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Process Modelling and Validation of LNG Re-Liquefaction

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Abstract

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. Kapitza and claude are the usually used LNG re-liquefaction cycles. The developments in the processes adopted for the liquefaction of LNG boil-off will be addressed. Detailed study about the practical cycle like kapitza and claude cycle are performed. The experimental values of these re-liquefaction cycles at each state point are available. ASPEN HYSYS software is used to model these re-liquefaction cycles. Validating the ASPEN software result with experimental values and finding the error in the values of temperature and pressure at each state point. From this validation process it is found that simulation result using ASPEN software has very good agreement with experimental values.
Keywords- LNG, ASPEN, Exergy, Validation, Re-Liquefaction

I. INTRODUCTION

The worldwide energy demand is increasing continuously and is projected to grow by an average of 1.2% per year. Even though fossil fuel resources are available, global CO_2 emissions are projected to rise by close to 30% between 2005 and 2030. In order to fulfill energy demands and to reduce environmental pollution, a drive to find alternative fuels to replace hydrocarbons and fossil fuels. Natural gas is one of the solution for these problems. Natural gas is one of them which are widely available renewable resource offers greenhouse gas reductions and produces fewer emissions compared to other traditional and alternative fuels. Thus, natural gas has emerged as the most important fuel due to its inherently environmental friendly, greater efficiency and cost reduction. For long distance transportation of natural gas, natural gas liquefaction has many advantages over pipeline transportation. By liquefaction process volume of natural gas reduces to 600 times the original volume. S C Sarkar [1]

Natural gas is a mixture of hydrocarbons like methane, ethane, propane and butane, ethylene etc. Apart from these hydrocarbons a small amount of carbon dioxide, hydrogen sulphide and nitrogen are present. But 98% of total composition contains methane. Natural gas is a low density and low sulphur content fuel as compared to gasoline, and is practically free from carbon monoxide emission. LNG is produced by cooling natural gas below -162 ˚C.

LNG is used in different areas. It is widely used as fuel in transportation fields. By the regasification process (heating process) of LNG, electricity can be produced. It is also used in cooking as well as heating of homes instead of LPG. 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. Satish kumar et al [2]

Natural gas is being transported as LNG to reduce the cost of transportation. However, during transportation a substantial amount of LNG gets evaporated generating Boil-off gas (BOG). Contrary to the steam turbines, the new propulsion systems (based on a combination of one or more slow speed engines with a re-liquefaction plant) do not use the BOG from the cargo tanks as fuel. So these vaporized gases are generally vented out unutilized. In order to avoid these wastage BOG is re-liquefied and brought back to storage tanks. Various researches are taking place in these re-liquefaction fields.

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Majority of LNG re-liquefaction system uses Claude cycle, Kapitza cycle, Reverse Brayton cycle. Dr K.D. Gerdsmeter et al. [3] 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. J.M. Moon et al. [4] did the experimental analysis on Kapitza and Claude re-liquefaction cycle and found that Kapitza cycle is more efficient than Claude cycle. Younggy Shin et al. [5] designed Reverse Brayton cycle using Aspen HYSYS and its static thermodynamic states at the design BOG load are presented. Thomas N. Anderson et al. [6] 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. Hoseyn Sayyaadi et al. [7] 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. Heinz C. Bauer et al. [8] 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.

II. RE-LIQUEFACTION CYCLES

In industry different re-liquefaction cycles used are Claude cycle, Kapitza cycle. The basic diagrams for these re-liquefaction cycle are shown in the fig 1, 2. A proposed design of a re-liquefaction plant for LNG ships consists of separate re-liquefaction and refrigeration units using nitrogen (N_2) as refrigerant. Challenges in the re-liquefaction plant are,
System should be designed in such a way that vessel motion should not decrease efficiency of the plant and should not increase the frequency of failures.
Plant should be designed by taking into account the space and weight limitations in LNG ships and also limit the spare parts in the ships.
Plant should be easy to operate with the available plant crews. Chang Kwang pil et al. [9]

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 than land based liquefaction plants. Failure of re-liquefaction system 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. If the pressure is not properly controlled there will be failure in the re-liquefaction plant. This led to loss of LNG and venting of hydrocarbon gas to the atmosphere.

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. [9]

III. METHOD OF ANALYSIS

A. Exergy Analysis

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

$$0 = \sum_j (1 - \frac{T0}{Tj})Qj - Wcv + \sum_i (me)in - \sum_i (me)out - Ed$$

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.
Specific exergy at every arbitrary state is equal to the physical exergy.

$e = e_{ph} = (h - h_0) - T_0 (s - s_0)$ Hoseyn Sayyaadi et al [10]

B. Aspen Hysys as the Simulation Tool

Aspen Hysys is a Process modeling tool for steady-state simulation, design, performance monitoring, optimization and business planning for chemicals, petrochemicals, metallurgy and cryogenic industries. Aspen Hysys solves the all engineering and operating problems that arise throughout the lifecycle of a process, like designing a new process, troubleshooting a process unit or optimizing operations. Aspen Hysys enables engineers to predict the behavior of a process using basic engineering relationships such as mass and energy balances, phase and chemical equilibrium, and reaction kinetics. Aspen Hysys software can model and simulate actual plant behavior.

Aspen Hysys features are listed below

- Easily enables the user to plot the simulation results.
- A large number of parameters values are obtained for a single state point.
- Easily generate tables and plots showing how process performance varies with changes to selected component specifications and operating conditions.
- To fit process model to actual plant data and ensure an accurate, validated representation of the actual plant.
- In Aspen Hysys features available for using different fluids like nitrogen, air, acetylene as per requirement. Also several fluid packages like BWRS, MWRS, and ASME are provided to calculate properties at different states.
- Determine Plant Operating Conditions that will maximize any objective function specified. Sunil Manohar Dash [11]

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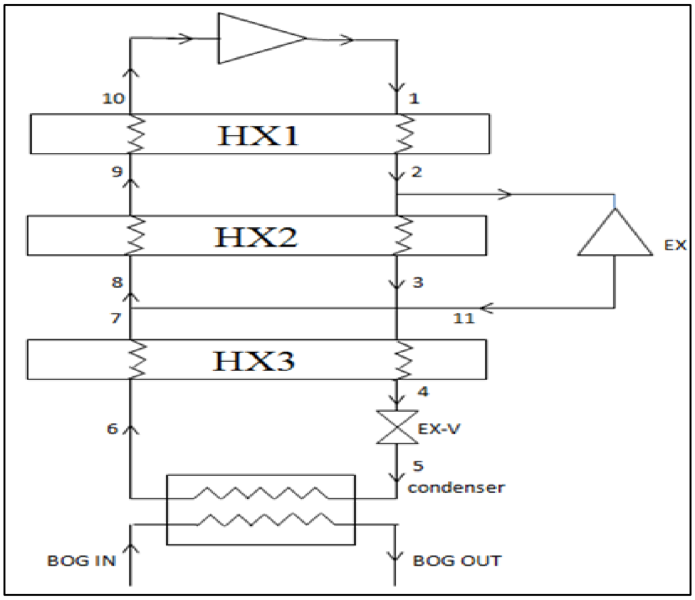

Fig. 1: Claude Re-liquefaction cycle

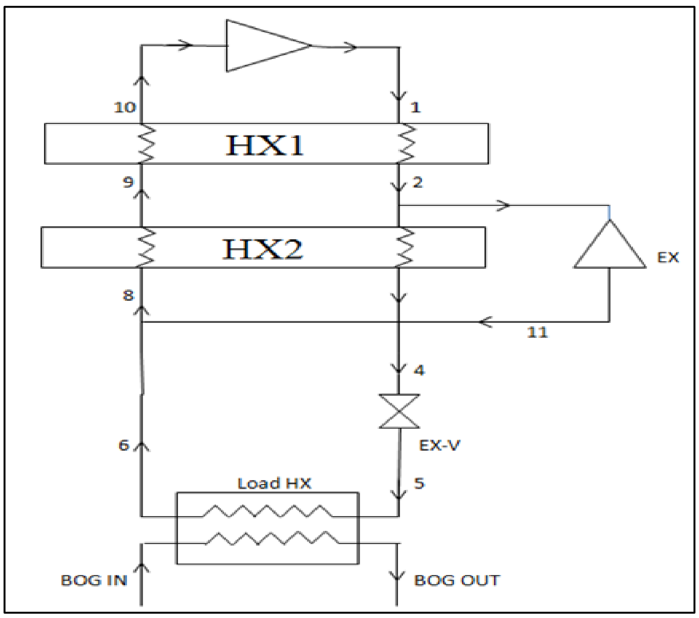

Fig. 2: Kapitza Re-liquefaction cycle

IV. EXPERIMENTAL RESULTS

J.W. Moon et al designed boil-off gas re-liquefaction plant based on nominal LNG boil-off gas rate of 0.15% of cargo capacity per day for a 220,000 m3 LNG carriers. The characteristics of the BOG to be liquefied are as follows.

- BOG-composition (mole %):
- Methane 92.56%
- Nitrogen 7.41%
- Ethane 0.03%
- Density (mixture): 427.5 kg/m2
- BOR: 5640 kg/h
- BOG pressure: 1.03 bar

In the claude cycle nitrogen gas is first compressed to high pressure and then passed through the first heat exchanger. 60% of the total flow of nitrogen gas is diverted into the turbo expander. 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. There are three heat exchangers in a claude cycle. The cold nitrogen vapors from the BOG condenser are returned through the heat

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exchangers to cool the incoming gas. The pressure drop in these three heat exchangers are 0.1 bar. The adiabatic efficiency of the turbo expander and the compressor are 0.8. The effectiveness of each heat exchanger are 0.95

The temperature difference between the inlet and outlet of third heat exchanger (HX3) is negligible (less than 1˚C). Therefore the basic Claude system is modified by eliminating the third heat exchanger to reduce the initial cost. This modified Claude system is the Kapitza system. The pressure drop in these two heat exchangers is 0.1bar. The adiabatic efficiency of the turbo expander and the compressor are 0.8. Effectiveness of HX1 is 0.95 and that of HX2 is 0.9 Moon et al [4]

V. RESULTS AND DISCUSSION

Validation of LNG re-liquefaction system is done with the help of ASPEN HYSYS software. The same practical system is modeled in the software. While designing the system using ASPEN HYSYS software, specifications of each component are given according to the experimental data. Experimental and software results of claude and kapitza system are shown in table 1 and 2. Percentage of error for each parameter is calculated for the experimental and theoretical results. From this validation process it is found that simulation result using ASPEN HYSYS software has very good agreement with experimental values. Maximum error occurred between experimental and theoretical works are 13%.

Figure shows the exergy destruction for each component in claude and kapitza system. It has been found that expander and expansion valve are the most destructive components in the kapitza and claude system. Expander is the most destructive part in these cycles.

Exergetic efficiency can be improved by reducing the destruction in each component. Researches try to design a cycle with less investment, better performance and high safety level.

Table 1: Validation of experimental and theoretical values of kapitza cycle

Kapitza system	Experimental			Theoretical			% error		
State point	Pressure P(bar)	Temperature T(K)	Mass flow rate m (Kg/s)	Pressure P(bar)	Temperature T(K)	Mass flow rate m (Kg/s)	Pressure	Temperature	Mass flow rate
1	59.30	316	27.51	59.30	316	27.51	0	0	0
2	59.05	193.49	27.51	59.05	193.73	27.51	0	-0.12	0
4	58.80	135.1	5.64	58.80	146.96	5.64	0	-8.77	0
5	14.75	110	5.64	14.75	110.1	5.64	0	-.09	0
6	14.50	133	5.64	14.50	148.27	5.64	0	-11.48	0
8	14.50	134.2	27.51	14.50	141.76	27.51	0	-5.63	0
9	14.25	174.7	27.51	14.25	171.44	27.51	0	1.86	0
10	14.00	313.6	27.51	14.00	313.6	27.51	0	0	0
11	14.5	134.8	21.87	14.5	137.5	21.87	0	-2.0	0
BOG IN	3.25	223.4	1.56	3.25	223.4	1.56	0	0	0
BOG OUT	3.00	112	1.56	3.00	124.6	1.56	0	-11.25	0

Table 2: Validation of experimental and theoretical values of claude cycle

Claude cycle	Experimental			Theoretical			% error		
State points	Pressure P(bar)	Temperature T(K)	Mass flow rate m Kg/s	Pressure P(bar)	Temperature T(K)	Mass flow rate m Kg/s	Pressure	Temperature	Mass flow rate
1	58	316	12.02	58	316	12.02	0	0	0
2	57.9	189.5	12.02	57.9	187.3	12.02	0	1.16	0

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3	*57.8*	*135.4*	*3.606*	*57.8*	*134.15*	*3.606*	*0*	*0.92*	*0*
4	*57.7*	*134.9*	*3.606*	*57.7*	*153.06*	*3.606*	*0*	*-13.46*	*0*
5	*14.6*	*109.8*	*3.606*	*14.6*	*114.58*	*3.606*	*0*	*-4.35*	*0*
6	*14.5*	*133*	*3.606*	*14.5*	*145.24*	*3.606*	*0*	*-9.1*	*0*
7	*14.5*	*135.2*	*3.606*	*14.5*	*137.15*	*3.606*	*0*	*-1.44*	*0*
8	*14.5*	*134*	*12.02*	*14.5*	*131.15*	*12.02*	*0*	*2.12*	*0*
9	*14.4*	*172.3*	*12.02*	*14.4*	*163.74*	*12.02*	*0*	*4.96*	*0*
10	*14.3*	*308.6*	*12.02*	*14.3*	*309*	*12.02*	*0*	*-0.12*	*0*
11	*14.5*	*133*	*8.41*	*14.5*	*128.69*	*8.41*	*0*	*3.24*	*0*
BOG IN	*3.3*	*223.4*	*1.56*	*3.3*	*223.4*	*1.56*	*0*	*0*	*0*
BOG OUT	*3*	*112*	*1.56*	*3*	*125.25*	*1.56*	*0*	*-11.83*	*0*

VI. CONCLUSION

Aspen software is an effective tool for studying the performance of a re-liquefaction cycle. This is because simulation result has very good agreement with experimental values. Experimental results need more time and the process is more risky. It is too difficult to find the optimum parameters using continuous experiment. So Aspen software helps the user to find the optimum parameter for each re-liquefaction cycle and helps to design an optimum cycle. Easiness in simulating a system makes the software more attractive.

Microanalysis of kapitza and claude re-liquefaction cycle shows that expander and expansion valve are the most destructive part in these re-liquefaction cycle. Exergetic efficiency can be improved by reducing the destruction in each component. Researches are taking place in this field to reduce the exergy destruction and improving exergetic efficiency.

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