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Research Article

Evaluation and optimization of BOG Re–condenser in the LNG reservoir process

T D Khoa*, N T N Ngoc, N S X An, P H H P Loi, T T Dat

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ABSTRACT

The liquefied natural gas (LNG) is a product of condensation of natural gas in very low temperature and stored at ambient pressure in the cryogenic tanks. For using, the LNG is re-gasified and supplied to power and chemical plants as fuel and material. Recently, the demand of using LNG has increased significantly because it is abundant, low price and CO_2 emission. Therefore, the LNG plays an important role in the global energy system as an input to power generation, heating and material in industry. Many projects of LNG receiving terminal are being constructed in Vietnam and operated in the next few years. However, during storage in the cryogenic tank, a considerable amount of LNG evaporates by solar absorption and generates boil–off gas (BOG) which causes of loss increasing and unsafety. As a result, the BOG generation problem is highlighted for operation optimization in the future. In this study, a retrofit BOG re–condensation process was proposed based on the existing plant at LNG Dapeng receiving terminal, China. The previous study evaluated the process only on energy analysis, hence the irreversibility was not realized. As a result, the total lost, 1130.9 (kW), in term of exergy loss is really high. Therefore, the exergy analysis method was considered to optimize the operating parameters of the process. The results indicated that the exergy loss was decreased by 2.6 times compares to the previous process, it reduces to only 434.9 (kW). In addition, BOG was completely condensed and optimum operating pressure of the condenser is determined in the range of 8–9 bars. Thus, the results give the engineers more options to select the optimum conditions for reduction of energy consumption and environment savings.

Key words: Boil–off gas, LNG reservoir, exergy analysis, simulation

Ho Chi Minh City University of Technology – VNU-HCM, Vietnam

Correspondence

T D Khoa, Ho Chi Minh City University of Technology – VNU-HCM, Vietnam

Email: khoatadang@hcmut.edu.vn

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INTRODUCTION

The natural gas is the most energy–efficient fossil fuel and being used instead of oil or coal. Although the primary use of natural gas is as a fuel, it is also a source of hydrocarbons for petrochemical feedstock. Its popularity as an energy source is expected to grow substantially in the future because natural gas can help reducing adverse impacts on global climate and the environment. Natural gas consumption has been growing steadily over the past two decades, and natural gas has strengthened its position in the world energy mix [1].

The natural gas is transported by pipelines or cryogenic tanks in the form of liquefied natural gas (LNG). The LNG has the advantages that it contains about 40% more heating value than liquid fuels derived from chemical conversions of natural gas [2]. Over long distances, it is more economical to transport natural gas in the form of LNG, because LNG has over 600 times lower volume compared with the gas phase of the same mass. However, its bubble point is below –161^{o}C, which requires a huge amount of energy for liquefaction process. The heat leak from ambient can make a considerable amount of LNG evaporate as boil–off gas [3], which causes safety and loss problems. Overtreatment of the BOG consumes excess energy. Hence, proper handling of BOG is required for an optimal design of an LNG receiving terminal.

BOG re–condensation process is widely used to liquefy and recover BOG due to its 30–60% higher energy–utilization efficiency than that of compressing BOG directly to distribution pipeline [4]. Although there are many studies to lower energy consumption of BOG re–condenser, the exergy analysis method is not investigated clearly yet. Realizing this shortcoming, this study investigates the retrofit design of a BOG re–condensation process at LNG receiving terminals, and uses exergy analysis curves to show the effect of operating parameters on the exergy loss.

METHODOLOGY

Exergy is a property of a system and its surrounding environment [4–6]. It means a quantity of exergy for a given system depends on the state of both system and its surrounding environment. Exergy is the combination of the first and the second laws of thermodynamics. It not only considers quantity of energy, but

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also its quality through entropy generation. For a system, exergy is an attribute that expresses the deviation of the system from its surrounding environment or reference state [4,7]. The exergy of a system is defined as the maximum work obtainable when it is brought from initial state to the environment state at temperature T_o and pressure p_o. The exergy content of a system is determined as below:

$$Ex = (H - H_0) - T_0 (S - S_0) \quad (1)$$

A process is performed by the system from initial state to final state, the exergy change of the system is determined as:

$$\triangle Ex = \triangle H - T_0 \triangle S \quad (2)$$

Exergy is only conserved in reversible processes and is always destroyed in any process that is irreversible. The exergy loss of the real processes is considered as the loss of energy quality. Exergy loss is also known as anergy production. Anergy is a part of energy that carries unavailable work. The exergy balance for a steady state system is used to perform exergy analysis, which helps the engineers evaluate the process performance.

$$\Sigma(Ex)_{in} = \Sigma(Ex)_{out} + ExL \quad (3)$$

The exergy loss of the process shows the irreversibility that cannot be identified by the energy balance in the conventional energy analysis. Thus, the exergy efficiency can be defined as:

$$\eta = \Sigma(Ex)_{out} / \Sigma(Ex)_{in} \quad (4)$$

CASE STUDY

BOG re–condensation process combined to pre–cooler

Normally, the BOG temperature is about -130^{o}C before entering to compressor. After being compressed to 8 bars, BOG is condensed by –158^{o}C LNG. The cryogenic LNG provides the sensible cold energy for BOG temperature decreasing, and phase change in condensation. The required amount of LNG for BOG temperature decreasing is almost 30% of total that of LNG. If BOG is pre–cooled before directed into re–condenser, LNG is only responsible for BOG phase change rather than for temperature decreasing. Thus, Yajun Li et al [8] recommended a BOG re–condensation process combined to pre–cooler as presented in Figure 1. This will be beneficial for the operation stability especially at the condition of a small LNG output load. The LNG stream out of high–pressure pump could be used to cool the compressed BOG to –120^{o}C in a pre–cooler. After pre–cooling BOG, the LNG stream is sent to the open rack vaporizer [8]. The advantages of this process is to reduce the requirement of LNG, a more logical control system than the conventional one for BOG re–condenser was investigated, which provided good operation stability, flexibility and reliability. However, the exergy analysis method is not considered. Thus, the optimum operation parameters are not determined clearly. Applying the exergy analysis to the process, the results indicates the total exergy loss is really high, around 1130.9 (kW) at 8 bars of re–condenser pressure.

Retrofit design for BOG re–condensation process

The LNG is stored and transported in tanks as a cryogenic liquid at temperature of –162^{o}C and pressure of one bar. Due to heat leaking of the storage and transportation, amount of LNG evaporates to BOG [8], normally 6.69 ton/h BOG in Dapeng receiving terminals. The BOG is absorbed by LNG from the cryogenic tank as depicted in Figure 2. Amount of BOG from the top product of re–condenser is sent to the flare for safety problem. The LNG at the bottom product can be fully recycled or extracted out for other purpose.

RESULTS AND DISCUSSION

The exergy loss of the compressor and pump [4,9] can be determined by following relation:

$ExL_{c/p} = W_{in} - \triangle Ex_{c/p}$

$= W_{in} - [\triangle H_{c/p} - T_o \triangle S_{c/p}]$ (5)

Whereas, the exergy loss of re–condenser [4,9] is calculated by:

$ExL_{re} = (Ex)_{in} - (Ex)_{out}$

$= -[(Ex)_{out} - (Ex)_{in}]$

$= -[(H_{Top} + H_{Bot} - H_{Vap} - H_{Liq})$

$- T_o (S_{Top} + S_{Bot} - S_{Vap} - S_{Liq})]$

$= -[\triangle H_{re} - T_o \triangle S_{re}]$ (6)

The exergy loss percentage of pump, compressor and re–condenser [4,9] is defined as:

$ExL_{c/p/re}$ (%)= $ExL_{c/p/re} .100\% / (ExL)_{c/p/re}$ (7)

Table 1 shows the properties of pump, compressor and re–condenser which calculated by the simulation environment ASPEN HYSYS Version 8.8, such as enthalpy change, entropy change and work. The results of exergy analysis as Equations (5,6,7) are presented in Table 2. The ambient temperature T_o and pressure p_o are 27^{o}C and 1 atm, respectively.

The results in Table 2 show that almost of exergy loss occurred in the re–condenser. The exergy loss of pump, compressor and re–condenser have a tendency

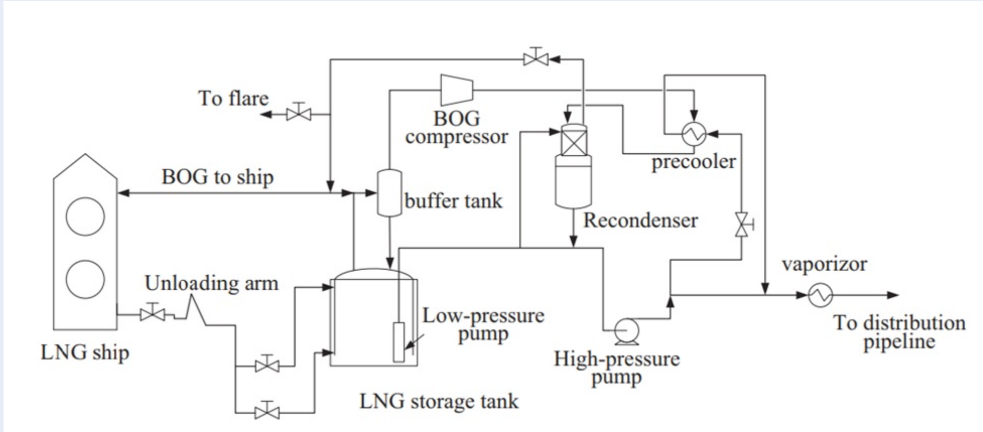

Figure 1: BOG re–condensation process combined to pre–cooler by Yajun Li et al in 2012 [8]

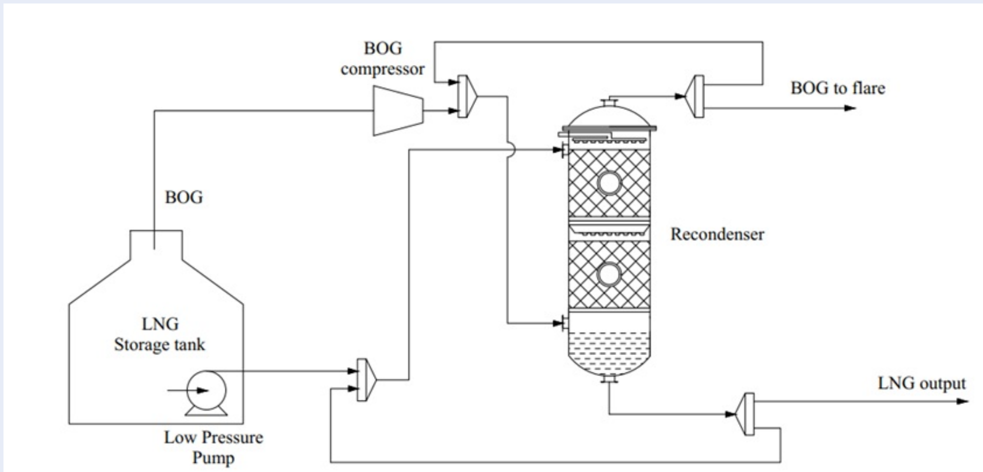

Figure 2: Retrofit design for BOG re–condensation process by absorption

to increase as pressure increasing, that causes the total exergy loss also tends to increase. The reason is as pressure of re–condenser increases, the system consumes much more work for pump and compressor, as well as increasing of the potential difference between the BOG and cryogenic LNG streams. The results in Table 2 also show the exergy loss percentage of re–condenser decreases as pressure increases.

The Figures 3 and 4 indicate the exergy loss of pump and compressor speeds up whereas the pressure increases from 2 to 4 bars, then steadily increasing until 11 bars of pressure.

The Figure 5 indicates that the exergy loss of re–condenser also rises up as the pressure reaches 4 bars, then increase slowly until 9 bars of pressure. However, the exergy loss increases rapidly after that.

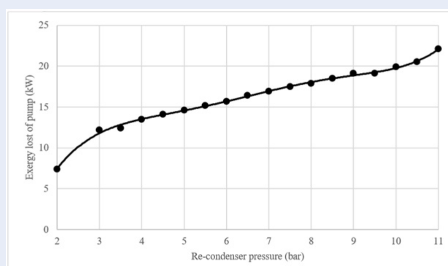

Figure 3: The correlation between exergy loss of pump and re–condenser pressure

The total exergy loss is indicated in the Figure 6 with the same tendency of them. The Figure 6 also shows

Table 1: The properties of pump, compressor and re–condenser.

Re–condenser pressure, P (bar)	LNG flow rate requirement, F (ton/h)	Pump properties			Compressor properties			Re–condenser properties	
		$\triangle H_p$ (kW)	$\triangle S_p$ (kW/K)	W_p (kW)	$\triangle H_c$ (kW)	$\triangle S_c$ (kW/K)	W_c (kW)	$\triangle H_{re}$ (kW)	$\triangle S_{re}$ (kW/K)
2.0	104.0	8.26	0.025	8.26	105.11	0.164	105.11	7.61	0.564
3.0	69.0	13.70	0.041	13.70	198.75	0.283	198.75	6.60	0.695
3.5	58.5	13.94	0.041	13.94	222.33	0.309	222.33	0.66	0.705
4.0	54.6	15.18	0.045	15.18	243.57	0.331	243.57	16.91	0.822
4.5	50.0	15.88	0.047	15.88	262.91	0.351	262.91	19.36	0.851
5.0	45.9	16.39	0.049	16.39	280.70	0.368	280.70	4.23	0.801
5.5	43.0	17.07	0.051	17.07	297.15	0.384	297.15	5.30	0.805
6.0	40.4	17.62	0.052	17.62	312.49	0.397	312.49	0.24	0.788
6.5	38.8	18.49	0.055	18.49	326.89	0.410	326.89	11.89	0.855
7.0	36.7	18.94	0.056	18.94	340.45	0.422	340.45	1.88	0.823
7.5	35.4	19.68	0.058	19.68	353.24	0.432	353.24	7.96	0.847
8.0	33.9	20.19	0.060	20.19	365.37	0.442	365.37	3.04	0.820
8.5	32.8	20.84	0.062	20.84	376.95	0.451	376.95	5.64	0.848
9.0	31.8	21.46	0.064	21.46	387.97	0.460	387.97	8.12	0.874
9.5	30.0	21.44	0.064	21.44	398.52	0.468	398.52	10.92	0.887
10.0	29.8	22.48	0.067	22.48	408.65	0.475	408.65	8.58	0.891
10.5	29.0	23.03	0.068	23.03	418.31	0.482	418.31	2.68	0.874
11.0	28.5	24.89	0.074	24.89	436.69	0.495	436.69	4.93	0.897

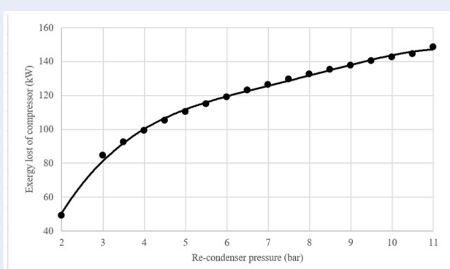

Figure 4: The correlation between exergy loss of compressor and re–condenser pressure

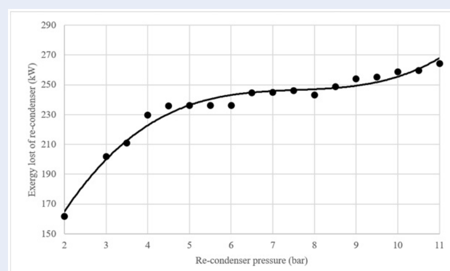

Figure 5: The correlation between exergy loss and pressure of re–condenser

under low operating pressure, the higher pressure of re–condenser is, the more exergy loss is because of the potential difference.

In condition of 11 bars of re–condenser pressure, the total exergy loss is about 434.9 (kW), that is still less than 2.6 times of that one in the process by Yajun Li et al [8]. This is very significant, that is about 61.5% of reduction. As results by Yajun Li et al [8], there are much exergy loss at the high pressure pump, pre–cooler and re–condenser. The main problem is the

Table 2: The exergy loss of pump, compressor and re–condenser.

Re–condenser pressure, P (bar)	LNG flow rate requirement, F (ton/h)	Exergy loss of pump, ExL_p		Exergy loss of compressor, ExL_c		Exergy loss of re–condenser, ExL_{re}		Total exergy loss, ExL (kW)
		(kW)	%	(kW)	%	(kW)	%	
2.0	104.0	7.4	3.4	49.3	22.6	161.6	74.0	218.3
3.0	69.0	12.2	4.1	84.8	28.4	201.9	67.5	298.9
3.5	58.5	12.4	3.9	92.6	29.3	210.8	66.8	315.8
4.0	54.6	13.5	3.9	99.4	29.0	229.7	67.0	342.6
4.5	50.0	14.1	4.0	105.2	29.6	235.9	66.4	355.2
5.0	45.9	14.6	4.0	110.5	30.6	236.1	65.4	361.2
5.5	43.0	15.2	4.1	115.1	31.4	236.2	64.4	366.5
6.0	40.4	15.7	4.2	119.2	32.1	236.2	63.6	371.1
6.5	38.8	16.4	4.3	123.1	32.0	244.6	63.7	384.1
7.0	36.7	16.9	4.4	126.5	32.6	245.0	63.1	388.4
7.5	35.4	17.5	4.4	129.7	33.0	246.1	62.6	393.3
8.0	33.9	17.9	4.5	132.7	33.7	243.0	61.7	393.6
8.5	32.8	18.5	4.6	135.4	33.6	248.8	61.8	402.7
9.0	31.8	19.1	4.6	137.9	33.5	254.1	61.8	411.1
9.5	30.0	19.1	4.6	140.4	33.9	255.2	61.5	414.7
10.0	29.8	19.9	4.7	142.6	33.9	258.7	61.4	421.2
10.5	29.0	20.5	4.8	144.7	34.1	259.5	61.1	424.7
11.0	28.5	22.1	5.1	148.6	34.2	264.2	60.7	434.9

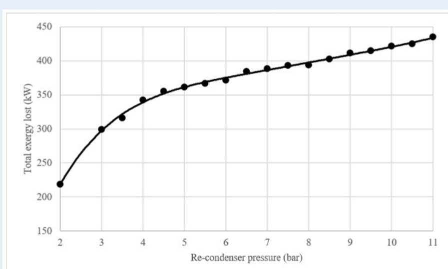

Figure 6: The correlation between total exergy loss and re–condenser pressure

pressure of pump be very high (90 bars) equivalent to the pipeline pressure, that causes the unnecessarily huge exergy loss in the storage operation. In the pre–cooler, there is existence of big pressure and temperature differences, because it's exergy loss is also high. In the re–condenser, the BOG inlets to the top, so the liquid – gas interaction and the mass transfer are inefficient. This increases the flow rate of LNG requirement, then the exergy loss rises. In the retrofit process, the pre–cooler is combined to the re–condenser into absorber structure with the BOG inlet at the bottom, which increases the efficiency of mass transfer and lower the flow rate of LNG requirement significantly. This factor also decreases the pump power dramatically. Besides, the pump pressure is limited at the reasonable level for the storage operation, as consequently, the exergy loss of pump and re–condenser reduces greatly. The reducing of operating pressure and eliminating the pre–cooler in the retrofit process that decreases the large exergy loss compared to the one by Yajun Li et al[8]. Therefore, the pre–cooler is inefficient in the BOG handling process, which cannot be realized by the energy analysis method. Because the energy analysis just concerned about properties of only a system, independent of environment properties, so this is the serious lack of this method.

CONCLUSION

The retrofit process was proposed based on a better methodology for exergy loss minimization. The results show that retrofit process eliminated completely the boil–off gas, which was burnt before, and pointed out that the operating pressure of the re–condenser is in the range of 8–9 bars. It also reduce 61.5% of exergy los because a heat exchanger is removed. The approach is useful to guide engineers to select the optimum specified values at minimum exergy los .

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ABBREVIATION

BOG: boil-off gas
LNG: liquefied natural gas
Ex: exergy (kW)
ExL: exergy loss (kW)
DEx: exergy change (kW)
F: LNG flowrate requirement (ton/h)
H: enthalpy (kW)
H_o: enthalpy in equilibrium to environment (kW)
DH: enthalpy change (kW)
S: entropy (kW/K)
S_o: entropy in equilibrium to environment (kW/K)
D : entropy change (kW/K)
T_o: ambient temperature (K)
p_o: ambient pressure (bar)
W_{in}: work inlet (kW)
h: exergy efficiency (%)
Subscript:
c: compressor
in: inlet
out: outlet
p: pump
re: re–condenser
Vap: vapor flow
Liq: liquid flow
Top: top product
Bot: bottom product

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interests.

AUTHORS' CONTRIBUTIONS

The research methodology was conceptually proposed by Khoa Ta Dang. Original draft was prepared by Khoa Ta Dang, Ngoc Nguyen Thi Nhu and An Nguyen Si Xuan. The research was supervised by Loi Pham Hoang Huy Phuoc and Dat Tran Tan. All authors have read and agreed to the published version of the manuscript.

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