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Research paper

A new boil-off gas re-liquefaction system for LNG carriers based on dual mixed refrigerant cycle

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ABSTRACT

A new boil-off gas (BOG) re-liquefaction system for LNG carriers has been proposed to improve the system energy efficiency. Two cascade mixed refrigerant cycles (or dual mixed refrigerant cycle, DMR) are used to provide the cooling capacity for the re-liquefaction of BOG. The performance of the new system is analysed on the basis of the thermodynamic data obtained in the process simulation in Aspen HYSYS software. The results show that the power consumed in the BOG compressor and the high-temperature mixed refrigerant compressor could be saved greatly due to the reduced mass flow rates of the processed fluids. Assuming the re-liquefaction capacity of the investigated system is 4557.6 kg/h, it is found that the total power consumption can be reduced by 25%, from 3444 kW in the existing system to 2585.8 kW in the proposed system. The coefficient of performance (COP) of 0.25, exergy efficiency of 41.3% and the specific energy consumption (SEC) of 0.589 kWh/kg (LNG) could be achieved in the new system. It exhibits 33% of improvement in the COP and exergy efficiency in comparison with the corresponding values of the existing system. It indicates that employing the DMR based BOG re-liquefaction system could improve the system energy efficiency of LNG carriers substantially.

1. Introduction

LNG, a kind of cryogenic fuel stored at 111 K and ambient pressure, is transported over sea by vessels equipped with insulated tanks. A considerable amount of LNG would be vaporized into gas (named boil off gas, i.e. BOG) because of the heat transferred from the environment, and the pressure of LNG tank is built up. In order to guarantee the safety of the tank, the continuously generated BOG must be handled when the tank pressure is higher than its allowable value [1].

Combustion of BOG in the propulsion system is a good option for a LNG carrier. In fact, dual fuel (DF) engines have been developed in the past two decades to innovate the LNG carrier propulsion systems [2]. Fernandez et al. [3] conducted an exhaustive review of the different propulsion systems for LNG carriers. They pointed out that the BOG produced in the cargo spaces could be used as fuel in DF steam turbines, gas turbines and diesel engines. Vedran et al. [4] conducted fuel consumption measurements of DF marine steam generators in a LNG carrier in ship exploitation at various loads. They found that the DF steam generators have lower energy and exergy efficiencies in comparison with the generators in land based power plants. Marine turbo-generators and steam turbines for the main feed water pump drive were investigated on the LNG carrier with steam propulsion by Vedran et al. [5]. The study results showed that replacing the steam turbine with an electric motor to drive the main feed water pump would increase the turbo-generator energy and exergy efficiencies by at least 1–3%. The review conducted by Fernandez et al. [3] indicated that the DF two-stroke (2S) diesel engines with a BOG re-liquefaction plant could achieve high efficiency (approximately 50%) and no losses in the cargo to be transported. If the consumption of the re-liquefaction plant could be substantially reduced and the emissions of NOx and SOx can be limited in the improved propulsion systems, the 2S engines can be an attractive option for LNG carriers. Therefore, many researches focused on developing more efficient BOG re-liquefaction processes on LNG carriers.

MAN B&W [6] developed 2S diesel engine with BOG re-liquefaction which is fuelled by BOG at a high pressure of 300 bar. A Laby@ GI BOG multistage compressor has been designed and developed by Burckhardt Compression AG (BCA) for the fuel supply at such a high pressure and BOG re-liquefaction [7]. So far, on the basis of the Laby@ GI compressor, two kinds of BOG re-liquefaction systems, a reverse Brayton cycle based process in cooperation with Hamworthy Gas Systems (HGS) [8] and an ethylene-propylene cascade process in cooperation with Tractebel Gas Engineering (TGE) [9], have been developed by BCA. In addition, various on-board re-liquefaction technologies have been developed and studied by many researchers. The control algorithm for a similar BOG re-liquefaction system has been developed by Shin and Lee

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Nomenclature

e	specific exergy ($kJ\,kg^{-1}$)
E	exergy flow (kW)
h	specific enthalpy ($kJ\,kg^{-1}$)
$\dot{m}$	mass flow rate ($kg\,h^{-1}$)
P	pressure (kPa)
Q	heat load (kW)
s	specific entropy ($kJ\,kg^{-1}\,K^{-1}$)
T	temperature (K)
W	work (kW)
x	quality

Greek symbols

Δ	change in a quantity
η	efficiency (%)

Subscripts

0	reference state point
Com	compressor
e	evaporation
EC	ethylene compressor
ex	exergy
HX	heat exchanger
in	inlet
M0-M8	state points of methane
MR1	low-temperature mixed refrigerant
MR2	high-temperature mixed refrigerant
out	outlet
V	valve

Acronyms

BOG	boil-off gas
COP	coefficient of performance
LNG	liquefied natural gas
SEC	specific energy consumption (kWh/kg(LNG))

using a dynamic simulation tool [10]. Romero et al. [11] carried out an intensive investigation on the refrigerating performances of a reverse Brayton cycle (RBC) for the re-liquefaction of BOG on LNG vessels. An on-board LNG-BOG re-liquefaction system based on nitrogen expanded Claude cycle has been optimized from the exergetic and exergo-economic perspectives by Sayyaadi and Babaelahi [12,13]. The thermo-economic optimization using the genetic algorithm was conducted to minimize the unit cost of the refrigeration effect in the BOG re-liquefaction plant [12]. Additionally, multi-objective optimization was also performed by the same authors to find a set of Pareto optimal solutions for the re-liquefaction system using NSGA-II algorithm in MATLAB [13]. They found that both economic and thermodynamic features of the system have been improved compared to the base case system by the multi-objective optimization.

In addition, a single-separator mixed refrigerant cycle (MRC) based BOG re-liquefaction system for LNG carriers was proposed by Nekså et al. [14]. A mini-LNG plant for marine applications has been implemented, and the test results were successful from both efficiency and operation points of view. A good agreement between simulations and the experiments has been achieved in their study. Recently, a new BOG re-liquefaction system based on Kapitza liquefaction cycle using BOG itself as working fluid has been proposed and compared with RBC system [15]. It was reported that a Kaptiza cycle based system performs the comparable exergetic efficiency as that of a RBC system. Furthermore, a pulse tube cryo-cooler with relative larger cooling capacity was proposed to reliquefy BOG in small LNG distribution stations [16]. It is a promising concept for mini-LNG BOG re-liquefaction if its exergetic efficiency can be further improved.

Romero Gómez et al. [17] conducted a comprehensive comparison of different BOG re-liquefaction technologies on LNG vessels. They concluded that the combination of re-liquefaction plant and DF propulsion system would be the tendency of the development of LNG carriers. The cascade based re-liquefaction system has become a serious alternative to the reverse Brayton cycle due to its higher efficiency and lower maintenance costs. An improved BOG re-liquefaction system combining the propulsion system with DF engine was investigated by Romero Gómez et al. [18], as shown in Fig. 1(b). On the basis of the re-liquefaction system developed by Tractebel Gas Engineering and Burckhardt (as shown in Fig. 1(a)) [9], a recuperator was added to recover the cooling capacity of BOG, and a cooler was used to reject the compression heat to the seawater. Hence, the author claimed that the coefficient of performance (COP) and exergetic efficiency of the new system could be 22% and 19% higher than the corresponding values of the original design, respectively.

As concerns about the air pollution caused by vessels emission and the system energy efficiency of LNG carriers becomes more and more pressing, the high-efficient BOG re-liquefaction technologies combining with dual fuel propulsion system would be promising for the new LNG carriers. Hence, it motivates the present authors to study the new system to achieve a higher energy efficiency without adding complicated devices. Dual mixed refrigerant cycle (DMR) has been regarded as a promising liquefaction system with higher efficiency. Here, a new BOG re-liquefaction system based on DMR will be proposed and investigated carefully. The improvement in system performance will be illuminated in details.

2. Analysis of the DMR based re-liquefaction system

2.1. Description of the proposed systems

A new BOG re-liquefaction system based on DMR is described in Fig. 2. Comparing the flow diagrams of the existing system in Fig. 1 and the proposed system in Fig. 2, it can be found that cascaded two-stage compression refrigeration systems in the existing [9] and Romero's systems [18] have been modified into two cascade simple compression refrigeration cycles in this study.

The compressors play the most important role in the BOG re-liquefaction system, and they are the main power consuming components. In the existing scheme, a Laby@ GI BOG multistage compressor designed by Burckhardt Compression [7] is employed to compress the BOG and the low-temperature refrigerant, ethylene. The high-temperature refrigerant, propylene, is compressed by an independent two-stage compressor. Correspondingly, a similar compression arrangement is conceived in the new system. The distribution of BOG compression stages are kept the same as the existing system considering the designed parameters of the Laby@ GI BOG multistage compressor. In addition, the compression of the low-temperature mixed refrigerant (MR1) is supposed to be achieved by the existing two-stage compression of ethylene in the Laby@ GI multistage compressor. The high-temperature mixed refrigerant (MR2) could be compressed by the propylene compressor in the existing system. Therefore, the outlet pressures of each compression stage are kept the same as the corresponding values of the existing compressors.

It should be noted that the re-liquefaction pressure of BOG is