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EXEXERGETIC ANALYSIS: INNOVATIVE APPROACH FOR IMPROVEMENT OF LNG REGASIFICATION PROCESS AT FSRU

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Abstract. Increase of natural gas production and supply causes drawback of onshore infrastructure and many environmental restrictions. The transportation of natural gas by carriers takes place in liquid form, so-called LNG, and its production up to 850 MJ per ton. The LNG consists of a material hardware, namely light hydrocarbons, and immaterial software, namely “cold energy”. The “cold energy” is usually wasted by Floating Storage Regasification Unit (FSRU) during LNG regasification process by dumping into seawater or the atmosphere.

It was verified LNG cold energy utilization possibilities during regasification process in FSRU performing the analysis of LNG properties, thermodynamic energy balance, and exergy analysis. Offered exergetic LNG regasification process mapping with its structured approach is an innovative tool for technological processes optimization and redesign. The complex analyse was performed for different cases in order to identify impact of LNG composition and regasification parameters to quantity of released cold energy. It was determined that the potential of LNG cold energy could reach 25 MWh at FSRU, when it is working full time regime.

Keywords: liquefied natural gas, floating storage regasification unit, exergetic analysis, cold energy.

Introduction

According to energy market prediction, the world demand for natural gas will increase about 2.1 % yearly to 2030 and a higher proportion for Asian countries (Faramawy *et al.* 2016).

The delivery of LNG from the place of gas obtaining to the final customers is planned and organized using special transport means and infrastructure (Simmer *et al.* 2014). Different supply options of LNG may be considered, including those with the use of gas grid, vessels and barges, trucks and containers (Calderón *et al.* 2016; Xu *et al.* 2015; Bittante *et al.* 2018). Supply chain structures are sought that minimize the costs associated with fuel procurement, tackle uncertainty in the demand, as well as allow transportation processes to be safe, time- and cost efficient (Bittante *et al.* 2018). While planning the transport chain provided through LNG terminal, different information should be examined, to set the places where particular services will be performed, including LNG liquefaction and regasification sites. In addition to liquefaction and regasification LNG terminals may provide such services as reloading, transhipment, loading of bunkering ships and trucks etc. The available studies show that purchasing LNG at the regasification terminal is convenient up to a terminal distance of 2000 km from the refuelling station (Calderón *et al.* 2016).

LNG releases a lot of cold energy during regasification process, when seawater, air, and industrial waste are used to vaporize LNG. Generated cold energy causes energy waste and pollution of environment (Bao *et al.* 2019). There are many options to utilise LNG cold energy especially in large-scale regasification units, where is demand energy for LNG vaporization and could significantly enhance the energy efficiency of whole LNG supply chain as well as to reduce greenhouse gas emission (He *et al.* 2019). The utilization of LNG cold energy could be direct (cold energy power generation, cryogenic air separation, refrigerated warehouse, manufacturing liquid CO_2 and dry ice, automobile refrigeration, automotive air conditioning, desalination of sea water) and indirect (cryogenic comminution and the treatment of filthy water) (Kanbur *et al.* 2017).

Exergy could be described what will happen with work input from the beginning of the analysed process, the significance of work is needed to perform process including environment impact, the quality of the process, electric energy kinetic energy and mechanical work to produce a pure exergy (Chen *et al.* 2015). The exergy analysis could identify exergy losses in different regasification stages in order to improve thermodynamic efficiency (Terehovics 2017).

The aim of this research work is to compare LNG regasification cases with different technological parameters including thermodynamical and exergy analyses by considering LNG cold energy utilisation options in large-scale FSRU type terminal.

Model of regasification process

LNG regasification process flow diagram

During LNG regasification process, LNG is sent into booster pump (2) which takes the LNG at -160 °C and discharges it through the BOG recondenser (3) at approximately 10 MPa pressure (Fig. 1).

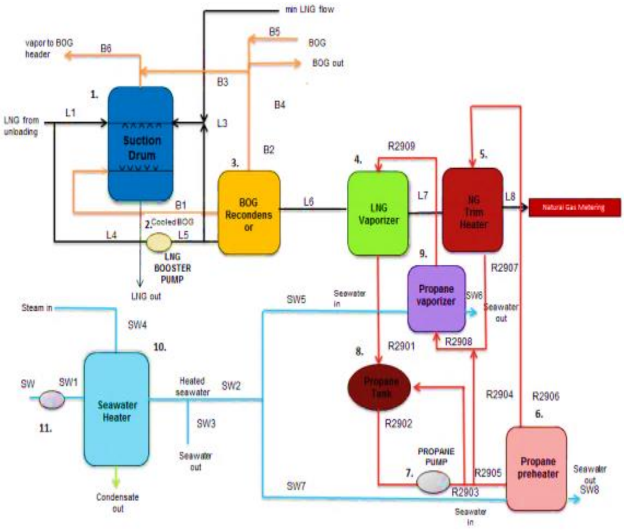

Fig. 1. Simplified scheme of regasification process in FSRU.

Propane, which is used in LNG vaporizer, runs in a closed loop and is circulated by a constant speed pump (7). The liquid propane circulated in a closed loop system by the propane circulation pump (7), which is situated downstream of the propane buffer tank (8). After LNG vaporization, condensed propane from the LNG vaporizer (4) is collected to the propane buffer tank. The propane pump inlet pressure reach 0.2 MPa and it increases to 1.1 MPa, when it enters the propane preheater (6) where heat is extracted from sea water. Preheated propane enters to the natural gas trim heater (5) where LNG is extracted heat from propane and this heat exchange rises natural gas temperature. The propane is mixed with cold propane by the propane pump after circulation in the natural gas trim heater and is transported to the propane vaporizer (9). In the propane vaporizer there is heat-exchange between sea water and propane. Propane is boiled due to heat transfer with sea water. Sea water is used as heating medium for LNG regasification as well as to heat and vaporize propane.

Mathematical modelling

Mathematical modelling is performed to calculate absorbed cold energy and maximum work (exergy) from LNG to propane during regasification process as well as to determine the best thermodynamic properties of regasification process varying LNG flow rates and regasification pressure. By using such regasification technology, the LNG cold energy is released into propane, which is heated by seawater. For determination of energy and exergy of the system, two methods are chosen: the work (exergy) method and energy method. The work method is based on the specification of the thermodynamic path with gas expansion and temperature exergy transfer to pressure exergy.

The mathematical model is performed in five different regasification cases in order to compare energy results and verify the most suitable case for exergy analyse. Moreover, LNG properties were calculated by standard ISO 6976:1995 and Klosek-McKinley method.

Results and Discussion

In the first part of research work, the mathematical model is performed in five different regasification cases in order to compare energy results and verify the most suitable case for exergy analyse.

Table 1. LNG regasification cases at FSRU.

Criteria	Case 1	Case 2	Case 3	Case 4	Case 5
Flow of LNG, kg/h	120,000	102,000	105,000	50,000	190,000
BOG recondensation	no recondensation	with BOG circulation	no recondensation	partly recondensation	partly recondensation
Composition of LNG, %	methane – 86; ethane – 8; propane – 4; i-butane – 1; n-butane – 1	methane – 100	methane – 96; nitrogen – 4	methane – 86; ethane – 8; propane – 4; i-butane – 1; n-butane – 1	methane – 86; ethane – 8; propane – 4; i-butane – 1; n-butane – 1
Pressure, MPa(g)	3.5	6.5	6.5	6.5	5.5

Criteria of regasification cases are selected according to technological procedures and physical LNG parameters to verify LNG cold energy generation. Table 1 presents LNG with methane content of 80% (volume basis) as well as lean LNG with methane content higher than 90% (volume basis). The Case 3 represents LNG with 96% (volume basis) of methane and 4% (volume basis) of nitrogen amount.

Released LNG cold energy is determined comparing input and output values of LNG mass enthalpy of whole regasification system (starting LNG transferring by booster pump and finishing NG heating process). The maximum value – 24,777 kWh is estimated in Case 5. The Case 3 with nitrogen content of LNG has more released LNG cold energy than Case 2. The difference between these cases is 1,153 kWh. The minimum amount of released LNG cold energy was observed in Case 4, because of the low energy demand onshore. The difference between minimum and maximum released LNG cold energy values are 2,147 kWh. The LNG cold energy average of all these cases is 22,342 kWh. The mean value of all cases characterizes that released LNG cold energy (22,342 kWh) could be utilised in more feasible technological way.

To evaluate drawbacks of regasification system at FSRU the exergy analysis was performed. The Case 2 was selected for the in deep analysis, because of the maximum amount of methane and flow rate which is high enough to release LNG cold energy. The reference state for exergy calculations set up as follow: T_0 = 15 °C and p_0 = 0.101 MPa(g). The estimated values of exergy analyse are calculated in every flow of fluids (LNG, propane, sea water) in regasification system to determine the losses in the regasification system.

Table 2. Exergy balance of regasification process at FSRU.

Equipment	Exergy input (kWh)	Exergy output (kWh)	Losses (%)
Booster pump	47,400	47,109	1
BOG recondenser	47,109	46,647	1
LNG vaporizer	64,997	52,324	20
NG trim heater	52,321	51,777	1
Propane preheater	37,443	32,719	13
Propane vaporizer	75,994	74,060	3

Table 2 shows the exergy input and output of regasification subsystem. The exergy input is 47,400 kWh and exergy output is 47,109 kWh when Booster pump performs works. The part of thermal exergy transfers to pressure exergy in booster pump, as LNG is pressurised and the temperature decreases. The minimum exergy input (47,109 kWh) and exergy output (46,647 kWh) was found in BOG recondenser because the process of BOG condensation has almost no effect on LNG temperature and pressure.

It could be seen that the highest exergy input (75,994 kWh) and output (74,060 kWh) is in Propane vaporizer, but the exergy losses (12,673 kWh) are not as considerable amount as in the LNG vaporizer (12,673 kWh). The effect of high exergy demand could be caused because of high seawater flow rate and propane precooling before propane vaporization process. The precooling could be done to decrease system work and propane temperature after NG heating in the NG trim heater. Furthermore, the large exergy input (64,997 kWh) and output (52,324 kWh) was found in the LNG vaporizer in which is high heat exchange between LNG and propane flows. The losses in this subsystem are high enough comparing with other subsystem in the regasification process. Assumption of high losses in propane evaporator is rejected because exergy loses estimated value is less than 3%. The other exergy losses in the other regasification parts do not exceed more than 1%. It could be seen, that the highest losses are in LNG vaporizer which are more than 19% and in Propane preheater, which are more than 13%. The main reason of this is that the loss of irreversible of heat transfer is high enough because of thermal difference between heat and cold fluid and the phase is not stable (Tirandazi *et al.* 2011).

Calculation of energy balance and exergy analys verified that the generated LNG cold energy of the regasification system at FRSU could be utilized by using cold energy capturing technologies and its integrating in LNG regasification process at receiving terminals.

The cold energy utilization could be performed in several LNG subsystems as Propane preheating, Propane vaporization and LNG regasification. During propane vaporization and LNG regasification, fluids expand and perform mechanical work which could be used to generate electricity. Integration of electric power generation cycles (Rankine, Direct expansion cycles) would be one of the technical solution to decrease electric resources of LNG regasification process as well as exploit cold energy in subsystems. The Propane vaporizer could be used as heat sink in Rankine cycle to chill working fluid after power generation cycle. The working fluid CO_2 could be used as heating medium in Rankine cycle, which would be recovered from flue gases from engine room at FSRU. However, electric power generation requires additional equipment for integration in regasification system and its implementation does not fully utilize LNG cold energy.

The better application would be cascade cold energy utilisation model for electricity and cold generation in other sectors with different temperature ranges. Comparing LNG regasification temperature ranges at FSRU, it was determined that inlet temperature of LNG vaporizer vary from -133.6 °C to -163.1 °C and it depends on methane content of LNG, LNG flow rate, and BOG recondensation. This low temperature range is suitable for many utilization processes as seawater desalination (temperature is below -5 °C), dry-ice production (temperature is below -78.5 °C), cryogenic comminution (temperature is from -140 °C to 120 °C), CO_2 capturing (temperature is -140 °C), light hydrocarbon separation (temperature is -145 °C), air separation (temperature could be -196 °C). As an example, after electric power generation other part of cold energy could be utilised for CO_2 capturing and dry ice production for dry blasting as cleaning and disinfection process of equipment.

Conclusions

1. It was calculated that the potential of LNG cold energy is up to 24,777 kWh at FSRU when LNG flow is 190,000 kg·h^{-1}, regasification pressure is

5.5 MPa (g), partly BOG recondensation is performed and methane content of LNG is 80% (Case 5). LNG cold energy decreases 18%, when LNG flow rate is 41% lower (Case 4) than in Case 5. Moreover, LNG cold energy is 9% lower in Case 1 than in Case 5, because of partly BOG condensation which has effect of LNG chilling in Case 5. Furthermore, LNG cold energy is 2.3% higher in Case 3 with 4% nitrogen and 96% of methane than in Case 2 with pure methane, because of low nitrogen boiling temperature (minus 196 °C) which could produce more cold energy.

2. It was determined that the maximum exergy input of the regasification system at FSRU is 75,994 kWh in Propane vaporizer and the minimum is 37,443 kWh in Propane preheater. Meanwhile, exergy input is estimated 47,400 kWh in Booster pump, 47,109 kWh in BOG recondenser, 52,321 kWh in NG trim heater and 64,997 kWh in LNG vaporizer.
3. To increase energy efficiency of whole regasification process, it is recommended to use cascade LNG cold energy utilization by combining thermodynamic cycles such as Rankine, Brayton, Direct expansion and etc. with LNG cold energy utilization for industry chain. After implementation of LNG Cold Energy Hub the cold energy which is recovered from LNG regasification process, could be fully utilized and supplied for the wide range of users.
4. A sustainable use of cold energy would have environmental and economic advantages. For this purpose, however, innovative technologies have to be developed in order to extract, store, transport and ultimately make the intangible cooling energy from the LNG as loss-free as possible.

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