Exergy analysis of different practical Re-liquefaction cycles for LNG system

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Abstract **--Liquefaction of natural gas provides a safer and economical alternative for transportation and also increases its storage capabilities. During transportation, there will be vaporization of LNG producing boil-off gas (BOG) and its re-liquefaction is required considering that large volume of BOG to be vented out. A cryogenic refrigeration cycle is utilized in order to re-liquefy the BOG and returns it to the cargo tank. The developments in the processes adopted for the liquefaction of LNG boil-off (more widely known as re-liquefaction) will be addressed The thermodynamic analysis of different practical re-liquefaction cycles for Liquefied Natural Gas(LNG) will be performed using both energy and exergy approaches so as to provide an environment friendly and cost effective solution. The practical re-liquefaction cycle considered are high pressure and low pressure Claude cycle, Kapitza cycle, Reverse Brayton cycle and BOG Mark I cycle.**

Keywords – exergy analysis, exergetic efficiency, exergy destruction, re-liquefaction cycle.

I. INTRODUCTION

The worldwide energy demand is increasing day by day. It is important to find out new method of energy production. So LNG has been recently introduced being natural gas clean, widely available, renewable, offers greenhouse gas reduction produces fewer emissions compared to other traditional and alternative fuels. Natural gas are used in different forms like compressed natural gas (CNG), liquefied natural gas (LNG) or blended with hydrogen. Natural gas is a mixture of hydrocarbon like methane, ethane, propane, butane, ethylene and a small amount of hydrogen sulphide, nitrogen, but 98% contain methane only. At normal condition LNG is a clear, odorless, non-toxic, non-corrosive cryogenic liquid. Production of LNG takes place by cooling natural gas below -162˚C (or 111K). By this liquefaction process volume of natural gas reduces by a factor of more than 600 [1].

LNG is used in different areas. It is widely used as fuel or oil in transportation fields as it has high octane number and easier maintenance. By the regasification process of LNG, electricity can be produced. LNG is also used in fertilizer industry. It is also used in cooking as well as heating of homes instead of LPG. LNG offers an opportunity to diversify energy supplies. In the recent years, use of LNG has gained much momentum and it would be the right time to review different process in the LNG [2].

Various researches are taking place in these re-liquefaction fields. Majority of LNG re-liquefaction system uses Claude cycle, Kapitza cycle, Reverse Brayton cycle. Dr K.D. Gerdsmeter et al. [2005] developed a BOG re-liquefaction system based on classical Brayton cycle for modern large LNG carriers, which offer superior energy efficiency and hence optimized economics [3]. J.M. Moon et al. [2007] did the experimental analysis on Kapitza and Claude re-liquefaction cycle and found that Kapitza cycle is more efficient than Claude cycle [4]. Younggy Shin et al. [2008] designed Reverse Brayton cycle using Aspen HYSYS and its static thermodynamic states at the design BOG load are presented. To make the cycle work for any BOG load, an idea was sought that would achieve a heat balance with the work extracted by the expander [5]. Thomas N. Anderson et al. [2009] has been applied shipboard re-liquefaction technology for the first time on the new LNG carriers to enable the use of slow-speed diesel engine to achieve higher efficiency and lower emissions than conventional LNG carriers [6]. Hoseyn Sayyaadi et al. [2010] performed exergetic optimization of high pressure Claude refrigeration for LNG system and found that increase in the pressure ratio of nitrogen compressor, BOG compressor, and increases expander mass ratio leads to increases in the plant exergetic efficiency [7]. Heinz C. Bauer et al. [2010] has developed an innovative concept for a boil-off gas re-liquefaction unit which include boil-off gas compression starting from cryogenic conditions, mixed refrigerant cycle with two heat exchangers bundles only [8]. S Baek et al. [2011] presents an investigation of novel re-liquefaction process where the cold exergy of sub-cooled LNG is utilized [9]. Marek Matyszczak et al. [2011] described the construction, principle of operation and properties of the hamworthy re-liquefaction systems MARK I and MARK 3 were described. The construction comparisons of both systems were carried out and technology development advantages of the re-liquefaction systems are presented [10]. Hoseyn Sayyaadi et al. [2011] optimized a LNG re-liquefaction plant with multi-objective approach which simultaneously considers exergetic and exergoeconomics objectives. In this regard optimization is performed in order to maximize the exergetic efficiency of the plant and minimize the unit cost of the system product [11]. Bongsik et al. [2012] studied the optimum re-liquefaction fraction of boil-off gas re-liquefaction system for semi-pressurized liquid carbon dioxide carriers [12].

II. RE-LIQUEFACTION

Natural gas is being transported as liquid (LNG) to reduce the cost of transportation. However, while being transported a substantial amount of LNG gets evaporated generating Boil-off gas (BOG). The vaporized gases are generally vented out unutilized. When the BOG is re-liquefied a substantial amount of energy can be saved and there exit different types of ways to perform the re-liquefaction. Nitrogen (N_2) is used as refrigerant in the refrigeration units. Nitrogen refrigerant is well proven onshore but it is not using in large LNG carriers. Challenges in the re-liquefaction plant are,

- System should be designed in such a way that vessel motion should not adversely affect the efficiency of the plant and should not increase the frequency of failures.
- Plant should be designed by considering the space and weight limitations of the LNG ships and also limit the spare parts in the ships.
- Plant should be easy to operate with the available plant crews 12].

Number of failures of re-liquefaction plant on ships are larger compared with land based liquefaction plants. Damages caused on ships take longer time to repair. Failure cause greater risk to LNG ships and environment. Liquefaction plants aims to produce adequate cooling capacity to maintain the pressure in the cargo tanks. Pressure should be slightly above the atmospheric pressure. Pressure is not properly controlled if there is a failure in the re-liquefaction plant. This led to loss of LNG and venting of hydrocarbon gas to the atmosphere. To obtain a high operational availability of the LNG re-liquefaction plant at the lowest possible cost. We must consider,

- Re-liquefaction cycle used to obtain an optimal redundancy.
- Preventive maintenance program used when the ships is in the harbor and on the sea.
- Spare parts available on the ships and the repairing activities when the ships are on the sea.

Researches aims to decide which cycle of the LNG re-liquefaction plant is best suited for higher operational availability and high safety level by reducing the investment and maintenance costs. Gas combustion unit (GCU) is introduced to reduce the investment costs. But flaring is not a good option because it causes the pollution of the environment and lost BOG. [Chang Kwang pil et al., 2007]

III. METHOD OF ANALYSIS

A. *Energy analysis*

Steady state energy balance equations for each component is

$\Sigma m_{in} h_{in} - \Sigma m_{out} h_{out} - W + Q = 0$

B. *Exergy analysis*

The exergy flow equation for each part is defined as below:

$$0 = \sum_j - \frac{T0}{Tj})Qj - Wcv + \sum_i me)in - \sum_i (me)out - Ed$$

Assuming adiabatic behaviors for all components the term Q_E is neglected in exergy balance equations.

D_E is exergy destruction due to the system irreversibility.

The magnitude of specific exergy at every state is determined from the following equation,

$e = e_{ph} + e_k + e_p + e_{ch}$

Where,

e_{ph} - Physical exergy,

e_k– Kinetic exergy,

e_p – Potential exergy,
e_{ch}– chemical exergy.
Physical, chemical and potential exergy is neglected. Therefore, specific exergy at every arbitrary state can be assumed to be equal to the physical exergy.

$e = e_{ph}= (h - h_0) -T_0 (s - s_0)$

Exergetic efficiency is given by

Exergetic efficiency, $\varepsilon = 1 - \frac{Ed)}{ExIN}$

Where,
E_d – Exergy destruction,
E_{xIN} – Exergy input. [7]

IV. RE-LIQUEFACTION CYCLES

In industry different re-liquefaction cycles used are Claude cycle, Kapitza cycle, Reverse Brayton cycle and BOG Mark I cycle. The basic diagrams for theses re-liquefaction cycle are shown in the fig 1, 2, 3 and 4.

In the Claude cycle, the part of mass flow that is diverted through the expander provides the precooling in the cycle and remaining mass flow that gets precooled will finally get liquefied after the J-T expansion. More the precooling there will be more liquid formed after the expansion. Both the latent heat and sensible heat of the two phase fluid is used to re-liquefy the BOG in the cycle. The temperature difference between the inlet and outlet of third heat exchanger (HX3) is less than 1˚C. Therefore the basic Claude system is modified by eliminating the third heat exchanger with the intent of reducing the initial cost. This modified Claude system is the Kapitza system. In the Reverse Brayton cycle, the entire part of mass flow is passed through expander. There is J-T expansion in the Reverse Brayton cycle. BOG is pre-cooled using second heat exchanger HX2. Entire mass flow gets liquefied after iso-entropic expansion process. Both the latent heat and sensible heat of the two phase fluid is used to re-liquefy the BOG in the cycle.BOG Mark I cycle is a modification of Reverse Brayton cycle. There are only two heat exchangers in BOG Mark I cycle whereas in Reverse Brayton there are three heat exchangers. Cooling produced by nitrogen cycle is used for the re-liquefaction of BOG.

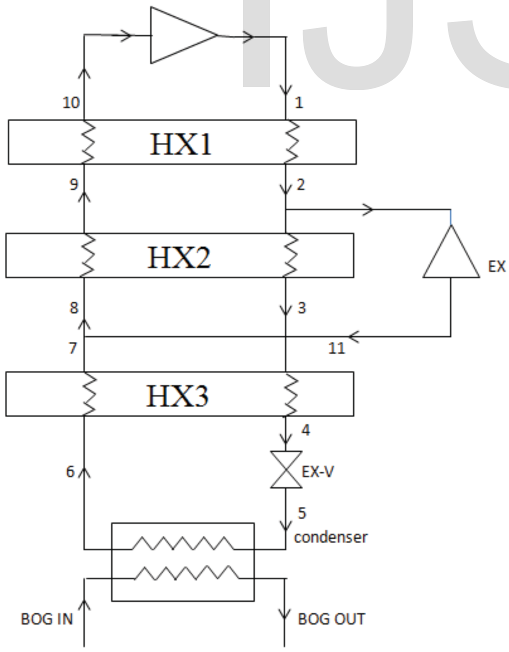

Fig 1 Claude Re-liquefaction cycle

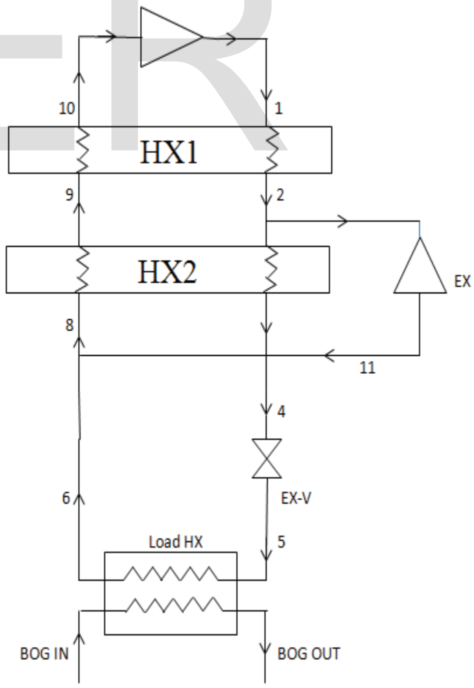

Fig 2 Kapitza re-liquefaction cycle

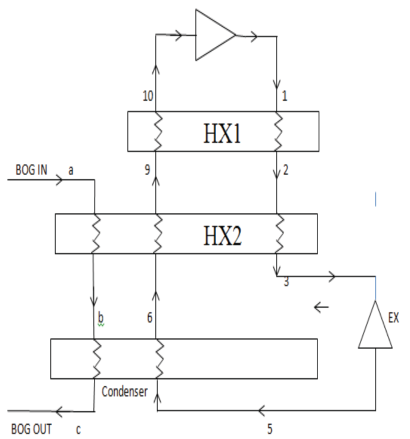

Fig 3 Reverse Brayton cycle

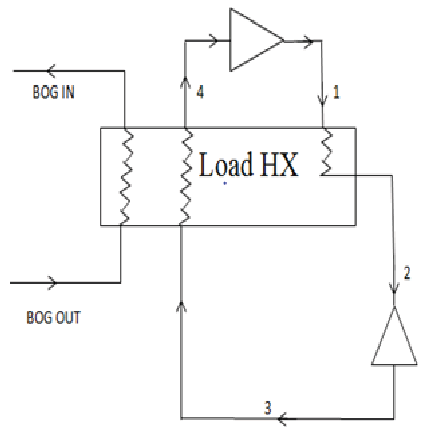

Fig 4 BOG Mark I cycle

IV RESULTS AND DISCUSSION OF PRACTICAL CYCLE

Exergetic efficiency (cold box) of different re-liquefaction cycle with and without work expansion is shown in the fig 5. If expander work is not using, then it is considered as destruction. So it is added with the destructive part while calculating the exergetic efficiency. Exergetic efficiency with work expansion is greater than exergetic efficiency without work expansion. Reverse Brayton cycle has the maximum efficiency compared with other re-liquefaction cycle. High pressure Claude cycle has the least exergetic efficiency. In actual practice when exit pressure of compressor increases, exergetic efficiency also increases, reaches an optimum value and then decreases. In the case of high pressure Claude cycle exit pressure of compressor is situated in the decreasing range of exergetic efficiency. That is the reason why the high pressure Claude cycle has lesser exergetic efficiency than low pressure Claude cycle.

A. Variation of exergetic efficiency

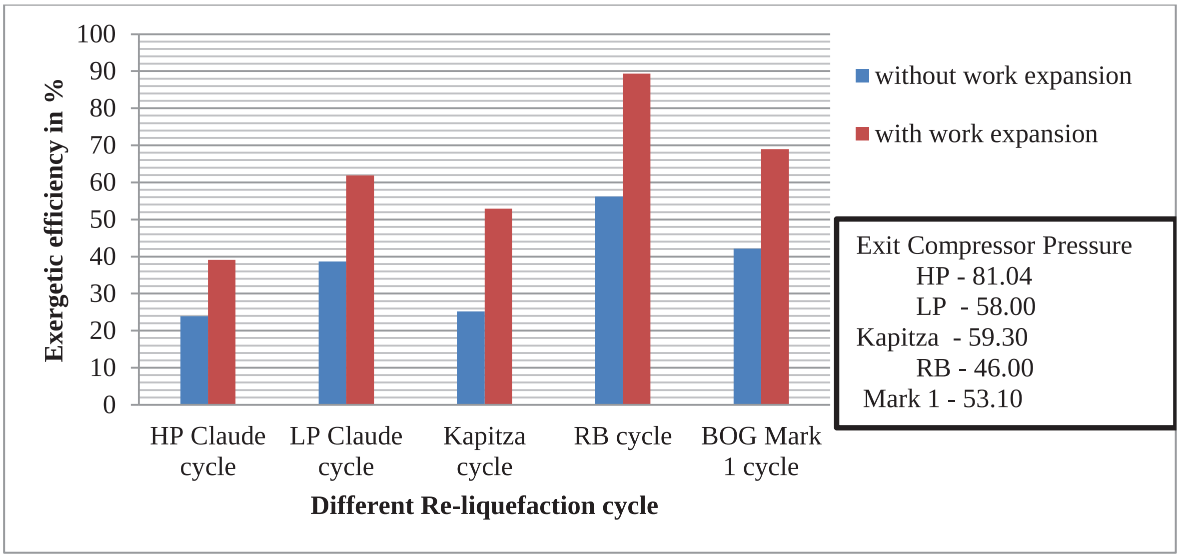

Fig 5 Exergetic efficiency of each cycle in %

Fig 6 and 7 shows exergy destruction of each component in % and KW. In the case of high pressure Claude cycle; expansion valve is the most destructive component. Increase in the pressure drop of expansion valve led to increase in exergy destruction. In the case of high pressure Claude cycle compressor exit pressure will be high. So pressure drop in the expansion valve is also high. That is the reason why the expansion valve becomes most destructive part in high pressure Claude cycle. In the case of Kapitza cycle heat exchanger is the most destructive components. In Reverse Brayton cycle 98% of total destruction is due to destruction in heat exchanger.

B. Exergy destruction of each components

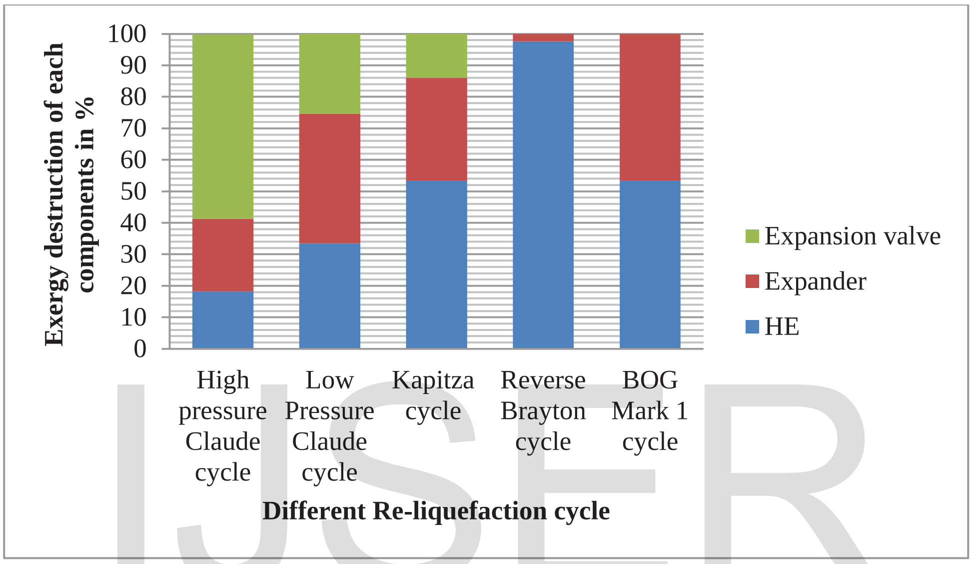

Fig 6 Graph showing the exergy destruction of each component in %

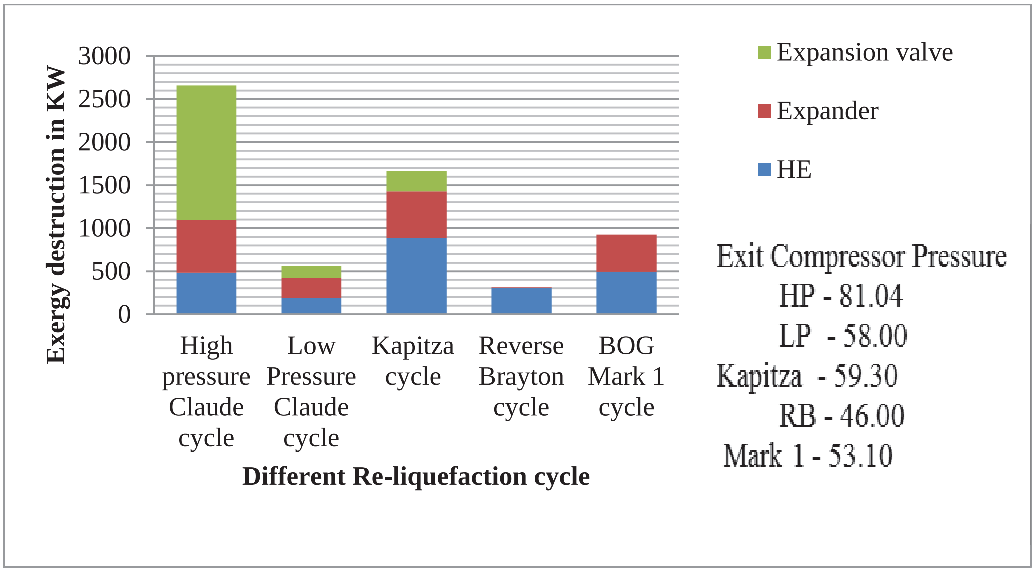

Fig 7 Graph showing the exergy destruction of each component in KW

C. Variation of exergy of each heat exchanger

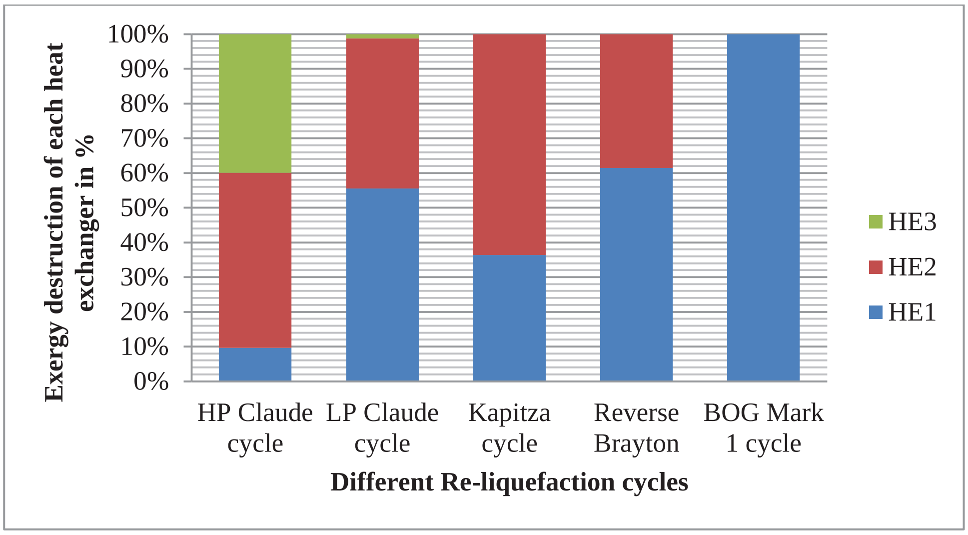

Fig 8 Graph showing the % of exergy destruction of each heat exchanger.

D. Variation of exergy destruction of each expander

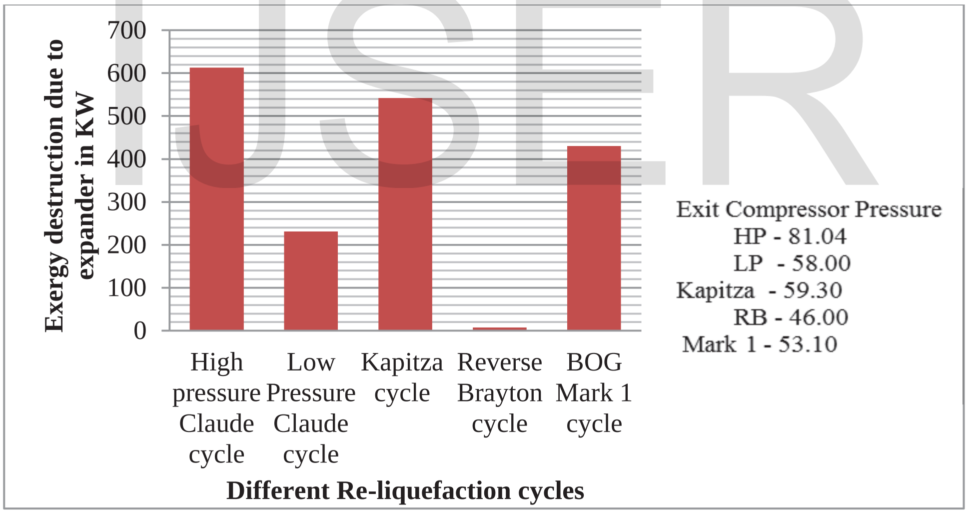

Fig 9 Graph showing the exergy destruction of expander in KW.

Fig 8 shows the percentage exergy destruction of each heat exchanger in different re-liquefaction cycle. Claude cycle has three heat exchangers. Kapitza and Reverse Brayton cycle has only two heat exchangers. BOG mark I has only one heat exchanger. In Reverse Brayton 98% of total destruction is due to destructive part of heat exchanger. Except Claude cycle above 50% total destruction is due to heat exchanger. So heat exchanger is an important destructive part in the re-liquefaction cycle. When exergy destruction in heat exchanger decreases, exergetic efficiency increases. Kapitza cycle has the larger exergy destruction compared with other re-liquefaction cycle in absolute value. Destruction in the heat exchanger depends on the effectiveness of it. By increasing the effectiveness of the heat exchanger we can increase the efficiency of the cycle.

Fig 9 shows the exergetic destruction of expander in KW. When pressure drop in the expander increases, exergy destruction also increases. It is also evident from the graph. In the high pressure Claude cycle pressure drop in the expander is greater, so its exergy destruction is also high. Pressure drop in the expander of Reverse Brayton cycle is small, so exergy destruction in expander is also small. In expander and expansion valve iso-entropic expansion and iso-enthalpic expansion process takes place respectively. Iso-entropic expansion valve has less exergy destruction than iso-enthalpic expansion process. Low temperature is obtained by iso-enthalpic expansion process. To increases exergetic efficiency iso-entropic expansion process is more preferred.

V. CONCLUSION

Aim of the study is to identify a potential cycle for re-liquefaction of LNG system. Literature survey is done in order to identify different system for re-liquefaction of LNG system. In this work cryogenic cycles like Claude cycle, Kapitza cycle, Reverse Brayton cycle, BOG Mark I cycle are used for the analysis. Exergy analysis of different practical system is done in order to find out the exergy losses in each component of the cycles. It is found that Reverse Brayton cycle has the maximum exergetic efficiency compared with other cycles. Claude cycle and Kapitza cycle has the least exergetic efficiency. Exergetic analysis shows that cycles with expansion valve are less efficient than cycle without expansion valve. Iso-entropic expansion valve has less exergy destruction than iso-enthalpic expansion process. Low temperature is obtained by iso-enthalpic expansion process. To increases exergetic efficiency iso-entropic expansion process is more preferred. Exergy destruction of each component is to be reduced to increases the exergetic efficiency. Some changes are needed in the cycle to reduce the total exergy destruction.

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