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Cold Energy Recovery Performance Study for Liquefied Natural Gas (LNG) Regasification Process

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The Earth's cleanest burning fossil fuel - natural gas (NG), is primarily methane (CH_4) with smaller quantities of other hydrocarbons. As the grid is decarbonizing, the role of NG on the road to a decarbonized future is indisputable. NG is often compressed and converted into liquified natural gas (LNG) that occupies 600 times less space than its gaseous form, optimizing its storability and delivery efficiency. This logistical flexibility helps improve the security of NG supplies worldwide and is making LNG one of the fastest-growing energy markets. At the LNG terminals, LNG is converted back into its gaseous state by regasification, then, distributed across the network, from remote production areas to distant markets where NG supplies are needed. Regasification of LNG releases a significant amount of cold energy. This paper examines the effect of Open Rack Vaporizer (ORV) efficiency and the potential of recoverable cold energy in the LNG regasification process. All data were collected from the industry-leading LNG regasification terminal in Malaysia – The Pengerang LNG (Two) Sdn. Bhd. (PLNG2). The results of this study showed that the monthly potential of recoverable cold energy is around 43 MW and the efficiency of ORV is ranged from 60 % to 95 %. In addition, it has been found that the flow rate of LNG and the flow rate of seawater are two significant parameters that affect the potential recoverable cold energy.

1. Introduction

In this era of unimaginable urbanization, the world continues to electrify, and the world energy consumption is growing steadily. Global energy demand has been surging fast and according to data from World Energy Outlook 2017 (IEA, 2017) by International Energy Agency, the world energy demand will expand 30 % till 2040 (Yu et al., 2018), and natural gas (NG) will become the second-largest fuel in the global mix after oil in the New Policies Scenario by 2040 (Kumar et al., 2011). The main reasons NG is crowned as primary source of energy is because of its exceptional performance as a clean energy source, its low contribution to the greenhouse gases emission despite its high combustion efficiency, and its ease in storability, transportability and marketability.

As NG is typically produced in remote regions, far away from areas of high gas demand, NG transportation is a critical part of the NG industry. Primarily, NG is transported by two well-developed NG transportation technologies. The first one is the transport of NG through the pipelines, pipelines are man's superhighways of gas transportation. While pipelines transportation is the quickest and the most efficient way to transport NG, NG can also be transported in liquid form as LNG. The transportation of NG generally depends on the distance between the production site and the destination, namely, market. If the distance is less than 2,000 kilometres, pipelines transportation will be prioritized. Pipelines transportation of NG is not technically and economically feasible for long-distance transportations for example transportation from nation to nation or, transportation across the oceans. Therefore, here come in the choice of LNG transportation in long-distance, which is larger than 2,000 km for cross-ocean, and offshore natural gas production (Kumar et al., 2011). LNG is the answer to the transportation of NG across nations and across the oceans. LNG is produced by compressing NG into about 1/600 of the original volume (Çengel, 2008), by cooling it to approximately −162 °C at close to atmospheric pressure (Mokhatab et al., 2014). Before the distribution of the gas to the end-user, the liquified NG must be regasified into its gaseous form. During the regasification process, considerable

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amount of cold energy will be released, i.e. approximately 200 kWh of cold energy produced in the regasification of 1 ton of LNG (Li et al., 2017). Regasification is a fundamental element in LNG utilization, it optimizes the potential of LNG in energy regeneration. In Malaysia, the two LNG regasification terminals located in Melaka and Johor respectively operate differently, one, located offshore, operate using the Intermediate Fluid Vaporizer (IFV) while the other, located onshore, operate using the Open Rack Vaporizer (ORV), where seawater is used as the heating medium in the ORV (Le et al., 2017).

Previously, researches have been focused around the cold energy utilization. Subjects such as the possibility of different aspects of the cold energy utilization like simple power cycle, poly-generation cycle, cryogenic air separation, cryogenic CO_2 capture, seawater desalination, cold chain for food transportation, and data center cooling were published (Khor et al., 2018). A review on potential cold energy for cold storage and transportation is done by Pospíšil et al. which studied and illustrated the amount of cold energy needed for energy regeneration utilization (Pospíšil et al., 2019). Based on the research of Lin et al., authors proposed that data center cooling is one of the best ways to utilize cold energy potential in the near future of China (Lin et al., 2010). Despite all those studies and researches, the performance study of cold energy recovery has not been addressed yet. The amount of recoverable cold energy is important as it measures and characterizes the potential of cold energy in those energy regeneration utilizations for example simple power cycle, poly-generation cycle, cryogenic air separation, cryogenic CO_2 capture, seawater desalination, cold chain for food transportation, and data center cooling. Hence, this research provides a better estimate of ideal recoverable cold energy from the regasification terminal. To exploit the recovered cold energy from the vaporizer, we need to compute the heat transfer efficiency of the vaporizer. Thus, the computation of vaporizer efficiency is essential to obtain the actual performance of the cold energy recovery from the LNG regasification. The actual performance of the cold energy recovery is depicted by the amount of recoverable cold energy left for utilization after compensating factor of losses in the equipment, for example, heat losses.

The present work aims to evaluate the performance of cold energy recovery in LNG regasification terminal where the type of vaporizer used in the terminal is the Open Rack Vaporizer (ORV). In this study, the real-time temperature changes in the regasification process have been recorded and the temperature changes in seawater and in LNG are analysed. The energy demand and the energy supply are then calculated, discussed further and demonstrated.

2. Methodology

Figure 1 shows the general methodology for this case study. Background studies on cold energy recovery are crucial for the understanding of the previous and current conditions of the regasification process. The expected concluding outcome from stage 1 of the methodology is the understanding of the average amount of recoverable cold energy from the LNG regasification process. In stage 2, on-site data collection will be performed continuously in a period of six months. In stage 3, on-site data collected will be simulated and analysed using Microsoft Excel, the general trend and the changing behaviour of on-site data as time progresses will be studied.

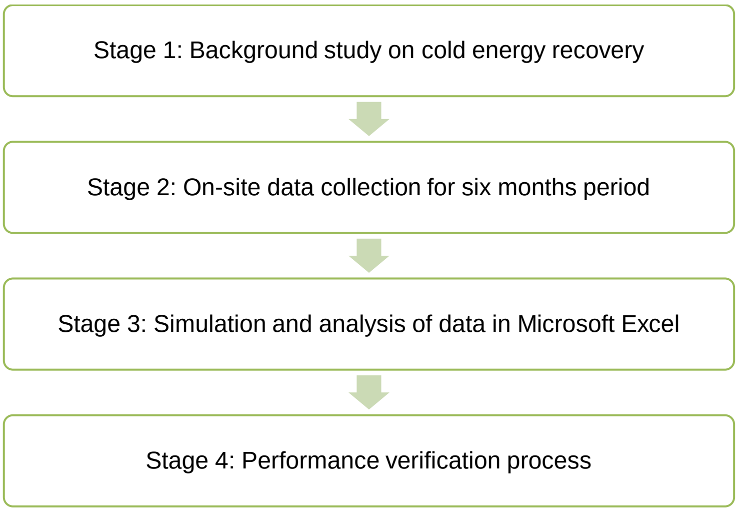

Figure 1: General stages of methodology

2.1 Measurement

Gathering and measuring information on variables of interest in a part of the data collection. The data collection was performed continuously in a period of six months and was done by using the live data management software (PI System). Collected data are shown in Table 1:

Table 1: List of data collected

Variables	Location
Seawater Temperature	Inlet and Outlet Streams
LNG/NG Temperature	Inlet (LNG) and Outlet Streams
LNG/NG Mass Flow Rate	Inlet (LNG) and Outlet Streams
Seawater Volumetric Flow Rate	Inlet and Outlet Streams

2.2 Performance assessment

Performance assessment refers to a sequence of procedures that evaluates, measures, verifies and documents the performance of the cold energy recovery concerning the design specification, energy demand, and energy supply. As the working fluid in the ORV is water and it is chemically inactive, no reaction occurs and the energy balance equation was derived based on the Eq(1):

Process Energy Demand = Changes in Enthalpy = Enthalpy of NG - Enthalpy of LNG (1)

Process energy demand is the energy required during the process of regasification from LNG to NG. By referring to the design basis of ORV, there is a set of data which represents the enthalpies of LNG/NG at certain temperatures. The enthalpy-temperature data is shown in Table 2.

Table 2: LNG/NG temperature-enthalpy and temperature-heat duty (PLNG2 Sdn. Bhd.,2019)

LNG/NG temperature (°C)	Enthalpy (kJ/kg)	Cumulative Heat Duty (MW)
-157.4	0	-
-123.4	123.701	7.175
-87.5	207.798	11.964
-53.5	502.841	28.926
-19.5	628.484	36.006
-0.9	719.253	41.143
16.1	808.282	46.200
22.3	823.600	47.068

A graph of enthalpy versus LNG/NG temperature is plotted by using the data from Table 2. Then, the best polynomial fit trendline equation generated by excel function is used to represent the relationship between the enthalpy and the LNG/NG temperature. This is essential for the determination of the enthalpy of LNG/NG at any temperature recorded in the PI system. Then, by measuring the actual inlet LNG temperature and outlet NG temperature at ORV, the process energy demand can be calculated by using the Eq(1).
The calculation of the actual heat duty of the heat exchange process in the ORV is also needed. By referring to the design basis of the ORV, there is a set of data visualizing the LNG/NG temperature, seawater temperature, net thermal rate (KA) and the length of tube. Meanwhile, the respective cumulative heat duty can be calculated using the heat exchanger concept.

Table 3: Design basis parameter of ORV (PLNG2 Sdn. Bhd.,2019)

Net thermal rate (W/m.°C)	Tube length (m)	Log mean temperature (°C)
200,900	0.22	162.3414
174,600	0.20	137.1510
438,600	0.32	120.8531
159,800	0.46	96.3153
120,500	0.68	62.6827
108,300	1.77	26.3811
108,300	0.86	9.3196

Table 3 shows the design basis parameter of ORV. The heat duty of ORV is calculated using Eq(2) as indicated below.

Heat duty of ORV = Net thermal rate (KA) x length of tube x Log mean temperature (2)

The net thermal rate (KA) has a unit of W/m.°C and the net thermal rate at a specific region of the tube is known as the specific net thermal rate. The log mean temperature is calculated based on the NG/LNG temperature and the seawater inlet and outlet temperature. The heat duties at all regions within the tubes are summed up to calculate for the cumulative heat duty of the ORV. The calculated cumulative heat duty is then tabulated in the third column of Table 2.
Same case with the enthalpy, a graph of cumulative heat duty versus LNG/NG temperature is plotted and the best fit polynomial trendline equation is used to determine the cumulative heat duty of the process to vaporize the LNG to NG form.
The efficiency of ORV can be calculated using Eq(3) as shown below,

$$\text{Efficiency of ORV} = \frac{\text{Amount of Energy Needed to Vaporise LNG to NG}}{\text{Total Heat Duty Provided by ORV}} \quad (3)$$

The assessed results will manifest the performance of the installed system and disclose its deviation from the established design and standard (if any) and identify the potential and scope for improvement.

2.3 Case study

Figure 2 shows the process flow diagram of LNG regasification at terminal which includes LNG storage tank, vaporizer, high-pressure pump, Boiled-Off-Gas (BOG) compressor, and BOG recondenser. The system consists of two main processes which are the regasification of LNG and the conversion of BOG back into LNG for economic and environmental purposes. The data collection point is labelled in Figure 2. The main focus of the process is the regasification at the vaporizer site. From the collected on-site data, the inlet stream of LNG into the ORV is at an average of -140 °C and will heat up until an average of 29 °C in the NG form. The mass flow rate of the LNG/NG will be set depending on the needs and requirements of the end-user. For the seawater, the average inlet temperature is around 30 °C and might drops until around 25 °C. Currently, the seawater is set to flow at an average rate of 6,100 m^3/h.

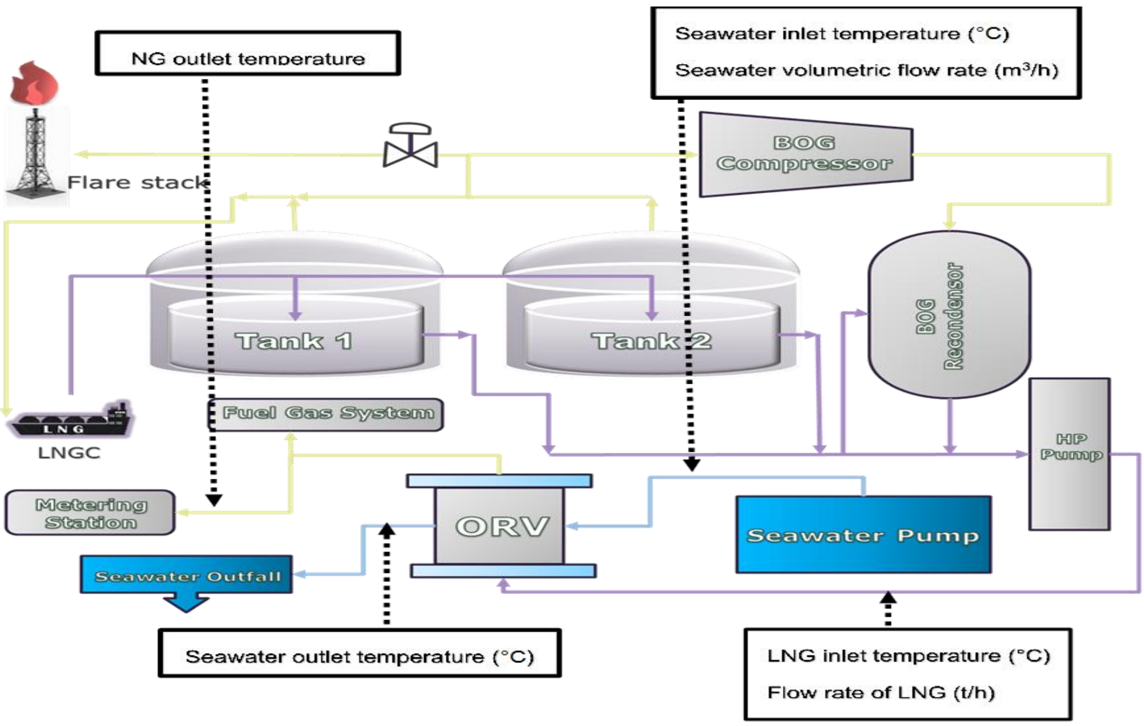

Figure 2: Process flow diagram of LNG regasification in PLNG2

3. Result and discussion

The average recoverable cold energy from November 2018 until May 2019 is shown in Figure 3. From Figure 3, the cold energy reaches up to 69 MW or even more when the ORV is operating under high send out condition. During the operation, the changes in the temperature of the seawater between the inlet and outlet streams should be maintained below 7°C to adhere to the standard set in the regulations. The operation runs 7 d a week and up to 24 h/d. Figure 3 also illustrates the trend of send out requirement (NG flow rate) throughout the period, the lowest send out rate is recorded in November 2018, the month where the plant first commercialized. The send out rate increased significantly after February 2019 which might be a result of increasing market demand. In May 2019, the send out rate decreased as the plant was shut down several times during that month due to unexpected circumstances. Figure 3 also illustrates the relationship between the recoverable cold energy and the send out requirements which is equivalent to the NG flow rate. As portrayed by the graph, the higher the send out requirement, the greater the recoverable cold energy during the regasification process. As the NG send out requirement is increasing over time, the amount of recoverable cold energy will also increase in the future.

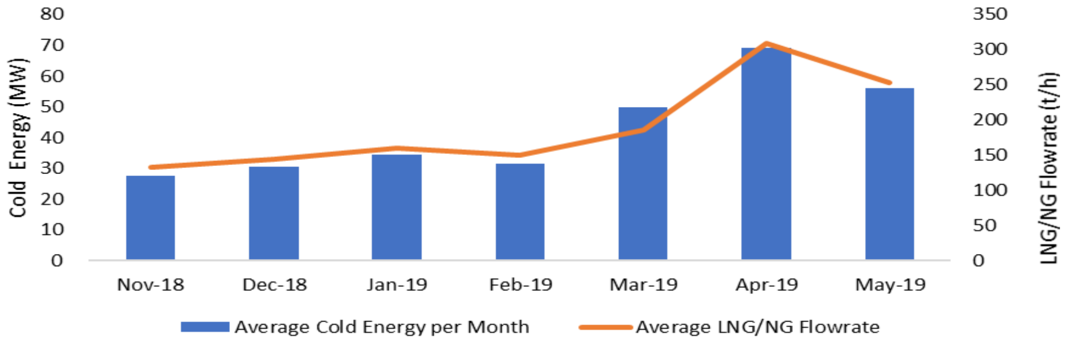

Figure 3: Graph of Average Cold Energy vs Send Out (NG Flow rate)

Figure 4 shows the comparison of heat duty with average cold energy recovery. Heat duty is the energy transferred by the seawater during the regasification process while cold energy is the actual energy needed by the LNG to be vaporized into NG. As in Figure 4, the efficiency fluctuations of the ORV ranged from 60 % to 95 %. The efficiency fluctuations are the result of the changes in the LNG flow rate. The efficiency of the ORV is a function of the LNG/NG temperature, seawater temperature, LNG/NG flow rate, and seawater flow rate. After conducting a few tests, the result concludes that a change in the temperature at the inlet and the outlet stream of LNG and the seawater, only imposes an insignificant disturbance to the ORV efficiency. Clearly, the efficiency fluctuates mainly because of a change in the flow rate of the LNG or seawater, not because of the temperature change.

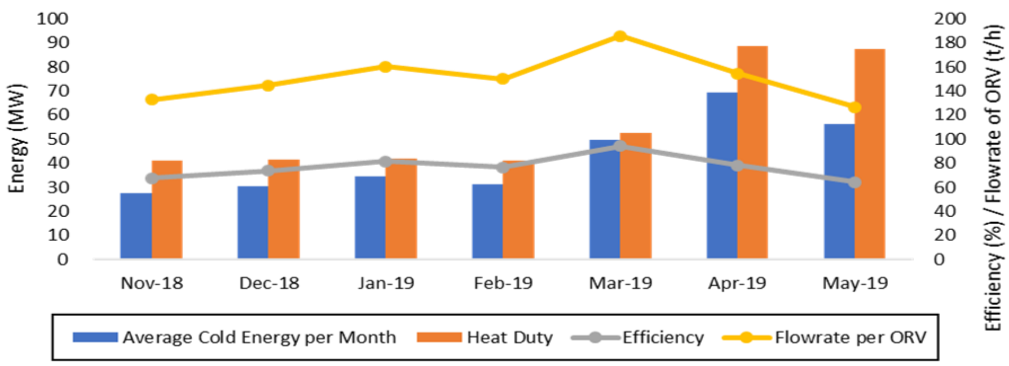

Figure 4: Graph of comparison of heat duty with average cold energy recovery

As the flow rate of the seawater is constant at around 6,100 m^3, therefore, the efficiency of the ORV is highly dependent on the flow rate of the LNG. Accordingly, to the observed trend, the higher the flow rate of the LNG, the higher the efficiency of the ORV. Because of the mechanical limits in the design, the maximum flow rate can only reach up to 250 t/h of LNG, therefore, the optimum LNG flow rate for each vaporizer can be determined to increase the efficiency. In addition, the efficiency of the ORV can also be increased by modifying the optimum seawater flow rate. For safety and integrity purposes, seawater flow rate is normally set at a constant value, accordingly to the standard set in regulations. If the seawater flow rate is to be modified, the installation of an automatic control and monitoring system with minimum human intervention is encouraged. This is because by using an automatic control and monitoring system, the seawater flow rate can always be controlled and maintained at its optimum level. This will lead to an increase in the efficiency of the ORV, and subsequently, an increase in the amount of recoverable cold energy. However, the installation of an automatic control and monitoring system will increase the cost, hence, reducing the profit.

4. Conclusions

In conclusion, the higher the send out rate, the greater the amount of LNG cold energy that can be recovered. It is expected that the density of recoverable cold energy from regasification process will increase as the natural gas demand worldwide is increasing. As different types of cold energy utilization require different quantity of cold energy, studies on the quantity of recoverable cold energy in a regasification terminal allow the determination of suitable cold energy utilization and application. As presented in this paper, the average monthly amount of cold energy that can be recovered by the regasification terminal is around 43 MW, based on this finding, a suitable application, could be determined to utilize that amount of recovered cold energy. From calculations, the efficiency of the ORV fluctuates in a range of 60 % to 95 % of its average. The fluctuations are mainly due to the flow rate of the NG/LNG and the flow rate of seawater. Therefore, the efficiency of the ORV can be improved by modifying the flow rate of LNG for each ORV and also the flow rate of seawater. For future research works, it is recommended that different polynomial graph fitting software or tools should be used in data analysation. This is to improve the diversities in the research methodology and to allow the comparisons of different analyses.

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