Energy Proceedings
Vol 28, 2022
ISSN 2004-2965

Possibility of utilizing LNG cold waste heat on the container ship

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ABSTRACT

Stricter ecological standards in combination with increasing demand for transportation of perishable cargo, demand changes in shipping industries in the years to come. Until more ecological power systems are implemented, increasing energy efficiency, and reducing carbon footprint have become a priority for shipping industries. Due to smaller greenhouse gas emissions, LNG-powered vessels are gaining more attraction and when LNG is used, considerable waste cold energy can be utilized. In this research, waste cold heat of LNG is used for precooling of outside air for cargo hold ventilation. It is shown that by precooling the air with LNG waste cold heat, the energy consumption of transported refrigerated containers can be reduced up to 25%.

Keywords: LNG, cold waste utilization, container ship, refrigerated container

1. INTRODUCTION

With global economic growth, it is expected that demand for transportation of goods will further increase. Consequently, shipping industries will be challenged between profit and securing the latest regulations regarding the environment. Transporting goods by sea was responsible for approximately 3,1% of global greenhouse gas (GHG) emissions between 2007 and 2012 due to the large size of the shipping sector [1]. To reduce GHG emissions by at least 50% by 2050 compared to levels in 2008, the shipping sector must adjust to stricter environmental regulations regarding NO_x, SO_x, and CO_2 emissions [2]. Until alternative fuels for zero-emission vessels such as electric batteries, biofuels, and hydrogen, which all have the potential to reduce GHG [3], become more developed and widely available, so-called transitional alternative fuels such as liquefied natural gas (LNG) and liquefied petroleum gas (LPG) are gaining more attraction. Currently, one of the most popular solutions, to reduce the environmental impact of the shipping sector is the use of LNG. This can be seen in the increasing demand for LNG-powered vessels in recent years (Fig. 1) [4].

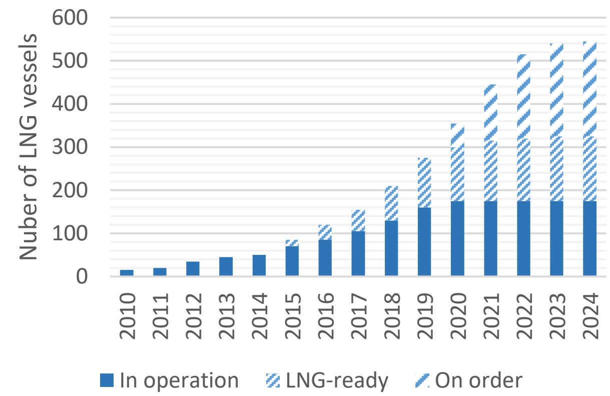

Fig. 1 Number of LNG-powered vessels from 2010 to 2020 with a forecast through 2024. [5]

LNG is less harmful compared to traditional heavy fuel oil with a higher hydrogen-to-carbon ratio resulting in 20-30% less CO_2 emission during combustion [6]. It is produced by cooling the natural gas below the saturation point, -162 °C at atmospheric pressure, and it can be used in low/high-pressure dual-fuel engines and gas turbines [7]. Before distribution to the propulsion system LNG must be evaporated. Around 830 kJ/kg of cryogenic energy [8] is released during the regasification process. So further improvement of LNG-powered systems by utilizing LNG waste cold energy has become a priority.

For sea transport of perishable products over long distances, refrigerated containers (reefers) are employed. The reefer container market has been the fastest-growing segment in container shipping in recent years [9]. Reefer containers have an integrated refrigeration unit which is used for maintaining a certain temperature within the insulated cargo space, therefore enabling the transport of temperature-sensitive products. To secure climate control inside cargo space and to prevent product deterioration during transportation, an integrated refrigeration unit requires a constant power supply. Electricity used for powering reefer containers on ships mainly comes from burning fossil fuels [10].

LNG cold energy utilization has been widely applied to various systems and it has shown promising results when low-temperature operating conditions are required. Implementation of LNG cold waste energy can be found in separation and desalination processes [11], cold storage systems [12], data centers [13], and many other processes. With an increasing number of LNG-powered vessels, the possibility of utilizing LNG cold energy on ships has been investigated by a few authors. Saeed et al. [14] proposed utilizing LNG cold energy on a fishing vessel to reduce the energy consumption needed for a refrigeration system that maintains fish quality while Pasini et al. [15] investigated the potential of utilizing LNG cold energy in energy recovery through supercritical Rankine cycle and using LNG as working fluid. The authors also showed that the proposed system allows the recovery of free cooling for onboard demand, such as air conditioning, food conversation, or even additional engine enhancement. Ahn et al. [16] investigated cooled air ventilation, linked to a marine power system, that recovers LNG waste cold heat produced during LNG vaporization for removal of dissipated heat from reefer containers. The authors concluded that this type of system could increase the electric efficiency of the ship.

Energy consumption of reefer containers on container ships has been recognized as an important part of the cold chain [17]. Improving the energy consumption of reefer containers on container ships has been investigated by Yang et al. [18]. The authors proposed water mist-spraying into the condenser fan of the integrated refrigeration system for the reduction of energy consumption. For fuel consumption reduction of a container ship, while providing necessary heating, cooling, and refrigeration capacity Cao et al. [19] proposed utilizing a waste heat powered system. The authors proposed utilizing waste heat in an absorption refrigeration system for supplying cold air into the cargo holds to lower the temperature inside cargo holds thus reducing the condensation temperature of the integrated refrigeration unit of the reefer container allowing better efficiency of the refrigeration system.

Improving refrigerated container energy consumption is a promising method for reduction of fuel consumption and consequently emission reduction on container ships. In the case of LNG-powered ships, the possibility of recovering cold energy opens a lot of possibilities for improving refrigeration systems on ships. This study focuses on utilizing LNG waste cold energy on container ships to reduce refrigeration load and improve refrigeration system energy consumption resulting in more energy-efficient reefer logistics.

2. CASE STUDY

2.1 Container ship

For purpose of this case study, a conceptual feeder ship will be used. All data regarding the ship is provided by the shipbuilding company *Brodosplit, Croatia*. A feeder ship is a freight ship used to collect containers from different ports and transport them to the central container terminal. Brodosplit's feeder ship has a capacity of 2000 TEU and it is equipped with a dual-fuel engine produced by MAN. The specified maximum continuous rating (SMCR) is 11 060 kW. Gas consumption is given in the next table:

Table 1. Engine gas consumption in Dual Fuel mode [16]

Ambient air [°C]	Engine load [% SMCR]	Gas consumption [kg/h]
25	100	1485
25	80	1130

On the ship, there are 375 sockets for reefer container power supply. 181 sockets are provided in three cargo holds under the deck. To dissipate heat produced from reefer containers [18] in the cargo hold, sufficient ventilation is provided. Ventilation capacity and the number of containers in cargo holds are given in the next table.

Table 2. Cargo hold ventilation

	Number of reefer containers (TEU)	Ventilation type	Ventilation capacity (m^3/h)
Cargo hold #1	19	Natural	37 000
Cargo hold #2	72	Mechanical	110 000
Cargo hold #3	90	Mechanical	250 000

2.2 Ship cold energy utilization system

The proposed system for utilizing waste heat is illustrated in Figure 2. LNG, which will be in steady-state thermodynamic analysis, for simplicity, assumed as pure methane at 3 bar and -146,44 °C, leaves the LNG fuel tank and is pumped to the LNG vaporizer. After the LNG vaporizer, the temperature of LNG is assumed to be 0 °C. The heat source for the LNG vaporizer presents a circuit of ethylene glycol which transfers waste cold heat to the cooling medium. The cooling medium is then pumped to an air cooler, which is located on the intake of fresh air for the ventilation system of the cargo hold. In analysis, the efficiency of all heat exchangers is assumed to be 85%.

2.3 *Refrigerated container*

There are a few different standardized dimensions of refrigerated containers so data for a 20-foot reefer container is used. Reefer containers are isolated with 90 mm of polyurethane which is located between a layer of 0.8 mm of aluminum and a layer of 0.9 mm of steel. Outside dimensions are standard and inside dimensions depend on the construction of the refrigeration unit. Inside dimensions are 5,44x2,29x2,27 m [17].

The energy consumption of the refrigeration unit is assumed to be equal to the energy needed to remove heat flow through container walls to maintain a constant temperature (cooling load). Heat is transferred by means of conduction, convection, and radiation. In this case, reefer containers are transported inside the cargo hold so solar radiation is neglected. To estimate cooling load, heat flow through container walls was calculated as:

$$Q_{cl} = \left(\frac{UA}{1000} + \frac{\rho_{air} \cdot c_{p_{air}} \cdot V_{in}}{3600}\right) \cdot (\vartheta_{outside} - \vartheta_{inside}) \qquad (1)$$

where U is the overall heat transfer coefficient (W/m^{2}K), A is an area of wall surface (m^2), are density (kg/m^3) and thermal capacity (kJ/kgK) of air and V_{in} is the volume flow of air in a container (m^3/h), set to 70. The inside temperature (ϑ_{inside}) is set to 0 °C while the outside temperature ($\vartheta_{outside}$) changes throughout the year. Temperature data [18] was taken from the city of Rijeka as the ship is expected to work around the port of Rijeka.

In a reefer container, most of the energy is consumed by the compressor so for simplicity only compressor consumption will be calculated. Energy consumption is calculated for every hour in a year by dividing the needed cooling load by the COP defined by current conditions. The compressor is chosen to have the same cooling capacity according to available data [14]. To obtain COP for different outside temperature data from the manufacturer is used [19]. For outside temperatures below 10 °C COP value calculated for 10 °C is used as the temperatures are out of the scope of polynomials provided by the manufacturer.

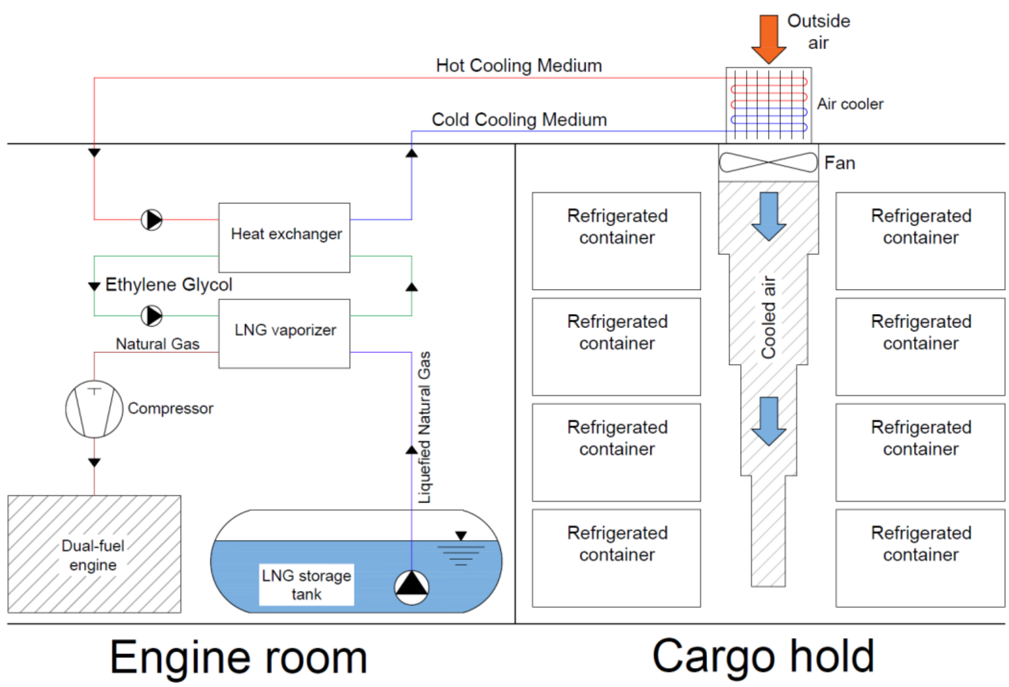

Fig. 2 System layout

2.4 *Results and discussion*

The annual cooling load of the 20-foot refrigerated container is 6399,5 kWh. To remove heat and maintain an inside temperature of 0 °C the compressor of the refrigeration unit uses 911,3 kWh. With cold system utilization, outside air temperature is lowered upon entering the cargo hold ventilation system. 181 kW of heat is removed from the air with the engine running at 100%. If all heat is removed from cargo hold number 3, air temperature can be lowered by 2,8 °C at full ventilation capacity. This will lower the annual cooling load to 5176,7 kWh and the annual energy consumption of the reefer container compressor to 683,3 kWh inside the cargo hold number 3. The reduction of cooling load and energy consumption of the compressor, depending on the engine load can be seen in the next figure. When the engine is running at 80% reduction of power consumption of the reefer container is expected to be 20%.

Even better results are expected if all heat is removed from cargo hold number 2 due to a smaller ventilation capacity. At the same time, fewer reefer containers can be transported in cargo hold number 2. If all heat is removed from cargo hold number 2 while the engine is running at 100% up to 50% reduction in power consumption of the reefer container is expected. The possibility of improving reefer container power consumption in cargo holds by utilizing LNG cold energy, will require optimization in storing reefer containers on the ship. Utilizing LNG cold energy for precooling air for cargo holds can lead to the smaller power consumption of reefer containers, consequently leading to smaller fuel consumption of the container ship.

Presented reductions in energy consumption are only related to the compressor. Depending on the reefer container regulation unit, savings in fan energy consumption are also possible which will be the next step in the development of the model. Reducing inlet temperature also leads to better performance of the ship ventilation system but an additional heat exchanger will increase pressure loss in the ventilation system. Detailed calculation of the complete container ship energy system will be the focus of further work as well as experimental validation of results.

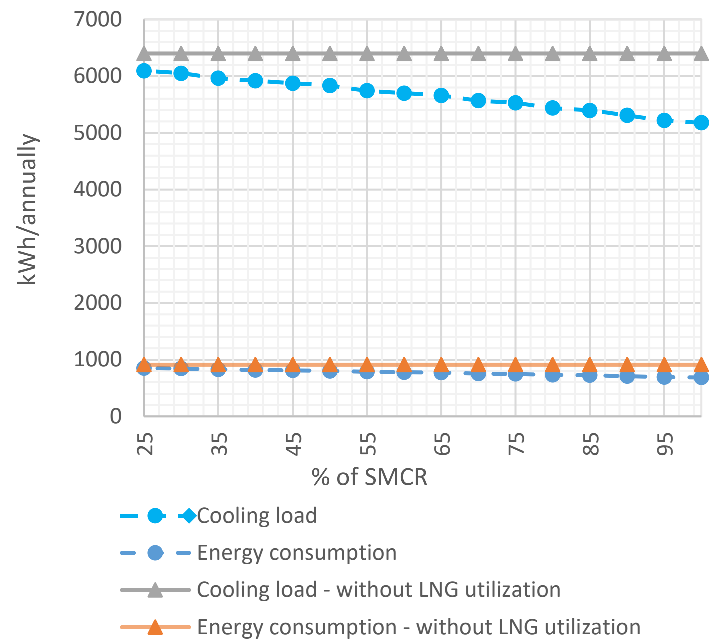

Fig. 3 Reefer container cooling load and energy consumption depending on engine load

3. CONCLUSIONS

With an increasing number of LNG-powered vessels utilizing cold waste heat is gaining more attraction. One possibility of utilizing cold waste heat from the LNG regasification process onboard a container ship is to precool outside air which is then used for removing heat from the refrigeration unit of reefer containers inside cargo holds. Based on the proposed model, utilizing LNG cold heat will result in a reduction of reefer container cooling load of 1222,8 kWh and compressor energy consumption of 225 kWh annually per reefer container. Even at a minimum engine load annual reduction of 7% of compressor energy consumption can be achieved. Future research will focus on the economical, technical, and ecological benefits of utilizing cold waste heat to improve container ships' energy efficiency.

ACKNOWLEDGMENT

The authors are grateful for the financial and logistical support from the CEKOM project from the European regional development fund, referent number KK.01.2.2.03., subproject IRI 4, in the scope of which this study is conducted.

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