expander mass flow ratio.

## III. OBJECTIVE OF THE STUDY

The main objective of the study is to evaluate the liquefaction cycles for 1.Nitrogen 2. Helium. This will be carried out by:

- Performance evaluation of various parameters of Liquefaction cycles using simulation tool Aspen Hysys
- Calculation of Liquefaction fractions, exergy efficiencies, exergy destruction in each components
- Investigations on the Effect of discharge pressure, best flow diversion, component efficiency etc. on the liquefaction fraction, exergy efficiencies, exergy destruction

## IV. METHODOLOGY

A. Exergy Analysis: Energy analysis is based on the first law of thermodynamics which embodies the principle of conservation of energy and is the traditional method to assess the performance and efficiency of energy systems and processes.
Since Energy is conserved an energy balance for a general system or process may be written as
Energy input –Energy output = Energy accumulation
By contrast, an exergy balance can written as
Exergy input – Exergy output – Exergy consumption = Exergy accumulation
Exergy rate balance for a control volume in steady-state flow can be expressed as

$$\sum \dot{Q}_j\left(1-\frac{T_0}{T_j}\right)-\dot{W}\ +\sum_i \dot{m}_i\, e_{fi}-\sum_e \dot{m}_e\, e_{fe}-\dot{Ex}_{DEST}=0$$

$$e_f=h-h_0\ -T_0(s-s_0)$$

If there is a single inlet and a single exit, denoted by *i* and *e*, respectively the equation reduces to

$$\sum \dot{Q}_j\left(1-\frac{T_0}{T_j}\right)-\dot{W}\ +\dot{m}(e_{fi}-e_{fe})-\dot{Ex}_{DEST}=0$$

Where, $\dot{m}$ is the mass flow rate. The term is $(\ e_{fi}-e_{fe})$ evaluated using equation given below

$$e_{fi}-e_{fe}=(h_i-h_e)-T_0(s_i-s_e)$$

B. Simulator: Aspen Hysys solves the critical engineering and operating problems that arise throughout the lifecycle of a process, such as designing a new process, troubleshooting a process unit or optimizing operations of a full process like a Rankine cycle plant. The process simulation capabilities of Aspen Hysys enables engineers to predict the behaviour of a plant using basic engineering relationships such as mass and energy balances, phase and chemical equilibrium, with reliable thermodynamic data, realistic operating conditions and the rigorous Aspen Hysys equipment models, they can simulate actual plant behaviour.

## V. RESULTS AND DISCUSSIONS

A. Linde Cycle

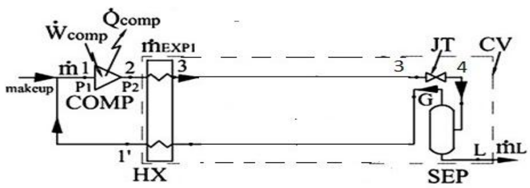


Fig. 1 Schematic of the Linde liquefaction cycle

Linde cycle is the simplest of all the liquefaction system and considered as the second used to liquefy the gases. A schematic of Linde system is shown in figure The Nitrogen gas is first compressed from ambient conditions to a point of higher pressure by

IJIREEICE
ISSN (Online) 2278-1021
ISSN (Print) 2319-5940
International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering
NCIET- 2020
National Conference on Innovations in Engineering & Technology
Govt., Polytechnic College, Palakkad, Kerala
Vol. 8, Special Issue 1, February 2020

reversibly and isothermally. The efficiency of compressor and both the expander are kept constant at 75%, where mass flow rate total is 1 kg/s, heat exchanges are given a constant effectiveness of 0.97, N2 is compressed from 1 bar to 200 bar, the heat exchanger is given a pressure drop of 1 bar for high pressure stream and 0.1 bar for the return stream, J-T expands $N_2$ to 1.2 bar. Process flow diagram of a Linde cycle modelled in Aspen Hysys by the above conditions is shown in Fig. 2.

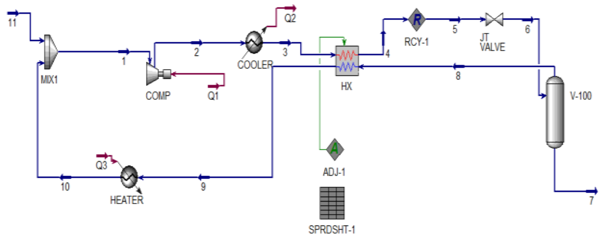


Fig. 2 Process flow diagram of Linde liquefaction cycle in process simulator

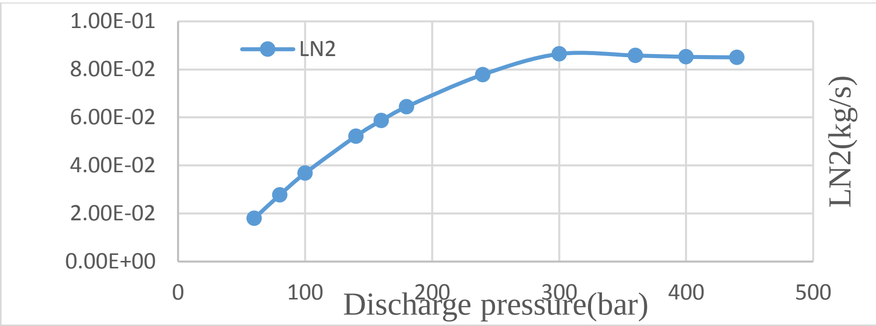


Fig. 3 Effect of discharge pressures on fraction of liquid produced in Linde cycle

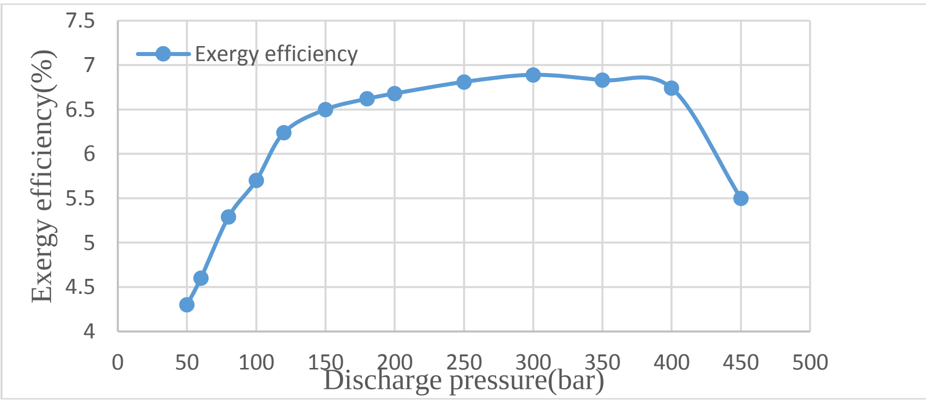


Fig. 4 Effect of variation of compressor discharge pressure on exergy efficiency of Linde cycle.

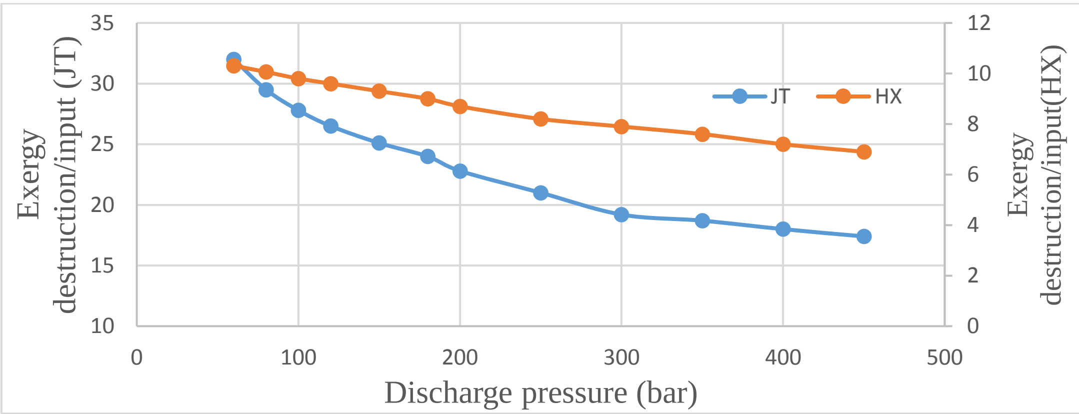


Fig. 5 Exergy destruction in each component as percentage of total exergy destruction in cold box.

B. Claude Cycle

A schematic of Claude liquefaction system is shown in figure. The liquefaction was done by compressing the Nitrogen gas to higher pressure by reversibly and isothermally. This high pressure gas is passed through first heat exchanger. Between 60 to 80 percent of gas is then diverted from main stream and expanded through an expander. This expanded gas is reunited with return stream below second heat exchanger. The stream to be liquefied goes through the second and third heat exchangers respectively and finally expanded through expansion valve to the liquid receiver.

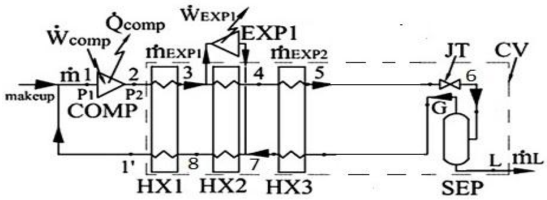


Fig. 6 Schematic of the Claude liquefaction cycle

For understanding the performance, the efficiency of compressor and both the expander are kept constant at 75%, where mass flow rate total is 1 kg/s, heat exchanges are given a constant effectiveness of 0.95. N2 is compressed from 1 bar to 40 bar, the heat exchangers is given a pressure drop of 0.1 bar for high pressure stream and 0.1 bar for the return stream, J-T expands $N_2$ to 1.3 bar. Process flow diagram of a Claude cycle modelled in Aspen Hysys by the above conditions is shown in Figure 8. In order to achieve isothermal compression a cooler is provided after the compression process.so the effect of isothermal compression is achieved. A separator which is provided at the exit of the J-T is the component in which the liquid nitrogen is separated and remaining gaseous Nitrogen fed back to cycle. RCY represent recycler which is used to provide initial guess values. For stating the process some guess values has to be provided. Here the operation conditions to the inlet of each heat exchanges are given some guess values provided through recycler. The effectiveness of the heat exchanger has to be fixed at 95%.In the software there is no provision for providing the value of effectiveness directly. Adjuster (ADJ) and spreadsheet are provided for heat exchanger in order to fix effectiveness

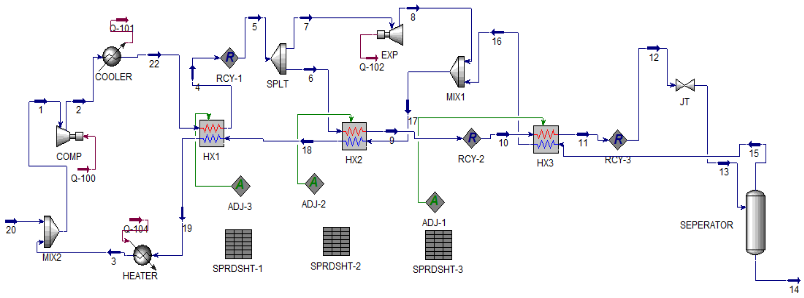


Fig. 7 Process flow diagram of Claude cycle in process simulator

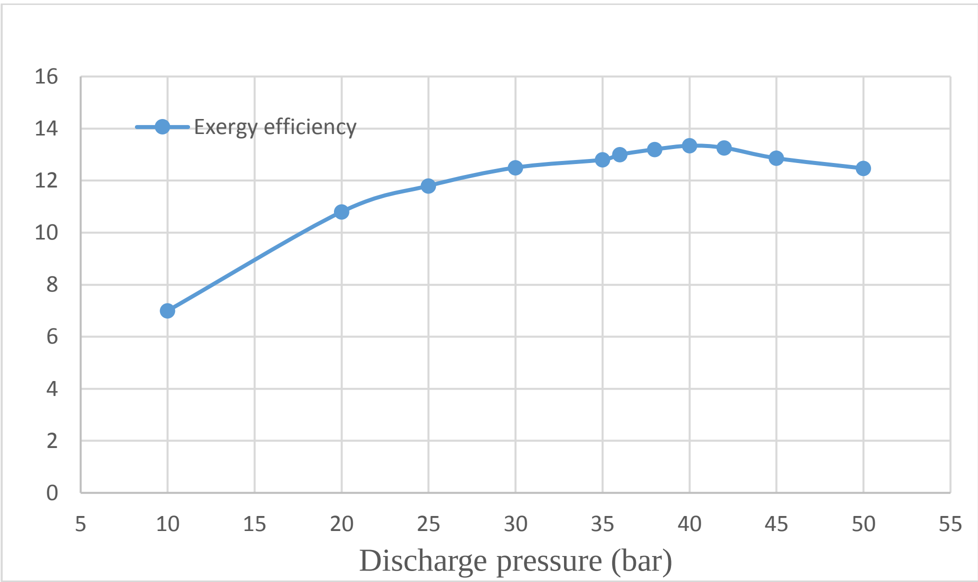


Fig. 8 Effect of variation of compressor discharge pressure on the performance of Claude cycle.

IJIREEICE
ISSN (Online) 2278-1021
ISSN (Print) 2319-5940
International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering
NCIET- 2020
National Conference on Innovations in Engineering & Technology
Govt., Polytechnic College, Palakkad, Kerala
Vol. 8, Special Issue 1, February 2020

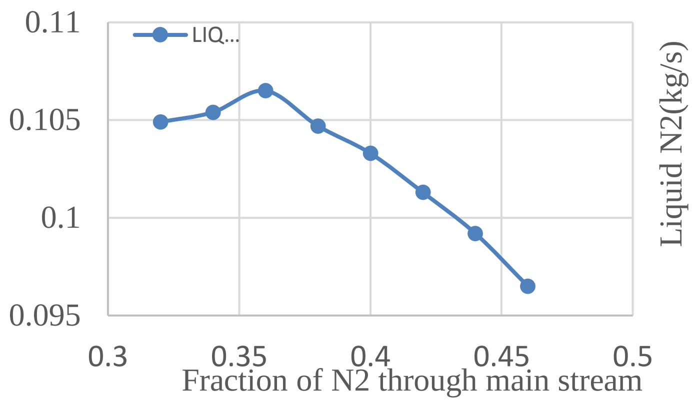


Fig. 9 Effect of variation of expander efficiency on the mass flow of liquid (60% Turbine efficiency)

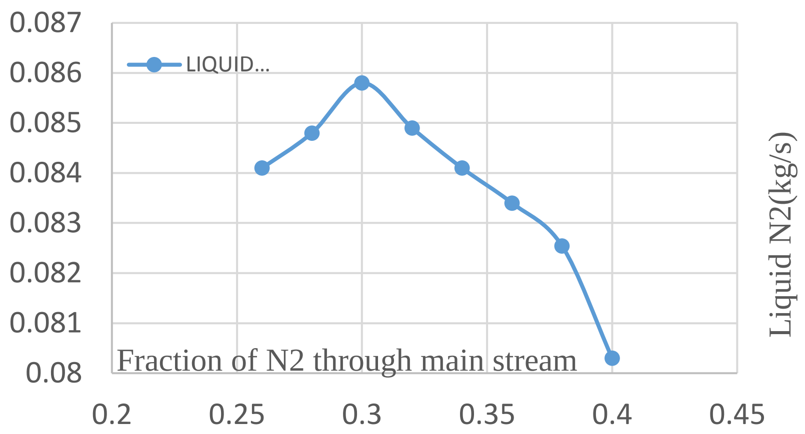


Fig. 10 Effect of variation of expander efficiency on the mass flow of liquid (50% Turbine efficiency)

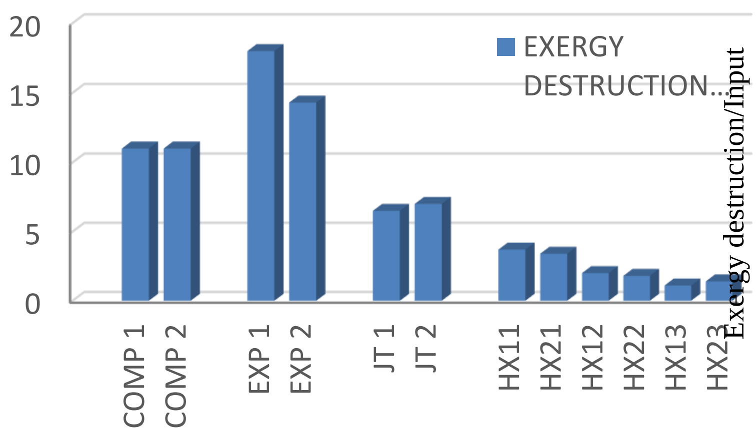


Fig. 11 Exergy destruction in each components in Claude cycle as a percentage of total exergy input (considering different Turbine efficiencies)

C. Collins Cycle

In Collins system, the Helium gas is first compressed to pressure on the order of 22 bar and then passed through first heat exchanger between 30 to 40% of gas is then diverted from mainstream, expanded through expander1, and reunited with return stream below the second heat exchanger. The remaining mainstream gas is then pass through second and third heat exchanger. About 30 to 40% of gas is then diverted from mainstream and expanded in expander2, and reunited with return stream below fourth heat exchanger. The remaining gas then pass through fifth heat exchanger and expanded in JT valve. Due to cooling effect some liquid may be formed. The remaining low pressure gas returns to the compressor inlet to repeat cycle. This system mainly operates between temperature ranges from 300K to 4.20K.

IJIREEICE

ISSN (Online) 2278-1021
ISSN (Print) 2319-5940

International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering

NCIET- 2020

National Conference on Innovations in Engineering & Technology

Govt., Polytechnic College, Palakkad, Kerala

Vol. 8, Special Issue 1, February 2020

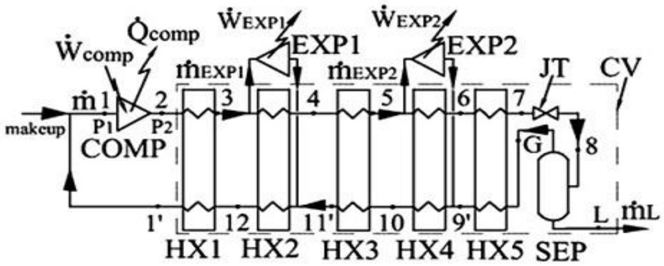


Fig. 12 Schematic of the Collins liquefaction cycle

In order to analyse Collins cycle in its simplest form, the efficiency of compressor and both the expander are kept constant at 70%, where mass flow rate total is 1 kg/s, heat exchanges are given a constant effectiveness of 0.95, Helium is compressed from 1 bar to 22 bar, the heat exchangers are given a pressure drop of 1 bar for high pressure stream and a total 0.1 bar for the return stream, J-T expands Helium to 1.2 bar. Process flow diagram of a Collins cycle modelled in Aspen Hysys by the above conditions is shown in Figure 13.

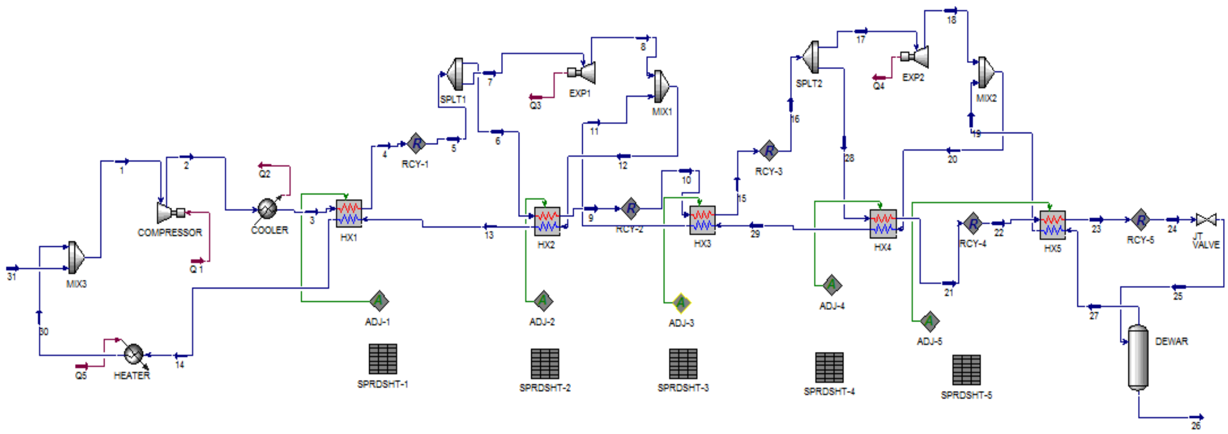


Fig. 13 Schematic of the Collins liquefaction cycle

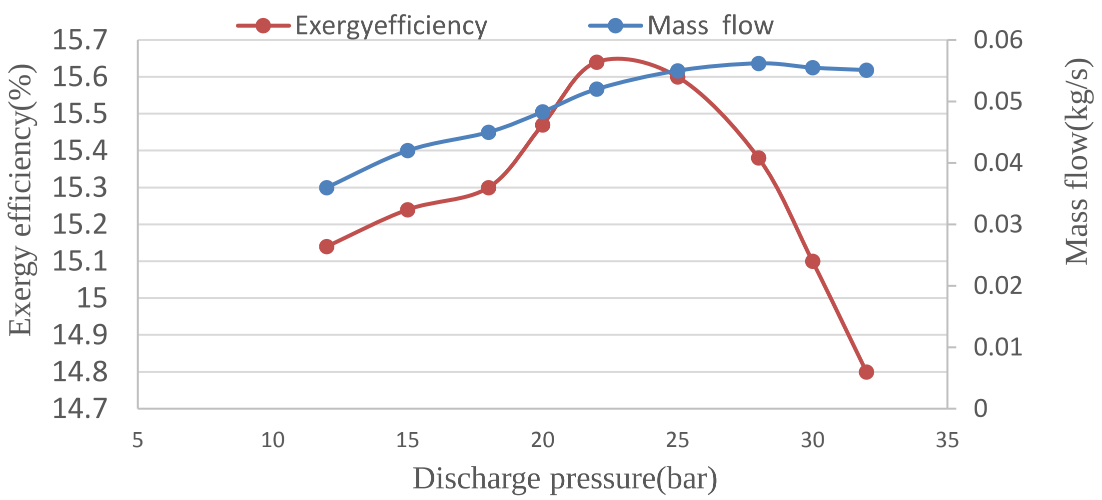


Fig. 14 Effect of variation of compressor discharge pressure on the performance of Collins Helium liquefaction cycle.

IJIREEICE
ISSN (Online) 2278-1021
ISSN (Print) 2319-5940
International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering
NCIET- 2020
National Conference on Innovations in Engineering & Technology
Govt., Polytechnic College, Palakkad, Kerala
Vol. 8, Special Issue 1, February 2020

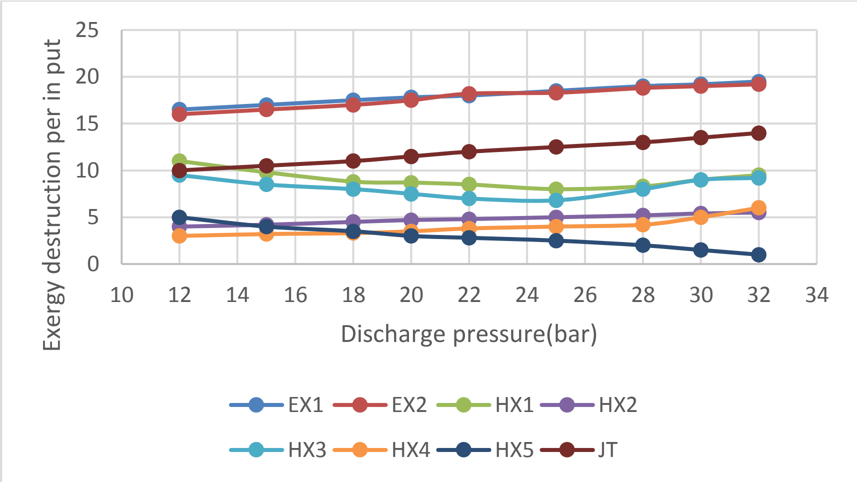


Fig. 15 Exergy destruction in each component as percentage of total exergy destruction in cold box

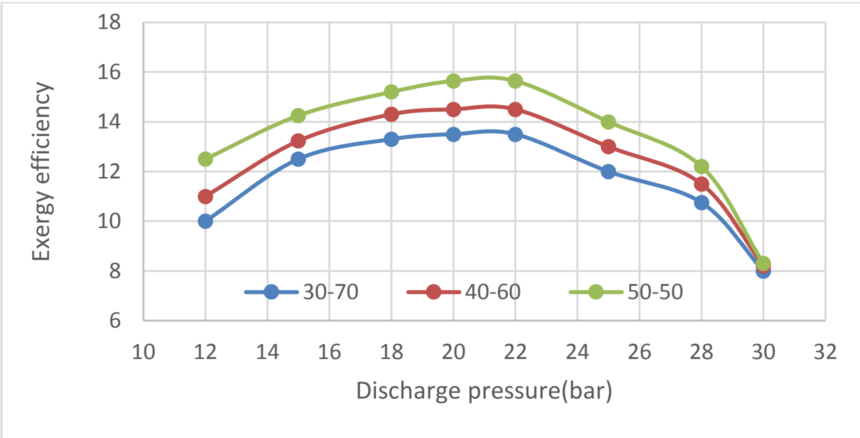


Fig. 16 Effect of variation of compressor discharge pressure on the best flow through each expander

## VI. CONCLUSION

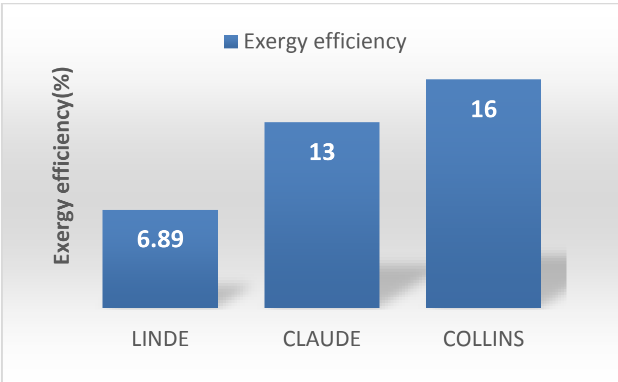


Fig. 17 Comparative evaluation of cycles on the basis of exergy efficiency

- For Linde cycle, 300 bar discharge pressure is considered as optimum pressure. Further increase in discharge pressure produces no noticeable change in liquid production.
- For Claude cycle maximum performance is obtained when 66 to 70% flow is diverted through the expander. Exergy destruction in all components except expander is not changed with increase in efficiency of expanders
- For Collins cycle, 22 bar discharge pressure is considered as optimum pressure. Further increase in discharge pressure produce no noticeable change in liquid production. Maximum performance is obtained when 40 % flow is diverted through the expanders and the total flow is 80% and rest 20% JT flow. Considering Exergy destruction in all components, expander is the most sensitive one and JT is the next. Equal flow distribution to the expanders gave maximum performance

IJIREEICE
ISSN (Online) 2278-1021
ISSN (Print) 2319-5940
International Journal of Innovative Research in
Electrical, Electronics, Instrumentation and Control Engineering
NCIET- 2020
National Conference on Innovations in Engineering & Technology
Govt., Polytechnic College, Palakkad, Kerala
Vol. 8, Special Issue 1, February 2020

## ACKNOWLEDGMENT

I wishes to acknowledge **Dr. Rijo Jacob Thomas**, for the expert guidance rendered during this work. I gratefully acknowledge the support given by Cryogenic Engineering Centre, Indian Institute of Technology, Kharagpur for completion of this work.

## REFERENCES

[1] Atrey, M.D. (1998). Thermodynamic analysis of Collins helium liquefaction cycle. Journel of Cryogenics, 38(12), 1199-1206.
[2] Devender, K., Mishra, R.S. (2014). Thermodynamic comparison of Linde and Claude systems for liquefaction of gases. International Journal of Advance Research and Innovation, 2(1), 40-49.
[3] Devender, K., Mishra, R.S. (2017). Exergy analysis of pre-cooled Linde system for liquefaction of gases for improving performance of Linde based cryogenics systems. International Journal of Research in Engineering and Technology, 1(5), 1-6.
[4] Dutta, R., Thomas, R.J., Ghosh, P., Chowdhury, K., Dynamic simulation of large-scale Helium liquefier using Aspen Hysys In: 23rd National Symposium on Cryogenics. Rourkela, India: NIT; Oct 28-30, 2010.
[5] Kanoglu, M. (2002). Exergy analysis of multistage cascade refrigeration cycle used for natural gas liquefaction. International Journal of Energy Research, 26,763–774.
[6] Kanoglu, M., Dincer, I., Rosen, M. (2008). Performance analysis of gas liquefaction cycles International Journel of Energy Resource, 32, 35–43.
[7] Recep, Y., Mehmet. K., Mehmet, K. (2002). Exergy analysis of vapor compression refrigeration systems, .Exergy, An International Journal, 2(4), 266-272.
[8] Mishra, R.S. &. Devender, K. (2018). Validation of various cryogenics systems using exergy analysis. International Journal of Research in Engineering and Innovation, 2(1), 97-104.
[9] Rahul, V., Rohan, D., Parthasarathi, G., Ananta K.S., Kanchan, C. (2015). Analysis of various liquid nitrogen pre-cooling schemes for large-scale helium liquefiers/ refrigerators. Indian Journel of Cryogenics, 40(1), 81.
[10] Randall, F. B. (1964). Fundamentals of cryogenics. Oxford University press, New York
[11] Yu J, Tian, G., Xu Z. (2009). Exergy analysis of Joule-Thomson cryogenic refrigeration Cycle with an ejector. Energy; 34, 1864.
[12] Wagner, U. (2000). Solutions for liquid nitrogen pre-cooling in helium refrigeration cycles. Conference Proceedings of ICEC-18, 18.

.