International Journal of Naval Architecture and Ocean Engineering xxx (2017) 1–8

Contents lists available at ScienceDirect

International Journal of Naval Architecture and Ocean Engineering

journal homepage: http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Development of partial liquefaction system for liquefied natural gas carrier application using exergy analysis

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ARTICLE INFO

Article history:
Received 31 July 2017
Received in revised form
6 November 2017
Accepted 17 November 2017
Available online xxx

Keywords:
Reliquefaction
PRS
Boil-off gas
Open cycle
Exergy analysis
Specific power consumption

ABSTRACT

The cargo handling system, which is composed of a fuel gas supply unit and cargo tank pressure control unit, is the second largest power consumer in a Liquefied Natural Gas (LNG) carrier. Because of recent enhancements in ship efficiency, the surplus boil-off gas that remains after supplying fuel gas for ship propulsion must be reliquefied or burned to regulate the cargo tank pressure. A full or partial liquefaction process can be applied to return the surplus gas to the cargo tank. The purpose of this study is to review the current partial liquefaction process for LNG carriers and develop new processes for reducing power consumption using exergy analysis. The developed partial liquefaction process was also compared with the full liquefaction process applicable to a LNG carrier with a varying boil-off gas composition and varying liquefaction amounts. An exergy analysis showed that the Joule–Thomson valve is the key component needed for improvements to the system, and that the proposed system showed an 8% enhancement relative to the current prevailing system. A comparison of the study results with a partial/full liquefaction process showed that power consumption is strongly affected by the returned liquefied amount.

1. Introduction

Boil-Off Gas (BOG) generated from a cargo tank during a voyage in a Liquefied Natural Gas (LNG) carrier (LNGC) should be treated for cargo tank protection. Environmental regulations have caused BOG to be used as a main propulsion fuel, and the Fuel Supply Unit (FSU) has been developed accordingly. Because of reduced fuel consumption from both the enhancement of ship efficiency and low speed operations, fuel gas consumption is not sufficient to treat all generated BOG. A liquefaction facility is therefore required to return surplus BOG to the cargo tank. The cargo handling system composed of an FSU and liquefaction unit is the second largest power consumer during a voyage.

The liquefaction process is well known, because it entails significant power consumption. Many methods have been studied for increasing liquefaction efficiency, with various processes using various heat exchanger types and refrigerants. Remeljej and Hoadley, 2006 compared the various processes for an offshore LNG production facility, using a Single Mixed Refrigerant (SMR), N_2, and CH_4. The results showed that SMR exhibited higher performance than other refrigerants, but an N_2 process and open loop cycle using CH_4 were recommended because of the compactness of the system. Shin and Leeb (2009) emphasized the value of non-flammable refrigerant offshore, and studied the liquefaction process using an N_2 refrigerant, which was applied to the reliquefaction of a large LNGC. Recently, adopting multiple refrigerants has been investigated as a method for increasing liquefaction efficiency in an LNG plant. Morosuk et al. (2015) suggested optimizing a PRICO liquefaction process where a pre-cooler (using propane as additional refrigerant) is added to the Mixed Refrigerant (MR) process. Ding et al. (2016) developed a pre-cooled propane N_2–CH_4 expansion process, and their results indicated that system performance fell between an MR process and a N_2 expansion process. Chang (2015) reviewed cryogenic refrigeration cycles for the liquefaction of natural gas, such as the Joule–Thomson and Brayton cycles, with pure and mixed refrigerant and thermodynamic irreversibility. Lee and Sanggyu et al. (2012) proposed that the cycle consists of pre-cooled carbon dioxide and a nitrogen expander liquefaction cycle for LNG FPSO. Most research into liquefaction has focused on natural gas applied in an on/off shore LNG plant. However, the composition of BOG in LNGC would be slightly different from that of natural gas.

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Peer review under responsibility of Society of Naval Architects of Korea.

https://doi.org/10.1016/j.ijnaoe.2017.11.001

Nomenclature

BOG	Boil-off gas
C3MR	C3 (propane) mixed refrigerant
E_x	Exergy [kJ/kg]
FG	Fuel Gas
FSU	Fuel Supply Unit
h	Specific Enthalpy [kJ/kg]
I	Irreversibility, Exergy destruction [kW]
JTV	Joule–Thomson Valve
LNGC	Liquefied Natural Gas Carrier
$\dot{m}$	Mass flow rate [kg/h]
SMR	Single mixed refrigerant
NG	Natural Gas
NOx	Nitrogen oxide or dioxide
PRS	Partial Reliquefaction System
s	Specific Entropy [kJ/kg k]
SMR	Single mixed refrigerant
SPC	Specific Power Consumption [kW/kg]
$\dot{W}$	Shaft Power [kW]
Subscripts	
ex	exergy
o	environmental state (25 °C, 1 bar)

From a ship operations point of view, the optimal cargo handling system should have both good liquefaction performance and good fuel gas supply performance. In particular, the required amount of liquefaction is relatively small relative to the fuel gas, so that it may be appropriate in an LNGC to apply different processes than those used in a conventional LNG plant. D.K. Choi et al. (2014) announced a Partial Reliquefaction System (PRS) with an open loop cycle using BOG as a refrigerant, which is optimized for supplying fuel gas to an engine that requires a gas supply pressure of 300 bar and can liquefy a small amount of surplus BOG.

The purpose of this study is to develop a new PRS for a medium pressure gas engine met Tier III requirement. An exergy analysis of the system applying the PRS for medium pressure gas engine was performed. To improve system performance based on specific power consumption through an exergy analysis, a modified PRS was proposed and compared. It was also carried out as a case study, with varying BOG compositions and liquefaction flow amounts.

2. System description

2.1. System condition

An FSU that meets the fuel gas conditions required by the main propulsion engine and a reliquefaction unit that liquefies the remaining BOG in the fuel supply are located in the cargo compressor room, as shown in Fig. 1. Consequently, system compactness is more important here than in other cases. An open loop cycle using process fluid as a refrigerant could be a promising solution for reducing space in the compressor room. System boundary conditions were considered as follows for analyzing and comparing the system.

The pressure of the cargo hold is maintained at 1.06 bar and the generated BOG is saturated vapor. However, the BOG entering the cargo room is heated by heat penetration through the pipe during transport. As opposed to LNG, BOG is primarily composed of methane and nitrogen. Shin and Leeb (2009) assumed the typical conditions of BOG to be a temperature of −120 °C, comprising approximately 8.5% nitrogen and 91.5% methane during the LNGC liquefaction process development. Those BOG composition ratios change over time. Initially, the nitrogen composition of BOG is larger than in LNG and decreases over time. Additionally, main propulsion gas consumption is not constant, and depends on operating conditions such as voyage mode, engine fuel mode, etc. This means that the load to be liquefied varies with fuel gas consumption and BOG rate.

Table 1 presents the system boundary conditions for the process analysis. In this research, it was assumed that 4000 kg/h of pure methane BOG was generated from the cargo tank. Of that BOG, 62.5% was supplied for fuel gas, and the rest was returned to the cargo tank through the liquefaction unit at the design stage. Performance was also reviewed by changing the nitrogen composition of BOG from 0% to 20%, and the flow amount of liquefied gas was reviewed by changing from 1000 to 2000 kg/h for a given BOG flow amount.

The process analysis was carried out in Aspen HYSYS with Peng–Robinson equation used as the equation of state. When compared with other systems, the assumptions and conditions for each component should be kept constant. Pressure loss in system components was not considered. A thermodynamic system analysis was performed based on the following general assumptions:

- Adiabatic efficiency of compressor: 75%;
- Pressure ratio in multi stage compressor: below 4 (according to GPSA guidance);
- Minimum approach temperature in heat exchanger: 5 °C; and
- Outlet process temperature of the inter coolers: 40 °C.

3. System analysis

3.1. Overall system efficiency

In process optimization studies, specific objective functions are optimized for specific variables. Cao et al. (2006) have compared SMR and N_2 expander liquefaction processes for small-scale natural gas liquefaction. They focused on the fact that temperature differences in the heat exchanger are a key parameter for optimizing power consumption. Nogal et al. (2008) compared the capital cost of a cascade mixed cycle with the required power for that cycle by changing the approach temperature of the heat exchanger. Alabdulkarem et al. (2011) optimized the required power consumption for a MR process using genetic algorithm optimization technique. Although the objective functions and process optimization variables vary among studies, ultimately many of these objective functions have aimed to minimize power consumption. The Specific Power Consumption (SPC) associated with fuel supply and liquefaction for a given BOG amount are defined as below. In this study, SPC is the main objective function used to optimize the system and it is key parameter, in which the developed system was compared with other systems.

$$SPC = \left(\frac{\sum \dot{W}_{comp}}{\dot{m}}\right)_{re-liquefaction} \quad (1)$$

3.2. Exergy analysis

Exergy analysis is a useful method for measuring the qualitative/quantitative use of energy in components and the overall system.