International Journal of Research in Engineering and Innovation (IJREI)

journal home page: http://www.ijrei.com

ISSN (Online): 2456-6934

Exergetic performance and parametric evaluation of simple linde liquefaction system using different gasses

R.S Mishra, Devender Kumar

Department of Mechanical, Production and Automobile Engineering, Delhi Technological University, Delhi, India

Abstract

An abbreviated methodology for exergy destruction estimation in simple Linde cryogenic systems discussed in this paper. Energy-Exergy analysis of every component at each stage is done using computational numerical technique. It helps in find out the losses and loopholes responsible for the reduced efficiency of the system. A thorough study is done to determine pressure ratio effect on the first law, second law, specific heat, NTU of heat exchangers and exergy depletion in each sub-component of Linde system. Different gasses are employed to check the compatibility of the regime with each gas at various pressure ratio. From the study, its summarize that due to various physical properties of gasses, same configure Linde system respond very differently in the process of liquefaction of each gas. From the comparison, graphical data of six gasses its notice that the 60-80 bar pressure ratio is optimum pressure ratio suiting all considered gasses for simple Linde system. It also depicted from research that exergy depletion or destruction in sub-component also depend upon the type of gas using for liquefaction. Various results show that first and second law efficiency of the system is still low providing future challenges of improvement in system and helping in decreasing exergy destruction for better performance of the system.

Keywords: Second Law Analysis, Super Critical Power Plant, Thermodynamic Analysis, Irreversibility optimization

1. Introduction

Cryogenics has always been an important area of refrigeration because many scientific and engineering types of research are done using low-temperature liquefied gasses. Cryogenics isa branch of physics which deals with theachieving very low temperatures (below the 173 K.) and study their effects on matter Cryogenic study presents broad goals for cryogenic support for various gas liquefaction systems. Due to the industrial revolution, various issues like cost, efficiency and reliability are the challenges factors in the employment of cryogenic support technology. In one of many ways,exergy can also be relatedto the ratio of useful effect and its cost to produce that effect. Standardization technique in cryogenic industry is one way of cost reduction and accessing reliability but other side increase in reliability result decrease in efficiency of the system e.g. using two over one expander in a Brayton Cycle. For improvement in the reliability factor, redundancy must be increased, but it hamper costing factor of the system. Generally, most of the refrigerators unit run approx. at 10 % to 30% of Carnot efficiency and biggest reason behind the low efficiency degradation of exergy in compressors and heat exchangers units. In most of cases largest amount of exergy destruction or irreversibility is take place in compressor of a cryogenic refrigerator Badescu [1] depicted that most exergy destruction in vapour compression heat pump is taken place in compressor and condenserunit, butfrom various research it stated that use of liquid nitrogen (LN)methodologywith estimated cost and reliability help in reduce the irreversibility in compressor [2] whereas irreversibility in heat exchanger could be reduced by proper insulation.Main causes of exergy destruction in the heat exchanger are heat exchange in between the two flows, loss of pressure due

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

to friction between fluid layers and losses due to the environment factors and these three phenomena occurred mutually in heat exchange process. From another minor factor which causes the losses in heat exchangers, streamwise conduction in the walls [3] is most prominent. Ren et al. [4] in research show that regenerative evaporative cooling technique shows highest performance and effectiveness of indirect heat exchanger is an important factor in enhancing the exergy efficiency of the regenerative unit. Whereas Bejan [5] work considered as the basis of exergetic analysis on heat exchangers. To design and evaluation any cryogenic plant, characterizing and understanding the exergetic behavior of a heat exchanger (HX) is very necessary.Numbers of research or studies partially or entirely based on the concept of rational efficiency ($\eta_{rational}$)which generally defined as the exergy received by cold fluid divided by exergy released by hot fluid [4].Irreversibility is the main factor due to which exergy of the cold fluid to the hot fluid are not equal. Exergetic behavior characteristic of an exchanger in term of total exergy loss discuss in the literature [5-6]. However, from various studies its notice that none of exergetic loss or rational efficiency tell exactly about the factors behind irreversibility, so to reduce exergy depletion in a heat exchanger (HX), it very important to find out which dominant factor causes the most destruction. Generally surrounding attached exergetic value of an exchanger is neglected, because of very small (10%)[7].According to Boyle-Mariotte principle, expectation of temperature change during expansion process is nil but in real gas expansion case, for every 1 bar pressure drop temperature drop in valve is approx. 0.25 °C. This indicate that this law not applicable for real gases. J. K. van der Waals (1873)in there research also explain about this effect and notice that compressed gas molecules doesn't interact each other nor freely move which leads to the temperature drop during decompression .Friction and eddy losses take place in the valve which in turn responsible for exergy loss in the valve of the cryogenic unit. Separation unit is very important part of cryogenic system, Joule-Thomson refrigeration effect and countercurrent heat exchange principle are breakthrough for cryogenic air separation leads lots of further research and development in separation unit. Rosen et al. [8] improve analysis of vapour compression system by introducing the concept that it's necessary to do exergy analysis to choose the refrigerant for a system. Major analysis is performed using different hydrocarbon refrigerant. In this paper we studied and discuss about the exergy analysis of simple Linde system. Exergy analysis of Linde system is done before [9] but it is done via using control volume technique. The losses in inner component of system is not dare cuss earlier. Exergy analysis is done at every state of the system to find out the losses in each individual component and they are calculated in term of exergy destruction. Further the effect of pressure ratio on liquefaction and various other performance parameters of system with gases like nitrogen, methane, argon, fluorine, oxygen and air respectively is studied in this paper. The whole parameters studied further help in improving the Linde system of liquefaction for different gas.

2. System Description

Cryogenic industries use various processes for liquefaction of gas in which some are complex with high efficiency, and some are simple with low efficiency. Here we are considered simpleLinde-Hampson cycle shown in Fig:1 The schematic diagram of cycle providing full algorithm about working of the system which in turn also useful in energy and exergy analysis of the system. Initially, compressor compressed the gas by the isothermal process. The temperature of the system is kept constant by rejecting heat of compressor using coolant jacket around it. After increasing the gas pressure in the compressor, it is cooled in counter flow heat exchanger work as regenerative in cryo cycle. The hot pressurized stream from compressor exchange heat with cold stream of uncondensed gas from the previouscycle of cryo system. After rejecting the heat to cold stream, the pressurized flow induced in J-T(Joule-Thomson) valve where it is throttled and two states (liquid-vapour) mixture of gas is obtained. The liquid part is collected using various distillation technique while vapourportionis routed back to the compressor and in the way, after regenerative, the vapour is mixed with the makeup gas for continuous running of cryo plant.

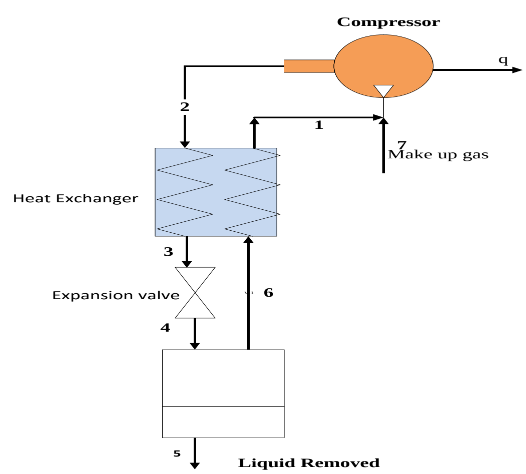

Figure 1: Schematic diagram of Linde-Hampson cycle

3. System Analysis

Various mathematical equations are used for exergy analysis of Linde system. Mathematic analysis of following components is done below

3.1. Compressor

The compressorplaysasignificant role in any liquefaction system and as per literature study above it also causes the highest destruction of energy mean most top exergy destruction take place in the compressor.

$$W_c = \left(m_2 * \left((h_2 - h_1)\right) - T_2 * (s_2 - s_1)\right) \quad (1)$$

Whereas 'W_c'represent the actual work done in the Linde system, h, s, T and m repestively are enthalpy entropy temperature and mass flow rate of gas at state 1 and 2.

$$COP = \frac{h_1 - h_6}{(h_2 - h_1) - (T_1 * (s_2 - s_1))} \quad (2)$$

The coefficient of performance (COP) of system represent the first law efficiency of the system, it is the ratio of refrigeration effect and work done on the system. Refrigeration effect can be defined as the heat removed from the gas state to saturated liquid state.

$$h_f = h_6 \quad (3)$$

whereash_f is enthalpy of saturated liquid state.

$$Ed_{comp} = \begin{pmatrix} m_6 * T_1 * (s_1 - s_2) - \\ \left(Q * \left(\frac{T_0}{T_1}\right)\right) \end{pmatrix} \quad (4)$$

Here Ed denoted the exergy destruction and Ed_{comp}represent the exergy destruction in compressor. Where as Q represent the energy given to the compressor andT_0 is the ambienttemperature. The term $\left(T_1 * (s_1 - s_2)\right)$ in above equation has significant use and represent the irreversibility.Irreversibility account for the exergy destroyed in closed system. Further division of equation $(s_1 - s_2)$represent the entropy generation at state 1 and 2.

3.2. Heat exchanger analysis

Due to their significant temperature difference exchanger is used to exchange thermal heat from hot to cold fluid. The energy and exergy balance equation of heat exchanger is following

$$m_{h_{HX}} * \left(h_{h,i} - h_{h,o}\right) = m_{c_{HX}} * \left(h_{c,o} - h_{c,i}\right) + q \quad (5)$$

$$Ex_{in_{HX}} - Ex_{out_{HX}} - Ed_{HX} = E_{x_{HX}} = 0 => \text{steady} \quad (6)$$

$$Ex_{HX} = m_i * \begin{pmatrix} (h_{in} - h_{out}) - \\ \left(T_0 * (s_{in} - s_{out})\right) \end{pmatrix} \quad (7)$$

$$Ed_{HX} = \left(\left(Ex_{in_{HX}}\right) - \left(Ex_{out_{HX}}\right)\right) \quad (8)$$

Here 'HX' term denoted to heat exchanger of the system. Exergy analysis of simple Linde system is to calculate the losses in the heat exchanger. The losses due to surrounding make an exergytransfer, but heat insulation technique avoided most of the exergy destruction due to environmental effect, so it is neglected. Another factors for the exergy destruction in HX are fluid friction across the wall and loss of the head of flow in pipes. The primary cause of destruction is temperature and pressure loss in pipes.

The specific heat energy rate q can be written as the function of flow rate (m) and difference of temperature of fluid at entry and exit(ΔT), the function can be written as

$$q_{specific} = f(m, \Delta T) \quad (9)$$

Heat transfer rates in exchanger's are found out by below formulations:

$$q_{HX} = C_{h,HX} * \left(T_{h_i} - T_{h_o}\right) \quad (10)$$

$$q_{HX} = C_{c,HX} * \left(T_{c_o} - T_{c_i}\right) \quad (11)$$

For maximum heat transfer following condition should be satisfied.

$$T_{h_i} = T_{c_o}; T_{h_o} = T_{c_i} \quad (12)$$

Maximum heat transfer rate capacity $q_{\max HX}$which is the maximum heat transfer between cold and hot fluid is formulated as

$$q_{max_{HX}} = C_{min_{HX}} * (T_{h_i} - T_{c_i}) \quad (13)$$

The representation of HX effectiveness (epsilon) is:

$$\varepsilon = q_{HX}/q_{max_{HX}} \quad (14)$$

$$\varepsilon = ((\text{Actual thermal energy})/ \\ (\text{actual exchange of energy}))/ \\ ((\text{Highest thermal energy possible})/ \\ (\text{Maximum energy transfer}) \quad (15)$$

$$Ntu_{HX} = (G_{HX})/C_{min_{HX}} \quad (16)$$

$$G_{HX} = U * A \quad (17)$$

NTU 'Number of Transfer Unit' is a dimensionless parameter which broadly provides the size of the heat exchanger, 'U' overall heat transfer coefficient whereas 'A' represent area of the heat exchanger. During the exchange of thermal energy in exchangers, the entropy of the hot side decreases. Heat exchangers which are used in refrigeration/ liquefaction units, the main purpose is to amplify the exergy of the high-pressurehigh-temperature fluid so it capable enough to receive heat from the outer load. Based on said condition rational exergetic efficiency written as:

$$\eta_{HX,Rational} = \left(m_h * \left(Ex_{h,out_{HX}} - Ex_{h,in_{HX}}\right)\right) /(m_c * (Ex_{c,out_{HX}} - Ex_{c,in_{HX}})) \quad (18)$$

In Linde system heat exchanger, change of exergy destruction is written in the following form

$$Ex_{in_{HX}} = m_2 * \begin{pmatrix} (h_2 - h_3) - \\ (T_0 * (s_2 - s_3)) \end{pmatrix} \quad (19)$$

$$Ex_{out_{HX}} = m_g * \begin{pmatrix} (h_6 - h_7) - \\ (T_0 * (s_6 - s_7)) \end{pmatrix} \quad (20)$$

$$Ed_{HX} = abs\left(\left(Ex_{in_{HX}}\right) - \left(Ex_{out_{HX}}\right)\right) \quad (21)$$

3.3. Joule-Thomson Valve

The expansion valve used in the system is J-T valve, which works isenthalpic

$$h_3 = h_4 \quad (22)$$

$$x_4 = \frac{m_f}{m_f + m_g} \quad (23)$$

Where 'x' defined as the dryness fraction after the Joule-Thompson valve effect.

$$Ex_{in_{Val}} = m_2 * \begin{pmatrix} (h_3 - h_0) \\ -\dot{T_0} * (s_3 - s_0) \end{pmatrix} \quad (24)$$

$$Ex_{out_{Val}} = m_2 * \begin{pmatrix} (h_4 - h_0) \\ -\dot{T_0} * (s_4 - s_0) \end{pmatrix} \quad (25)$$

$$Ed_{Val} = \left(Ex_{in_{Val}} - Ex_{out_{Val}}\right) \quad (26)$$

3.4. Separator Analysis

$$m_2 * h_4 = m_f * h_5 + m_g * h_6 \quad (27)$$

$$Ed_{sep} = T_0 * \begin{pmatrix} \left(m_g * s_6 - \dot{m_2} * s_4\right) \\ + \left(\frac{m_g * h_6 - m_f * h_5}{T_0}\right) \end{pmatrix} \quad (28)$$

$$Ed_{Linde\ sys} = Ed_{comp} + Ed_{HX} + Ed_{Val} + Ed_{sep} \quad (29)$$

4. Case study

A Mathematical technique for simple Linde gas liquefaction cycle has been formulated using numerical computational technique with the help of EES (engineering equation solver) commercial. In the thermodynamic analysis of cycle, considered parameters like COP, liquefaction rate, compressor work and exergy destruction are varied with the cyclic pressure ratio, which have a direct relationship with the performance of cycle. Effect of these parameters on the performance of the system is calculated with other gasses to get the optimum performance parameters of the regime for each gas liquefaction. In the process of study compressor (COMP) efficiency and HX effectiveness is considered stable at 85% and 0.85respectively. An illustrative example is presented here for the oxygen liquefaction with simple Linde cycle shown in figure 1 at 40 bar outlet pressure ratios of the compressor. Apart from above constant terms following other assumption are also considered while working on cycle like the compression process is isothermal; expansion process in J-T valve is completely is enthalpic, and there is no heat leakage to the surrounding. Furthermore, the gas is taken is oxygen at the inlet of the compressor is 1 bar at 300 K. With all these assumptions and constant parameters each of system components is studied at every state with other gasses of liquefaction. Various results are being listed in Table 1-2.

Table: 1 Different performance parameters at 40 bar pressure ratio

$COP = 0.6776$	$\varepsilon_{HX} = 0.85$	$NTU_{HX} = 4.092$]
$\eta_{2nd_{\%}} = 19.76$ %	$m_2 = 1$ [Kg/s]	R$=Oxygen
$P_1 = 1$ [bar]	$m_f = 0.08951$[Kg/s]	
$P_2 = 40$ [bar]	$m_g = 0.9105$[Kg/s]	
$W_c = 284.57\ kj/kg$	$m_{HX} = 1$[Kg/s]	

Table:2 System Properties at different stages at 40 bar pressure ratio

Temperature $[K]$	Enthalpy $[kJ/kg]$	Entropy $[kJ/kg-K]$	Specific Heat $[kJ/kg-K]$
$T_0 = 298$	$h_0 = 0.4348$	$s_0 = 0.0012$	$cp_{c_{f_{HX}}} = 0.9158$
$T_1 = 300$	$h_1 = 1.403$	$s_1 = 0.0049$	$cp_{h_{f_{HX}}} = 0.826$
$T_2 = 300$	$h_2 = 8.039$	$s_2 = 0.9757$	
$T_3 = 148.7$	$h_3 = 210.6$	$s_3 = 1.998$	
$T_4 = 90.19$	$h_4 = 210.6$	$s_4 = 1.315$	
$T_5 = 90.19$	$h_5 = 404.7$	$s_5 = 3.467$	
$T_6 = 90.19$	$h_6 = 191.5$	$s_6 = 1.103$	
$T_7 = 268.5$	$h_7 = 27.47$	$s_7 = 0.0096$	

The properties of different gases are obtained using computation software. The analysis is repeated at different pressure ratio and as a part of analysis, exergy destructions of each component is computed and various results of these studies are discussed in Fig 2-11.

5. Results and Discussion

From the figure 2 its notice that every gas show different trend in COP and second law efficiency due to their individual physical properties at various condition (P,T).From graph study, it determined that Methane gas liquefaction process have highest COP and exergyefficiency at 60 bars while best-suited pressure ratio performance wise for the simple Linde system is between 60-80 bar for all other given gasses liquefaction process. Beyond the 80 bar, the system performance starts decreasing and finally start hampering the output of the system. From figure 3 showing that liquefied mass rate process. Beyond the 80 bar, the system performance starts decreasing and finally start hampering the output of the system. From figure 3 showing that liquefied mass rate. Start dropping after 80 and 100 bars for gasses. In this Methane and Argon show slightly unusual trend because after 200 bar methane liquefaction mass rate again start increasing while a decrease in output of argon is very slow after 100 bars or it shows almost constant line after 120 bar compressor.

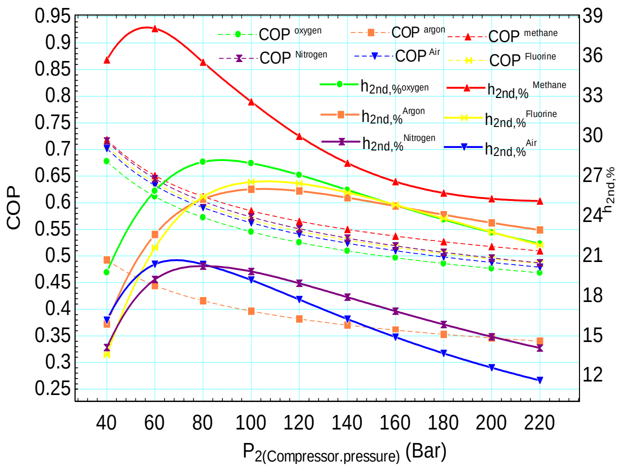

Figure 2: COP and the exergy efficiency versus compressor pressure for various gasses

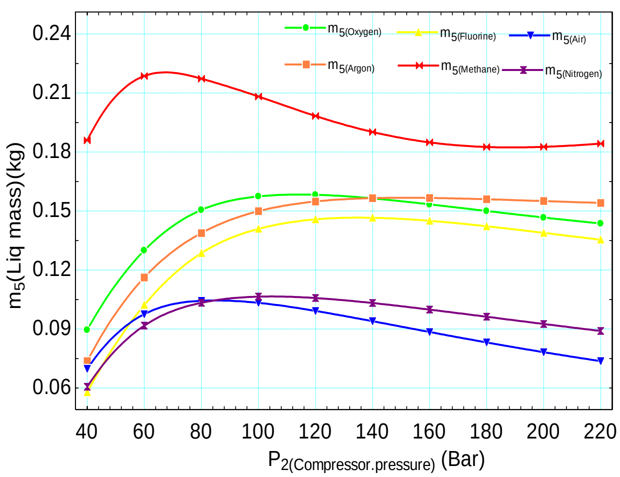

Figure 3: Liquefied mass (m_5) versus compressor pressure for differentgasses

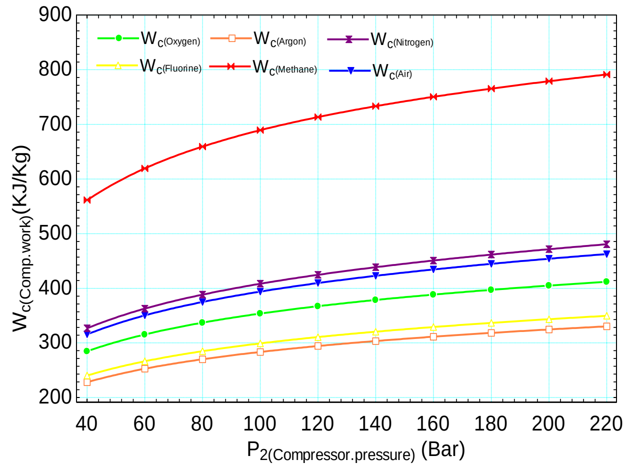

Figure 4: Compressor work input versus compressor pressure for various gases

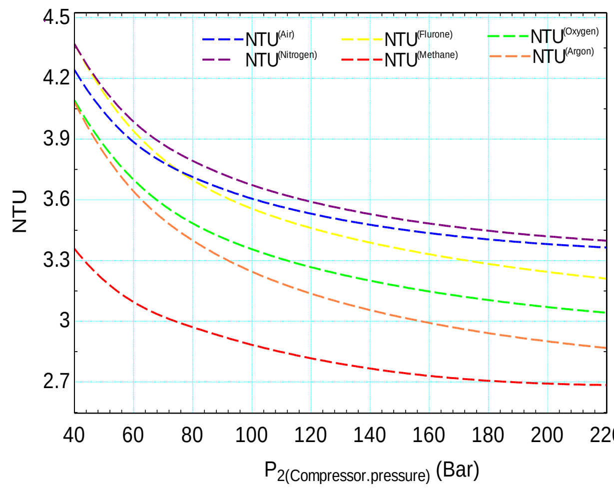

Figure 5: NTU versus compressor pressure for various gases

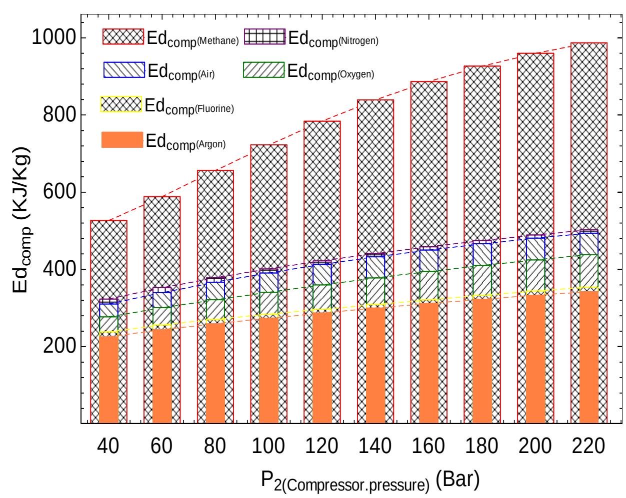

Figure 6: Exergy destruction in compressor versus compressor pressure ratio

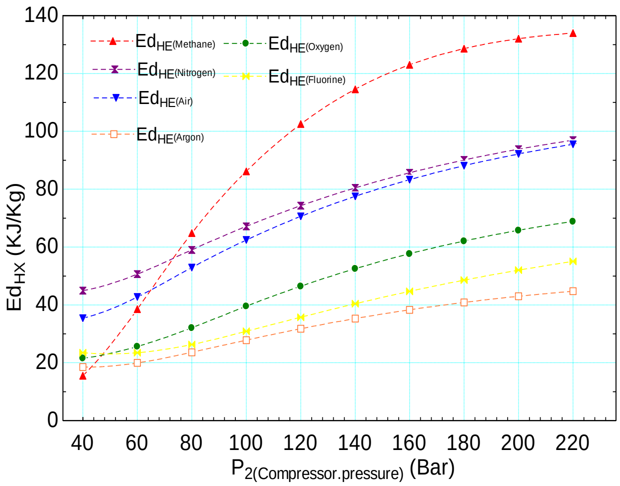

Figure 7: Exergy destruction of HX versus compressor pressure for various gases

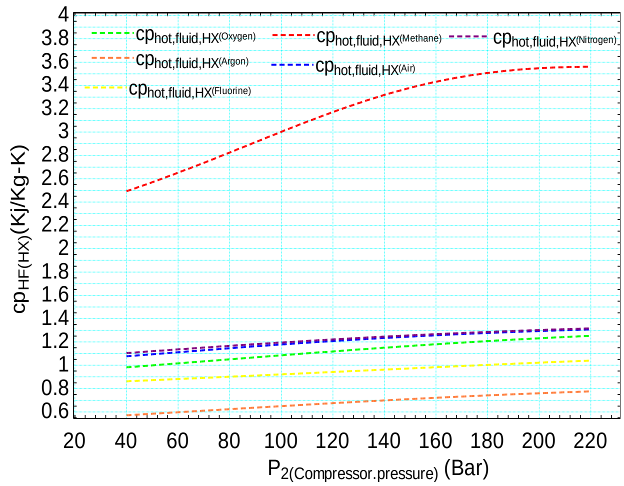

Figure 10: Specific heat of hot fluid versus compressor pressure for differentgasses

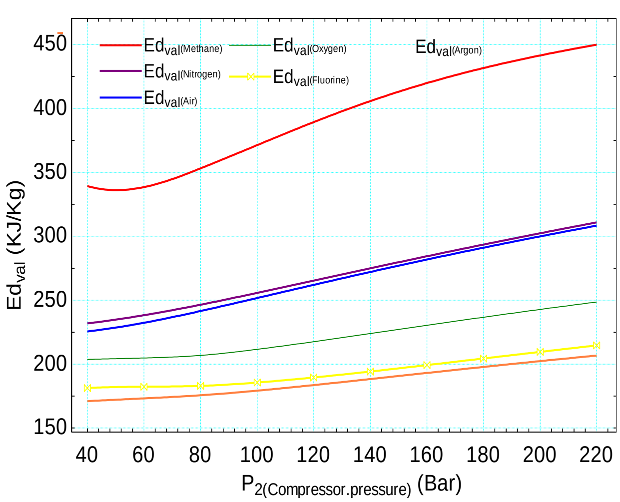

Figure 8: Exergy destruction of J-T valve versus compressor pressure for various gases

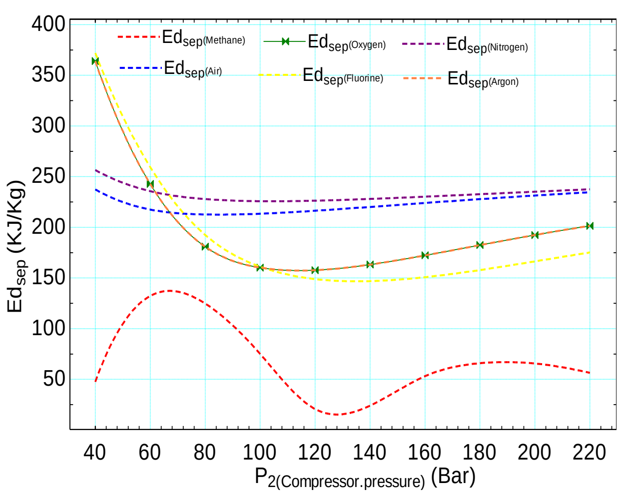

Figure 9: Exergy destruction of separator versus compressor pressure for various gases

For the liquefaction process amount of actual work requirement is gradually increases with increase in pressure ratio or compressor pressure. Figure 4 show amount of real work needed for liquefaction of any given gas. It indicates that Methane gas required highest energy and slope of increment of methane also highest among other given gasses. The requirement of actual work for Methane in optimum pressure ratio range 60-80 bar is in between 600-700 kJ/kg while other gasses requirement is in between 200-400 kJ/kg. Figure 5 determine the dimensionless character NTU of system heat exchanger which help in knowing the area required of the heat exchanger of a liquefied system that very useful in designing the system. In exergy analysis calculating the exergy destructions component wise and whole of the system play a crucial role in the improvisation of the system performance. Figure 6-9 show exergy destructions in an individual component of simple Linde system with different gasses. But the variation in exergy destruction with compressor pressure for differentgasses is different for a differentpart. Figure 6-9 Show the exergy destructions in respectively in compressor heat exchanger-T valve and separator of the system. From the analysis, it notices that working with Methane gas is produces highest exergydamages in the compressor and J-T valve as compared to other gasses while heat exchanger shows highest but after 80 bar pressure ratios before it methane show lowest at 40 bar and highest increasing slope between 40 and 80 bars. The separator of Linde system shows adifferent trend of exergy destructions for each gas. Methane liquefaction shows thesinusoidal distribution of exergy destruction increasing from 40 to 60 bar and after that start decreasing up to the lowest at 124 bars then start increasing again with less slop of increment as previous one. Gasses like oxygen, argon, and Fluorine show the almost same slope of decrement of exergy destruction in separator while Air and Nitrogen show similar fallout. From figure 9 study, the lowest loss of exergy destruction will result in between 60 to 80 bar for most of the gasses except methane. Valve and separator have to work at extremely low temperature, and they are the cold unit of systems. If the exergy at low temperature is not fully utilized, the irreversibility become too high, and exergyis used it by heat transfer with a secondary fluid, the exergy loss is dependent on the outlet temperature of the cooled secondary fluid [10].Specific heat of fluid in HX highly influence the performance of the system. For HX in the system, the specific heat capacity of the hot fluid is graphically representedas a function of cycle pressure ratio in figure 10-11 using different gasses. From figures its depicted that Fluorine and, Argon has lower Cp_{hf} (specific heat of hot fluid) while Methane has highest Cp_{hf} as estimated to other gasses used in cycle study. With pressure ratio increases, the Cp_{hf} of the gas increases very slowly. Cp_{hf}between pressure range is 60-80 is an average of the Cp_{hf} calculated upto 220 bars. The slope of increment in every individual gas is mostly like each other except Methane which showing the steep slope of increase in Cp_{hf} with increasing compressor pressure.

6. Conclusions

Various performance parameters studied with increasing pressure ratio. Exergy analysis of Linde system and its component with different gasses help in determine the loophole and best performance parameters for each given gas liquefaction process. Following points are concluded from the present investigation

(1) COP and Second law efficiency of system is degrading at high pressure for all gasses
(2) The optimum performance pressure ratio range for system is 60-80 bar
(3) Among all six gases methane gas liquefaction process required more attention.
(4) Gas of the liquefaction is very important factor in determine the most exergy destructions causing component of same Linde system
(5) Well insulated heat exchanger has the lowest exergy destructions among all component for most gases
(6) Specific heat of the gas at every stage play a vital role in designing of system.

References

[1] Badescu, V., First and Second Law Analysis of a Solar Assisted Heat Pump Based Heating System, Energy Conversion and Management, Vol. 43, pp. 2539–52, 2002.

[2] M. J. Gouge, J. A. Demko and B. W. McConnell, ORNL,J. M. Pfotenhauer, University of Wisconsin “Cryogenics Assessment Report” Final version, May 2002.

[3] Kotas, T.J. The Exergy Method of Thermal Plant Analysis; 1995 Ed.; Krieger Publishing Company: London, UK, 1985.

[4] Ren, C., Li, N., Tang, G., Principle of Exergy in HVAC and Evaluation of Evaporative Cooling Schemes. Building and Environment, Vol. 37, pp.1045–55, 2002.

[5] Bejan, A. General Criterion for rating heat-exchanger performance. Int. J. Heat Mass Transf. 1978, 21, 655–658.

[6] Wu, S.T.; Yuan, X.F.; Li, Y.R.; Xiao, L. Exergy transfer effectiveness on heat exchanger for finite pressure drop. Energy 2006, 32, 2110–2120.

[7] Franco, A.; Russo, A. Combined cycle plant efficiency increase based on the optimization of the heat recovery steam generator operating parameters. Int. J. Therm. Sci. 2002, 41, 843–859.

[8] Saidur, R.; Ahamed, J.; Masjuki, H. Energy, exergy and economic analysis of industrial boilers. Energy Policy 2010, 38, 2188–2197.

[9] Ignacio Lopez Paniagua *, Javier Rodrıguez Martın, Celina Gonz´alez Fernandez,AngelJime´nez A lvaro and Rafael Nieto Carlier.” A New Simple Method for Estimating Exergy Destruction in Heat Exchangers” Entropy 2013, 15, 474-489; doi:10.3390/e15020474.

[10] Rosen, M.A., Leong, W.H., Le, M.N., Modeling and Analysis of Building Systems that Integrate Cogeneration and District Heating and Cooling, In: Proceedings of eSim Conference. 2001

[11] Mehmet Kanoglu, Ibrahim Dincer and Marc A Rosen, “Performance analysis of gas liquefaction cycles” Int. J. Energy Res. 2008; 32:35–43.

[12] Kim, Youngmin and Favrat, Daniel, "Energy and Exergy Analysis of a Micro Compressed Air Energy Storage and Air Cycle Heating and Cooling System" (2008). International Refrigeration and Air Conditioning Conference. Paper 950.

Nomenclature

T	temperature (K)
h	specific enthalpy (kJ/kg)
s	specific entropy (kJ/kg K)
Cp	specific heat (kJ/kg K)
m	rate of mass flow (kg/s)
Q	rate of heat transfer (kW)
W	work(kJ/s)
C	heat capacity,(kW/K)
CR	heat capacity ratio
Ex	rate of exergy flow (kW)
Edest	rate of exergy destruction (kW)
Sgen	rate of entropy generation (kW/K)
COMP	compressor

Subscripts

c_i	cold stream in
c_o	cold stream out
h_i	hot stream in
h_o	hot stream out
H	hot stream reference state
HX	heat exchanger
J-T Val	Joule Thompson valve