The Influence of Energy Consumption of Gas Vapour Reliquefaction on the Structure of the LNG Carrier Power Plant

Utjecaj ponovnog ukapljivanja plina na potrošnju energije u strukturi LNG brodskog postrojenja

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Summary

This paper discusses the issues of reliquefaction of natural gas vapors on the Q-Flex type LNG tankers. DRL gas carrier power plant has been presented. The principle of operation of a BOG reliquefaction plant has been described. An energy analysis referring to nominal operational conditions has been performed. DRL LNG carrier's power plant load at laden voyage has been estimated. The results have been confronted with the values typical for conventional LNG carriers. General conclusions on the size of the Q-Flex LNG tanker's power plant have been drawn.

KEY WORDS
LNG carrier
operational states
ship power plant
natural gas reliquefaction

Sažetak

Ovaj članak raspravlja o pitanju ponovnog ukapljivanja prirodnih plinova na Q-Flex tipu LNG tankera. Prikazuje se DRL postrojenje za prijevoz ukapljenog plina. Opisuje se princip rada BOG postrojenja za ponovno ukapljivanje plina. Izvršena je analiza energije koja se odnosi na nominalne radne uvjete. Procijenjeno je DRL LNG postrojenje pri ukrcanom brodu na putovanju. Rezultati su uspoređeni s vrijednostima tipičnima za konvencionalne LNG prijevoznike. Izvedeni su općeniti zaključci o veličini Q-Flex LNG postrojenja.

KLJUČNE RIJEČI
LNG prijevoznik
radni status
brodsko postrojenje
ponovno ukapljivanje prirodnog plina

1. INTRODUCTION / *Uvod*

Development of power plants of LNG carriers is accompanied by the changes of their structure adjusting them to functioning in particular operational states. Evolution of LNG carrier power systems, from conventional steam turbine ones, through Dual-Fuel Diesel Electric to direct ones with slow-speed two-stroke diesel engines led to power system reaching efficiencies similar to those of other cargo ships [1, 2, 5]. Solving the problem of cargo evaporation throughout its subsequent liquefaction allowed application of direct systems on the latest LNG carriers. This type of power system known as Diesel with Reliquefaction Plant (DRL) [2] is installed on the biggest LNG carriers of the Q-Flex and Q-Max type with cargo tank capacities exceeding 200,000 m3 and 250,000 m3 respectively [9]. The main advantages of this type of power system is the high efficiency of main engines and not "burning" the carried cargo as it takes place on conventional LNG carriers driven by steam turbines or on vessels with DFDE power systems. Operational states of DRL gas carriers where there is a need for boil off gas reliquefaction generate new demands for electrical energy fluxes, which do not occur on other LNG carriers.

2. THE POWER SYSTEM OF AN LNG CARRIER OF THE Q-FLEX TYPE / *Sustav napajanja LNG prijevoznika tipa Q-Flex*

An example of a power system of a Q-Flex type gas carrier together with a ship power plant is shown in Fig. 1. It consists of two power units with low-speed two-stroke diesel engines of the MAN B&W type 6S70ME-C with nominal power of 17,500 kW directly driving a fixed pitch propeller. The ship power plant consists of five medium–speed four-stroke diesel engines MAN B&W 7L32/40, each with the power of 3500 kW and rotational speed of 720 rev/min. Each of the five engines drives an electrical generator of 3360 kW supplying the ship network of 60 Hz 6.6 kV [8]. The number of generator sets operating at a given moment is dependent on the current requirement for electrical energy, thus it depends on the operational state of the carrier [3].

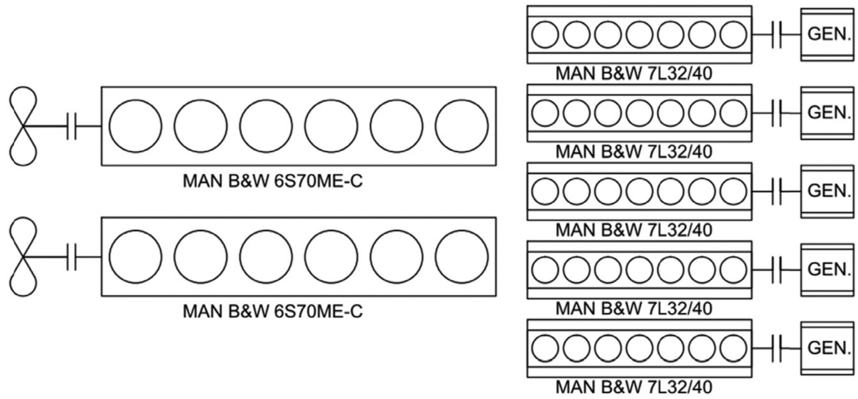

Figure 1 A simplified diagram of the main power system and an auxiliary power plant of an LNG carrier of the Q-Flex type
Slika 1. Pojednostavljeni dijagram sustava glavnog napajanja i pomoćnog postrojenja LNG prijevoznika Q-Flex tipa

3. IDENTIFICATION OF RELIQUEFACATION PLANT/ *Identifikacija postrojenja za ponovno ukapljivanje*

The task of the LNG reliquefaction installation is the subsequent condensation of boiling off gas to avoid its losses due to natural cargo evaporation transported at – 163°C by sea. In the case of newer technological solutions (Mark III) the boil-off rate does not exceed 0.15 % of the tanker capacity [1,6].

The value of BOR (boil off rate) may change at voyage (air and sea water temperature) and with the time of ship operation (tank insulation condition deteriorates). Therefore, the reliquefaction installation is adjusted to the operation in different conditions of cargo evaporation connected with the amount of gas to liquefy.

A simplified diagram of a reliquefaction installation together with equipment necessary for its functioning, accounted for in the energy analysis of the system, is shown in Fig. 2. The installation consists of two sea water pumps (1), fresh water cooler (2), two fresh water pumps (3), two companders (4), nitrogen container (5), cryogenic heat exchanger (6), liquid separator (7), two LNG pumps (8), pre-cooler (9) and two BOG compressors (10).

This installation consists of two main cycles of the working media and the equipment cooling system. In the first cycle the medium is the LNG vapour which is later liquefied and directed back to the tanks. The second cycle is the one of the refrigerant – nitrogen. The interception place of the both cycles is the cryogenic heat exchanger in which BOG is liquefied. A cooling water cycle is an auxiliary installation whose part is shown in Fig. 2

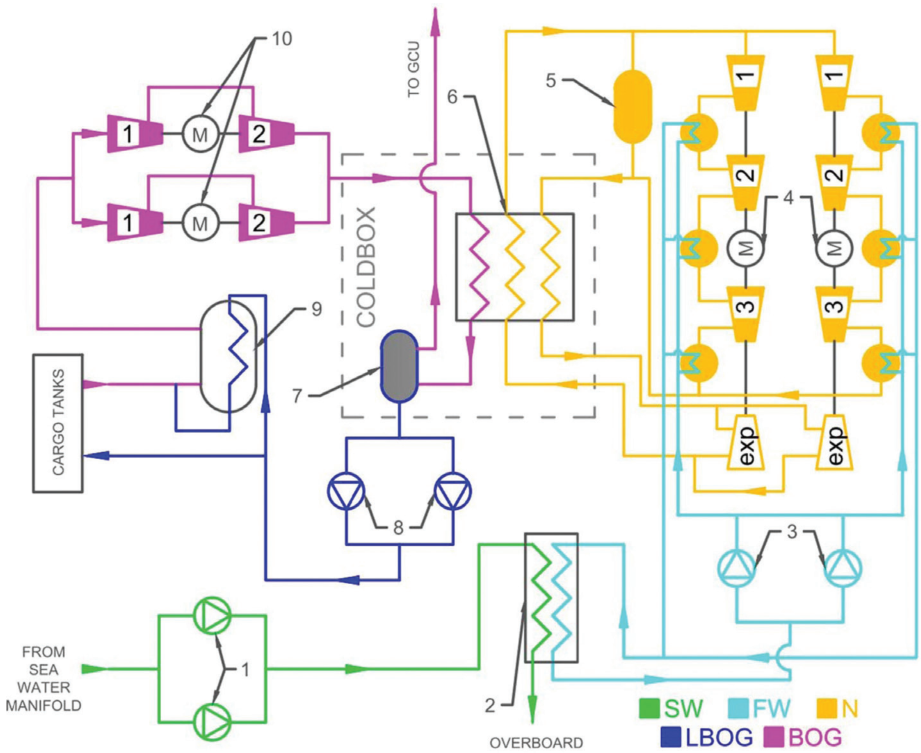

Figure 2 Diagram of an LNG reliquefaction plant: SW – sea water; FW – fresh water; N – nitrogen; LBOG – liquid BOG, GCU – Gas Combustion Unit
Slika 2. Dijagram LNG postrojenja za ponovno ukapljivanje; SW-morska voda; FW-slatka voda; N-nitrogen; LBOG-tekući BOG, GCU – jedinica za izgaranje plina

The cycle of the liquefied medium is realized according to the following procedure:

- LNG vapours from cargo tanks are directed to a pre-cooler where they are initially cooled by the already condensed medium. Its presence enables maintaining a constant temperature of the medium at the discharge of BOG compressors and additionally it plays the role of a separator separating LNG droplets from its vapours in this way protecting the compressor from its "wet" operation. LNG vapours are cooled here from the temperature of –100 °C to –120° C.
- Subsequently they get into one of the two double-stage centrifugal BOG compressors. Their operation is controlled by the pressure signal from cargo tanks. In the case when one compressor is unable to ensure sufficient pressure in the tanks, automatically the second one is put into operation.
- Compressed boil off gas is directed to a cryogenic multi-pass heat exchanger with a separator (Coldbox) where it is cooled down and liquefied. The heat from BOG is absorbed by the refrigerant – nitrogen.
- In the separator the liquefied gas is separated from the uncondensed one which is directed to GCU (Gas Combustion Unit), while LBOG goes to LNG transport pumps.
- Transport pumps of variable capacity (supplied by an inverter) are controlled by the signal of the level of liquid in the separator. In the case of an insufficient flow, the LNG pump may work in the on- and off- mode, whereas in the case when the capacity of one pump is insufficient another one is switched into operation. The pumps direct LNG back to cargo tanks.

Fig. 2 in a simplified way shows the cycle of the refrigerant. It does not comprise nitrogen supplying BOG compressor sealing and the installation maintaining the amount of nitrogen at a sufficient level – supplementing nitrogen losses in the installation. The most important equipment of the loop is the compander , a combination of a multi-stage centrifugal compressor and a single-stage expander. The loop of the refrigerant looks as follows:

- The refrigerant is compressed throughout the three stages of the centrifugal compressor with the inter-stage cooling with fresh water in the coolers placed between the first and the second stage and also between the second and the third stage of the compressor.
- Behind the third stage the refrigerant cooled in the subsequent cooler and in the cryogenic heat exchanger is directed to the expander. At the same time only one compander can be in operation.
- The expanded nitrogen reaches the heat exchanger where the heat is absorbed from LNG vapours and their liquefaction takes place.
- The cycle gets closed when the refrigerant is once again directed to the suction of the first stage of the compressor. The required amount of nitrogen in the loop is maintained thanks to a nitrogen reservoir placed in the installation.

The cooling water system consists of two basic loops – that of sea water and of fresh water. The pumped sea water flows through one of the two heat exchangers (in Fig 2 only one is shown) absorbing heat from fresh water and then it is directed overboard. Fresh water, on the other hand, circulates in a closed circuit flowing through the oil cooler of the BOG compressors, oil coolers of companders, compander inter-coolers and it cools the driving engines of these machines. The installation also comprises an expansion tank (not shown in Fig. 2). In order to simplify the installation diagram, Fig. 2 only shows a part of the fresh water loop.

Most of the equipment in the installation was doubled. The doubled machines operate alternately, for example the sea water pump nr 1 is the master pump and the pump nr 2 is at stand-by waiting at the "hot reserve" and it gets into operation in the event of faults in pump nr 1. Such a solution increases the redundancy of the system and additionally enables the servicing of particular pieces of equipment without the necessity to stop the whole installation.

4. INSTALLATION ENERGY ANALYSIS / *Analiza instalacije energije*

All the equipment indispensable for correct operation of the liquefaction installation require to be supplied with a definite flow of energy. Its identification is necessary to asses both the efficiency and profitability of the operation of the reliquefaction plant. Assuming nominal conditions of LNG evaporation from the tanks and thus the nominal conditions of installation operation, electrical energy flows supplied by the ship power plant have been analyzed and listed in Table 1 [8].

The most energy–consuming piece of equipment is the compander. The required values of power for the other pieces are comparable, however, even the BOG compressor power is not nearly as high as the required power of the nitrogen compander. Thus, it is apparent that the energy flow necessary for the nitrogen loop is the biggest. The pie diagram presents energy consumption in the described cycles in percentages.

Table 1 Nominal driving power required by the equipment of LNG reliquefaction plant
Tablica1. Nominalna porivna snaga koja se zahtjeva opremom LNG postrojenja za ukapljeni plin

Item number	Machine name	Number of machines in the installation	Number of operating machines	Nominal power of driving engines
1	Sea water pump	2	1	170 kW
2	Fresh water pump	2	1	220kW
3	Compander	2	1	5400 kW
4	LNG pump	2	1	4 kW
5	BOG compressor	2	1	460 kW
			TOTAL =	6254 kW

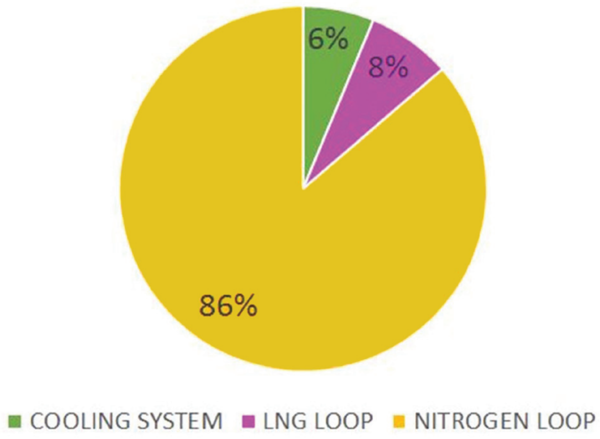

Figure 3 Electrical energy required by different cycles
Slika 3. Potrebna električna energija prema ciklusima

The total power of the ship power plant is in the case of the discussed gas carrier of the Q-Flex type equal to the sum of electrical power values of five current generating units and equals to 16800kW. The requirement for electrical energy in nominal operational conditions coming from the reliquefaction installation which is the sum of power values of all pieces of equipment taking part in the liquefaction process is equal to 6254 kW. Thus, it shows that the electricity requirement of this installation exceeds 37% of the total output of the ship power plant which is equal to the operation of two generator sets with a 93% load. In the case when LNG evaporation conditions deteriorate (unfavorable hydro meteorological conditions, insufficient tank cooling before loading) and when the amount of BOG increases, the second compressor may be switched into operation which will cause a slight increase in the electrical power requirement. In such a case, the power necessary to carry on the process of reliquefaction and thus maintaining the correct pressure in cargo tanks will be equivalent to the operation of two generator sets at a 99% load. Obviously a situation like this is unacceptable and the automatic Power Management System will switch on another set.

5. THE POWER SYSTEM OF A REFERENCE LNG CARRIER / *Sustav napajanja određenog LNG broda*

Fig. 4 presents a simplified diagram of a power system with a ship power plant of a conventional LNG carrier assumed as reference. It is used on LNG carriers with a steam turbine power system and cargo tanks in the range between 120,000 to 160,000 m^3 [9]. At the moment, vessels of this kind comprise the most numerous group of LNG carriers in operation. Their share in the fleet is at present equal to around 64 % with the foreseen decrease to about 50% in the year 2020 [2].

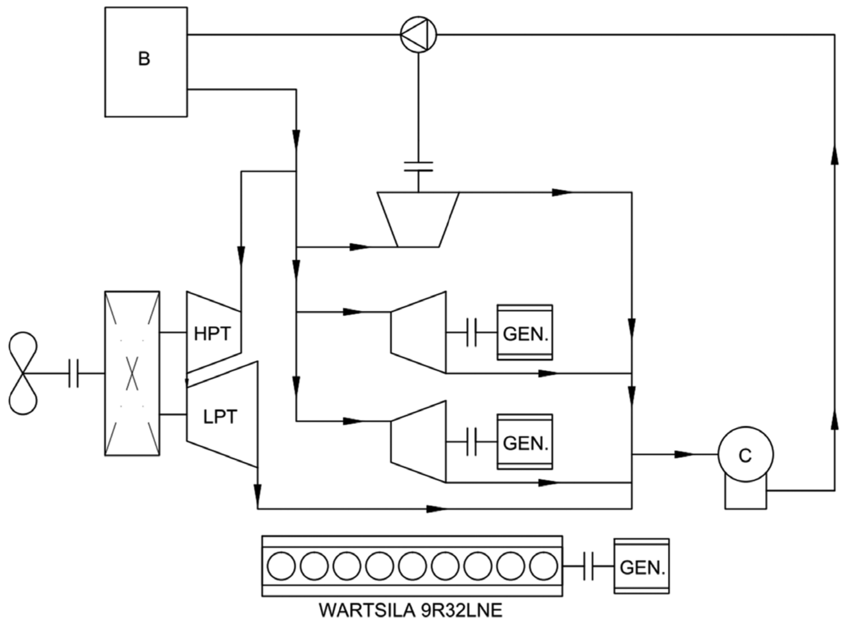

Figure 4. A simplified diagram of the main power system and the ship power plant of a conventional LNG carrier C – condenser, B – main boiler, HPT – high pressure turbine, LPT – low pressure turbine
Slika 4. Pojednostavljeni dijagram glavnoga porivnog sustava I brodskog postrojenja konvencionalnog LNG prijevoznika C-kondenzator, B-glavni kotao, HPT- turbine visokog tlaka, LPT- turbine niskog pritiska

The propeller of the steam turbine conventional gas carrier is powered by a double-body steam turbine unit with a cumulative transmission gear supplied with overheated steam from the main boilers. The same overheated steam also supplies auxiliary turbine generator sets and turbines driving boilers feeding water pumps. In order to simplify the diagram, Fig. 4 only shows one main boiler and one feeding pump (although there are always two). The used steam finishes the cycle in the main condenser (with negative pressure) from which it is pumped again to the boiler. The diagram also does not show some of the less important elements of the installation.

A representative example of this type of power plant is the application of the main steam turbine unit, Kawasaki UA-400 of the nominal power equal to 29000kW and Shinko RG92-2 turbines of 3450 kW driving generators supplying the power network of 6.6 kV, 60 Hz. Additionally in the ship power plant there is a generator set with a medium-speed diesel engine, manufactured by Wartsila, driving a generator of 3450 kW [7].

There is a significant difference in the power of ship power plants on both types of discussed LNG carriers. The total power of the electric power plant of the conventional LNG carrier is equal to almost 62 % of the power of the ship power plant of the LNG carrier of the Q-Flex type. It turns out that at voyage with load, when boilers are supplied only with the naturally boiled off cargo LNG, electrical energy is generated solely by one turbine generator and its load does not exceed 1600 kW. Hourly gas consumption in the boiler may be estimated for 6.3 t/h [7].

6. CONLUSIONS / *Zaključci*

At a sea voyage of an Q-Flex type LNG carrier with LNG reliquefaction, the load on the power plant will be much bigger than for a conventional LNG carrier. Summing up the power of the equipment for liquefaction with the power of the most important machines operating in a continuous way at a voyage, such as all types of pumps (for example those of cooling water, oil circulation), air conditioning compressors, seperators – the load on the power plant can be estimated to exceed 7,600 kW. This value corresponds to about 75 % load on three current generating units. Assuming the specific fuel oil consumption of auxiliary engines to be equal or close to 190g/kWh, then their hourly fuel consumption is about 1444 kg, whereas fuel consumption of the engines from the main power at a specific fuel oil consumption of 162.8 g/kWh at 85% engine load of the Maximum Continuous Rating (2x 14914 kW) is equal to 4856 kg [8]. As a result the total hourly fuel consumption of marine diesel oil for propulsion and electric power generation is close to 6.3 t/h.

The presence of the reliquefaction plant “enforces” the operation of two additional electrical energy sources and the energy consumption on the ship can be over five times higher. It is connected with additional amounts of fuel used for the needs of this installation. In a general balance the amount of fuel used for generating energy to liquefy the gas comprises about 23 % of the total ship daily fuel consumption. Especially high requirement for electrical energy coming from the reliquefaction plant makes the Q-Flex type LNG carrier power plant very developed.

The total power of the conventional gas carriers ship power plants is much lower than that of the Q-Flex one. Energy-consuming properties of the reliquefaction installation cause that at laden voyage the power plant load exceeds 7600 kW, which requires the consumption of 1.4 t of fuel per hour in the engines, whereas the load on the power plant in the conventional LNG carrier does not exceed 1600 kW.

The specifics of operational states of LNG carriers of the Q-Flex type requires a particularly careful configuration of the ship power plant with the view of its rational usage. At the same time there is a question whether it makes sense to install a system for waste energy utilization on this type of ships. Application of a steam utilization turbine may have a positive effect on the total energy balance of operational states of LNG carriers of the DRL type [4].

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