



SELECTED PROBLEMS OF BOIL-OFF GAS UTILIZATION ON LNG CARRIERS

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Abstract

Heat inflow to a cargo of liquefied natural gas (LNG) from the surroundings causes generation of vapours called boil-off gas (BOG) and thus an increase of a vapour pressure in cargo tanks. The paper discusses selected issues related to handling of boil-off gas on LNG carriers. Presented are general conditions permitting vapour pressure increase during the voyage, conditions enabling its venting and burning in gas combustion units (GCU, thermal oxidizers). Particular attention is given to BOG utilization as a fuel in steam or gas turbines or reciprocating engines. Presented are general comments on selection criteria for choosing a solution of LNG carrier propulsion system. Attention is drawn to an increase of possibilities of heat recovery from exhaust gas from Diesel engines and gas turbines. This is due to a lowering of exhaust gas dew point temperature thus deeper cooling of the exhaust gas in exhaust gas boilers is possible. This enables production of larger quantities of steam which can be directed to auxiliary steam turbine and as a result increasing the efficiency of the ship's energy system. The paper also addresses the specifics of fuel installation operation on ships utilizing LNG vapours as a fuel.

Keywords: *engine room, LNG carrier, boil-off gas, gas burning, exhaust gas heat recovery*

1. Introduction

An evaporation of liquefied natural gas (LNG) during transport resulting from heat inflow from the surroundings causes an increase of the vapour pressure in the cargo tanks. In the case of gas carriers transporting fully refrigerated or semi-pressurized cargoes, it is necessary to maintain strict control of LNG temperature and vapour pressure throughout the voyage. The most straightforward way of coping with generated vapours, called boil-off gas (BOG), is to accept pressure rise within cargo tanks. Under certain conditions it is also possible to vent an excess of BOG to the atmosphere or to burn it in a gas combustion unit (GCU, called also thermal oxidizer), but this is obviously loss of cargo. Common practice is to utilize BOG as a fuel for ship's engines and several years ago, in the case of the largest LNG carriers transporting cargo over long distances, re-liquefaction has been put in place.

2. Conditions permitting vapour pressure increase during voyage

An acceptance of vapour pressure increase inside cargo tanks is possible provided that the increased pressure can be accepted by the receiving terminal. Such a solution is sometimes used in the case of small distribution terminals which utilize pressure tanks for LNG storage. Minimal design pressure of such tanks ranges from 0.371 to 0.400 MPa, depending on the material used in their construction. Spherical tanks of Kværner Moss Rosenberg system are able to withstand pressure of abt. 0.9 MPa [11], however, their maximal allowed operational pressure equals 125 or 170 kPa.

Fig. 1 shows the results of a simulation of vapour pressure increase caused by vapours accumulation in closed type C tank fabricated from nickel steel (9% Ni) or stainless steel (AISI 304L).

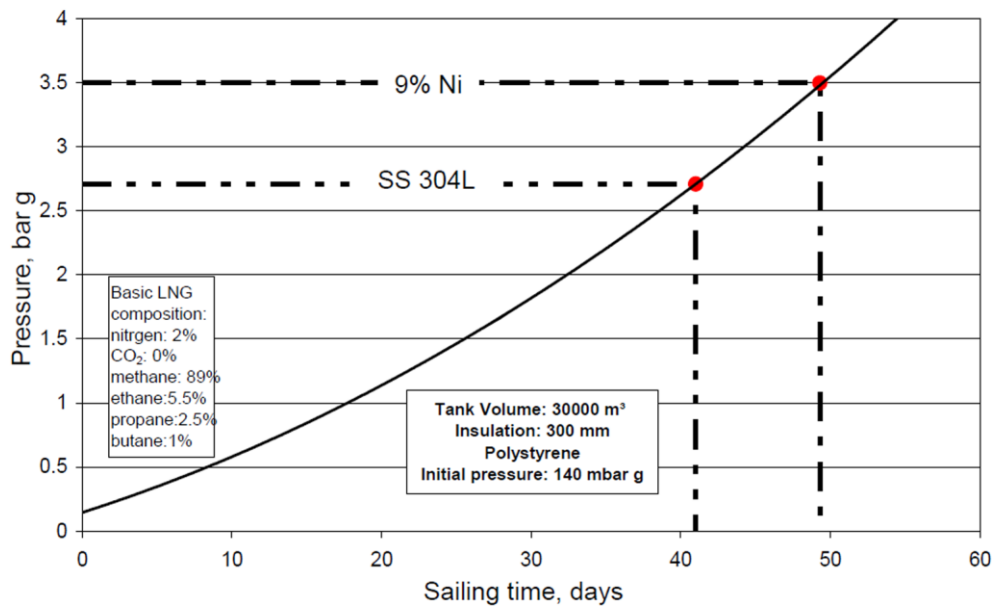


Fig. 1. Results off simulation of vapour pressure increase in closed type C tank caused by LNG evaporation [12]

The results indicate that during the first ten days tank pressure will increase only by less than 0.05 MPa (0.5 bar) and the design pressure of the tank fabricated from AISI 304L [i.e. 0.371 MPa (2.71 bar g)] will be reached in 41st day of the voyage.

In the case of short voyages on ships equipped with pressure tanks there is no need to install additional equipment to cope with the BOG excess. For example two very small LNG carriers with cargo capacity of 2500 m³ engaged in coastal shipping in Japan are not equipped with any BOG handling system [2, 7]. Another two vessels are operating in coastal waters off Norway.

3. Venting of boil-off gas to the atmosphere or burning in the gas combustion unit

In order to maintain the pressure on required level, BOG can be vented to the atmosphere or burnt. The decision to choose the appropriate method depends on many primarily economical and legal factors. For example some regulations may prohibit venting or burning BOG in certain areas. In most areas in the vicinity of ports and within ports venting of toxic or flammable cargo vapours is in fact prohibited.

Notwithstanding the regulations, in good operational practice venting to the atmosphere should be avoided as far as possible. Under no circumstances venting should take place on territorial waters. However, if this is necessary, venting should be carried out with due regard to safety.

In such a case it is essential to enable quick dispersion and dilution of outgoing vapours so their concentration in the atmosphere drops below lower flammable limit.

The temperature of the vented vapours is lower than the dew point temperature of the ambient air (Fig. 2). This leads to the formation of clouds of condensed water vapour, which is heavier than air, while the cargo vapours might be lighter [5]. As a result there may be difficulty in determining the direction of movement of cargo vapours escaping the vent mast. If the vapour temperature would be lower than abt. $-110\text{ }^{\circ}\text{C}$, vapours after leaving the vent would descend and at certain relative wind velocity vector could accumulate on ship's deck and flow into ventilation openings of superstructures. Thus, at low relative wind speed, venting operation might have to be ceased. Furthermore, air turbulences may promote formation of vapour pockets on the leeward side of the superstructures. In this case, in order to facilitate vapours dispersion, a course or speed alteration may be required. Normally LNG carriers are fitted with a heater to warm up vented BOG thus decreasing its density which facilitates quicker dispersion after leaving the vent outlet.

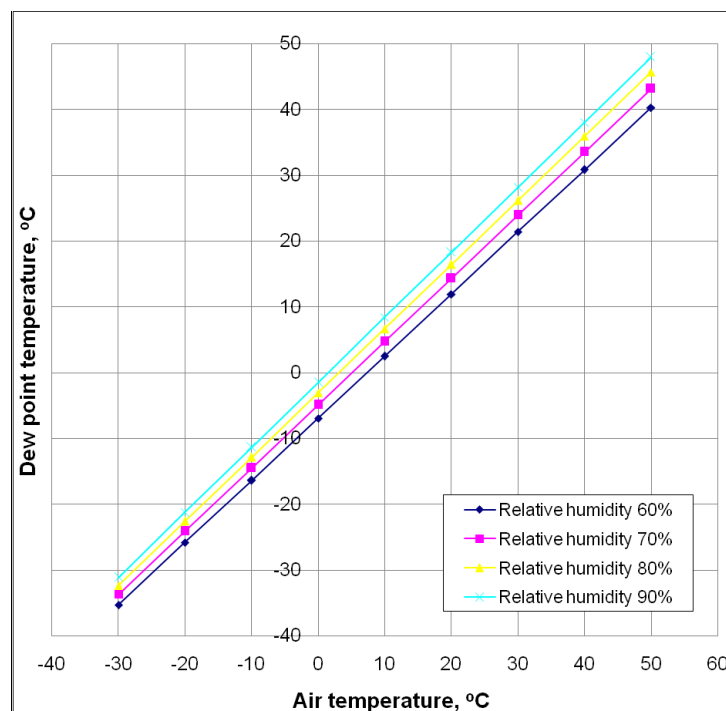


Fig. 2. Dew point temperature of atmospheric air

According to a safety management system (required by ISM Code¹) of one of the shipowners venting is permitted only during daytime, when relative wind speed exceeds 10 m/s, visibility is good, and there is no traffic in the vicinity. All the ventilation fans within gas hazardous zones shall be constantly turned on in order to disperse any potential vapour pockets. In any case when cargo vapours may be present on deck, air conditioning system should be switched in re-circulation mode. Venting should be discontinued for the time of electrical storms. Furthermore, during venting operation no work should be carried out on deck which could create a spark, i.e. rust removal, hammering or use of power tools [5].

If the increase of the vapour pressure is unacceptable, an excess of the BOG may be burnt in specially provided device – gas combustion unit [GCU, also called thermal oxidizer or combustor]. Although it is a total waste of potential fuel, such a solution may turn out to be economically justified, particularly for short passages. To improve the economics, part of the BOG

¹ International Standard for the Safe Management and Operation of Ships and for Pollution Prevention.

may be utilized for example in oil heaters for heating purposes and above all, LNG vapours may be used as a fuel for main and auxiliary ship's propulsion systems.

4. Utilization of boil-off gas as a fuel

An important factor influencing authorization of use of BOG as a fuel is fact that it consist mainly of methane and thus is lighter than air in ambient temperature. This enables safe handling of BOG because in the case of a leakage in the engine room, BOG can escape through ventilation openings outside the engine room and is not going to accumulate on its bottom. Therefore, LNG or more precisely its vapours are the only cargo permitted by IMO to be used as a fuel on board ships [2].

Traditionally on the great majority of LNG carriers BOG has been burnt in boilers in order to produce steam supplying a turbine. For over 50 years steam turbine has been, with a few exceptions, the sole means of propulsion on LNG carriers. Due to the simplicity of burning BOG in boilers and high reliability of steam turbine propulsion, this solution were maintaining its unwavering position, which in other sectors of shipping has long been lost to motor propulsion. Gradual loss of the primacy of this propulsion solution over other solutions on LNG carriers is a result of its relatively low energy efficiency, which translates into a negative impact on operating costs. This factor plays an increasingly important role in today's shipping, particularly in the LNG sector. It should be noted that the cargo capacity of LNG carriers since about a decade has been increasing. In the recent years cargo capacities of these vessels increased from 145000 to 266000 m³ together with the increase of shipping distances. This is related to economies of scale - an increase of cargo quantity shipped at a time allowed to lower unit transport costs. Also a price of natural gas has risen significantly. These circumstances led to a need to verify the design and technical solutions applied on this type of ships.

An attractive alternative to steam turbine propulsion must be at least comparable in terms of reliability and safety. Additionally, it must be superior in terms of energy efficiency and be less burdensome for the environment. Fig. 3 presents available power and efficiency ranges for various propulsion system solutions for LNG carriers.

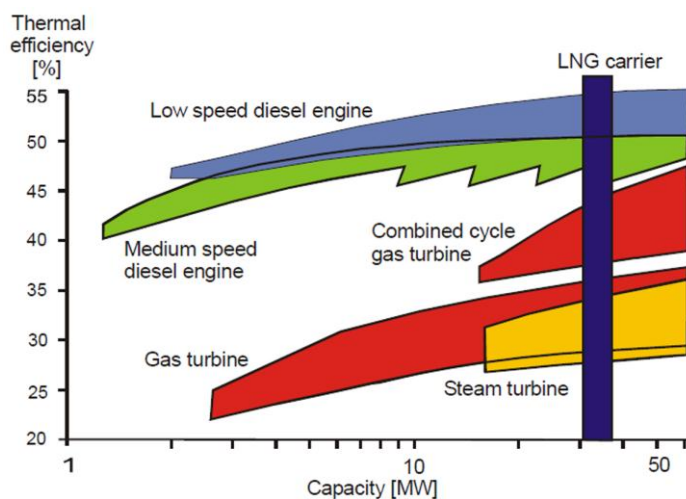


Fig. 3. Power and efficiency ranges for various propulsion systems of LNG carriers [8]

As an alternative to steam turbines on board LNG carriers, several years ago Diesel-electric propulsion system with medium speed dual-fuel engines as well as low speed Diesel engines together with BOG re-liquefaction plant were introduced. In total they already cover over a half of shipbuilding orders in the LNG sector. Two other solutions – low-speed dual-fuel Diesel engine

and gas turbine are making their way to the commercial application. Also a new generation of steam turbines improved their competitiveness through an increase of the efficiency thanks to the introduction of inter-stage steam superheating. Furthermore, after the successful debut of Diesel-electric propulsion system, gas turbine electric system gained on the interest.

5. Factors influencing decision about selecting propulsion system solution for LNG carrier

A decision concerning selection of propulsion system type of LNG carriers is not simple. One of the reasons for the particular complexity of the problem is an intention for the most useful BOG utilization within ship's propulsion system and system producing electric power, which is in high demand on board LNG carriers due to the presence of electric-powered cargo pumps. Another reason is complex evaluation of the economic efficiency of possible solutions, which takes into account both capital expenditures and operating costs to be incurred in the lifetime of the ship. It is important to bear in mind the diversity of conditions in which the ship's energy system is going to be operated. Most of the LNG carriers before the construction begins are already assigned to a particular transport project with a specified sailing route. Therefore the differences in traffic intensity, length of passages, typical sea and air temperatures and forecasted sea states etc. should be taken into account. Selection of a given solution should be preceded by an analysis of the potential system taking into account uncertainty factor with due regard to the design cargo capacity, voyage conditions and environment protection regulations of countries and ports of call as well as other specific technical requirements. The propulsion systems of LNG carriers are closely connected with BOG handling method. It is therefore reasonable that the considerations regarding the selection of a type of propulsion system cover also a method of electric power generation and BOG handling. An analysis of possible propulsion systems solutions of LNG carriers has been presented *i.a.* in [1].

One of the criteria used for classification of propulsion systems of LNG carriers is the adopted method of BOG treatment/handling. The main division is dependent on whether the BOG is recovered through re-liquefaction or utilized as a fuel. In the latter case it can be burnt simultaneously with fuel oil in dual-fuel systems or separately (Fig. 4). At the same time apart from the natural (i.e. naturally evaporated) BOG, in order to achieve the required power output there is usually a need to force a vaporization (in a dedicated vaporizer) and then burn an additional amount of LNG (so called forced BOG). Studies carried out by several authors have shown that forcing vaporization may be economically justified [4, 6, 9]. The forced BOG is less expensive than conventional liquid fuels (Fig. 5).

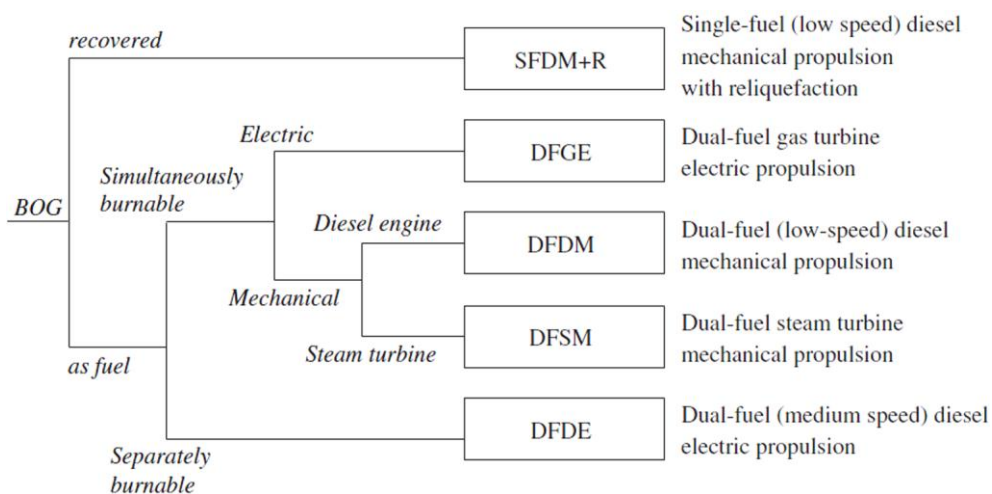


Fig. 4. Classification of LNG carrier propulsion systems in terms of BOG utilization [based on 3]

Moreover the LNG from which BOG is generated is lighter than oil, so the weight of required bunker fuel is reduced which enables to carry more cargo at the same displacement [9]. In the case of a gas turbine propulsion volume of the machinery space is also reduced.

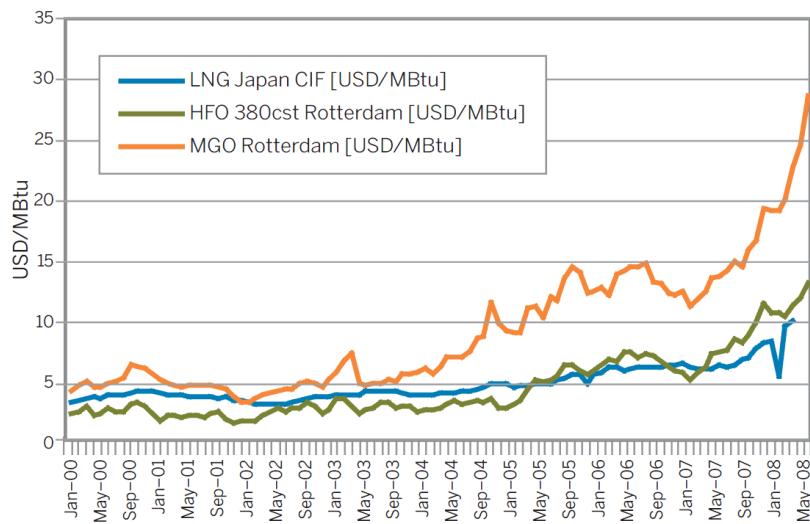


Fig. 5. Price of fuel types used on LNG carriers in years 2000-2008 [6]

The use of only natural and forced BOG as a fuel is characterised by exceptionally low emission of harmful exhaust gases (according to Wärtsilä the reduction is 10-fold compared to the amount of emissions from low-speed Diesel engines fuelled by liquid fuel [9]. In the open sea BOG may constitute main fuel, although it is required to supply also some amount of fuel oil as a pilot fuel. In the case of chartered voyages the way of BOG handling/utilization and fuel usage is usually defined by the charterer.

It should be noted that the use of natural gas as a fuel, particularly in Diesel engine or gas-turbine propulsion, offers great opportunities of exhaust gas heat utilization. A significant limitation of heat recovery capabilities in ships' energy systems utilizing especially heavy fuel oils with relatively high sulphur content is high dew point temperature of exhaust gases. Its average value in ships' conditions is shown on Fig. 6.

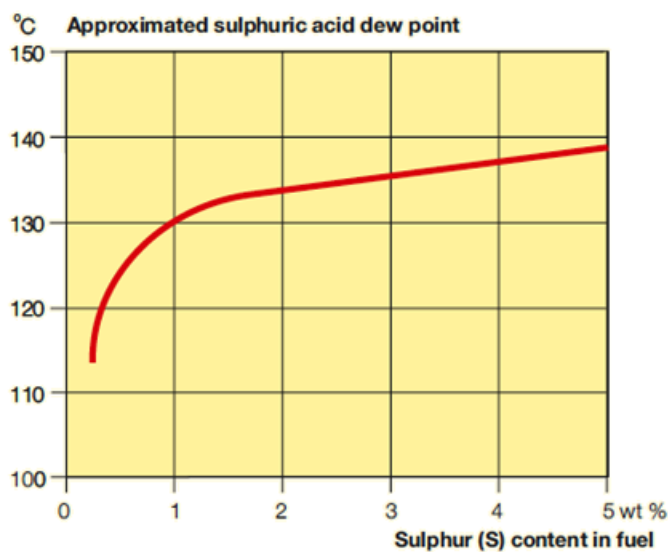


Fig. 6. Dependence of the approximate exhaust gas dew point temperature on fuel's sulphur content [10]

In the case of combustion of natural gas having trace sulphur content, dew point temperature is close to the values shown on Fig. 2. This enables fitting of condensing boilers as it is in the case of land-based heating systems. Theoretically, it becomes possible to increase twice heat utilization of exhaust gas stream. In many cases, despite having to solve additional technical problems, it may be economically justified to apply steam turbogenerator, thanks to which the energy system's efficiency will increase and the emission of toxic compounds from auxiliary engines will reduce.

6. Specifics of fuel installation

The presence of high-pressure gas in a machinery space constitutes major technological challenge and serious safety hazard. According to newly developed provisions of American Bureau of Shipping (ABS), in the case of a gas leakage within machinery space, an alarm shall activate if gas concentration will reach 30% of lower explosive limit (LEL) and propulsion system shall turn off if concentration will reach 60% of LEL [9]. The criteria are even more rigorous in the case of a gas turbine – the alarm shall activate at 5% of LEL with simultaneous switching to liquid fuel mode and at 10% of LEL the machinery space shall be closed down. In order to prevent gas leakage, in the case of DFDE (medium speed Dual Fuel Diesel Electric) and DFDM (low-speed Dual-Fuel Diesel Mechanical) propulsion systems, fuel supply installation shall be fitted with double-walled pipes.

Gas fuelled engines can be operated by engineers with ordinary Diesel engines experience who have undergone additional training [8].

In order to ensure stable gas supply of Diesel generator sets on ships with electric power transmission in normal operating conditions at sea, natural BOG is sent to the sets by means of a compressor through a gas heater. The flow rate is controlled by appropriate adjustment of the compressor's capacity. If for some reason the BOG cannot be used by generator sets' engines or if the available BOG quantity exceeds the demand, the excess of BOG may be burnt in GCU.

Normally BOG before sending to the engine room is heated and compressed to the required pressure dependant on the working parameters of the fuel supply system, sometimes it is also odorized. Higher gas temperature promotes better combustion conditions and in the case of a gas leakage gas can escape from the engine room more quickly. Moreover warmed gas may be transported in pipelines which do not have to be made of special steel resistant to low temperature.

The absolute pressure in the cargo tanks' ullage space equals at least 111 kPa and is generally sufficient to ensure its stable free flow from cargo tanks' gas domes to demister (mist separator) and then to (turned off) compressor(s) followed by boil-off warm up heater and through main control valve (also called master fuel gas valve) to the boilers' burners in the engine room [10]. In the case of too low tank pressure, low-duty compressor can be turned on to facilitate stable flow rate. During the voyage, in order to take full advantage of the available BOG quantity and to relieve the boilers, BOG demand should be controlled by speed alterations of the ship. If the BOG quantity is insufficient, special pumps pump required amount of LNG to the vaporizer, where it is turned into BOG and then directed to the demister and warm up heater and finally to the boilers. The whole operation of the forced LNG vaporization installation is automatic.

7. Conclusion

The specificity of gas carriers is the increase of vapour pressure in cargo tanks caused by heat transfer from the surroundings into the cargo. There are various techniques used to cope with generated BOG. In the case of large carriers transporting LNG over long distances, if re-liquefaction is not put in place, BOG except being vented (what often may be prohibited) may be burnt in the boilers or combustion engines. In the latter case noteworthy is the possibility

of better exhaust gas heat recovery by on-board waste energy utilization systems, what combined with lower price and weight of LNG reduces transport costs.

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