

LNG systems for natural gas propelled ships

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Abstract. In order to reduce the atmospheric pollution generated by ships, the International Marine Organization has established Emission Controlled Areas. In these areas, nitrogen oxides, sulphur oxides and particulates emission is strongly controlled. From the beginning of 2015, the ECA covers waters 200 nautical miles from the coast of the US and Canada, the US Caribbean Sea area, the Baltic Sea, the North Sea and the English Channel. From the beginning of 2020, strong emission restrictions will also be in force outside the ECA. This requires newly constructed ships to be either equipped with exhaust gas cleaning devices or propelled with emission free fuels. In comparison to low sulphur Marine Diesel and Marine Gas Oil, LNG is a competitive fuel, both from a technical and economical point of view. LNG can be stored in vacuum insulated tanks fulfilling the difficult requirements of marine regulations. LNG must be vaporized and pressurized to the pressure which is compatible with the engine requirements (usually a few bar). The boil-off must be controlled to avoid the occasional gas release to the atmosphere. This paper presents an LNG system designed and commissioned for a Baltic Sea ferry. The specific technical features and exploitation parameters of the system will be presented. The impact of strict marine regulations on the system's thermo-mechanical construction and its performance will be discussed. The review of possible flow-schemes of LNG marine systems will be presented with respect to the system's cost, maintenance, and reliability.

1. Introduction

One of the most important challenges of the modern world is the reduction of air pollution. The combustion of fuels for transportation purposes is considered to be one of the major sources of air pollution from non-natural sources. In 1997, the International Marine Organization (IMO) adopted annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) which limits the main air pollutants contained in ships' exhaust gas, especially nitrous oxides (NO_x) (Regulation 13) as well as sulphur oxides (SO_x) and Particulate Matter (Regulation 14) [1]. Figure 1 presents the emission limits set by the MARPOL Annex VI, revised in 2008. This same revision established the Emission Control Area (ECA) which presently covers waters up to 200 nautical miles from the coast of the US and Canada, the US Caribbean Sea area, the Baltic Sea, the North Sea, and the English Channel where the pollution emission of SO_x is much more restricted than in other nautical areas. The future extension of the ECA to the Mediterranean Sea as well as to sea coasts along Norway, Mexico, Japan and Singapore is under consideration.



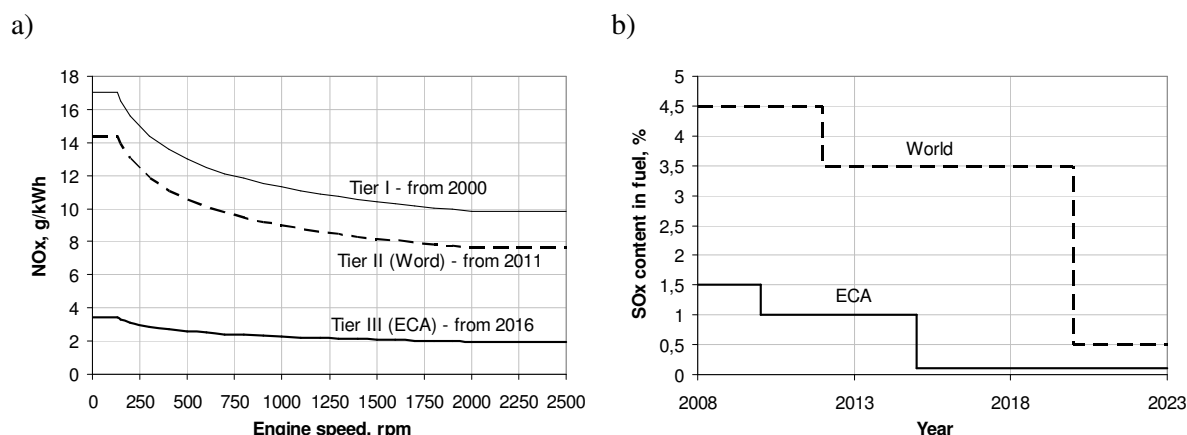


Figure 1. a) NO_x emission and b) SO_x content in fuel limits for ships in acc. with MARPOL Annex VI.

Most of the presently used marine fuels fulfill the MARPOL Annex VI Tier II NO_x emission limits. However, compliance with Tier III requires lowering the fuel combustion temperature or using Exhaust Gas Recirculation systems [2]. In both cases, engine efficiency is reduced which incites operational costs for the ship. The second NO_x reduction technique, commonly used in onshore industry and transportation, is Selective Catalytic Reduction (SCR). However, this technology for use on ship engines is still under development.

In order to meet the requirements of the MARPOL Annex VI SO_x emission limits with both commonly used and relatively inexpensive Marine Diesel Oil (MDO) or Marine Gas Oil (MGO), the exhaust gas can be treated with scrubbing technology. Although this technology is well developed, its application on the ship has a lot of disadvantages: the ships' hull volume consumption, increase of the ship's deadweight, ascension of the ship's center of gravity (reduction in ship stability), as well as the need for storage and handling of washwater (wet scrubbers) or consumables (dry scrubbers) [2]. One option for the scrubber technology is found in using fuels with low sulphur content. Low Sulphur Diesel Oil (LSDO) is known as a trouble-free fuel and can be used with traditional engines after minor modifications to the fuel system. However, the price of LSDO and its present market availability are the main issues. Some low-sulphur hybrid fuels which are much cheaper and comparatively priced to MDO/MGOs are under development and presently offered by a few gas companies. However, the particular fuel type is available only in limited global areas. This, together with the necessity of major modifications to the fuel system for compatibility and the illicit mixing of hybrid fuels with distillate oils (MDO/MGO), strongly constrains a ship's sailing range [2]. A prospective alternative for meeting MARPOL Annex VI emission limits is found in natural gas, which is stored on board in LNG form. Its burning product contains 25% lower CO₂ and 85% lower NO_x emission values than the MDO/MGO, and it is not comprised of any SO_x or PMs either. LNG combustion in gas engines has proven to be reliable technology in onshore applications. The fast development of gas-Diesel dual-fuel engines for marine applications has been observed over the last few decades - by the end of 2014, up to 1,000 dual-fuel engine-driven vessels are estimated to have been under operation [3]. In addition, LNG is widely available all over the world. Its price is comparative to MDO/MGO and is expected to drop in coming years. Using LNG as fuel requires the installation of an extensive, independent, and relatively complex and dangerous (explosive risk) system, which would increase the cost of the propulsion system by 30%. In addition, due to the energy density of LNG being much lower than that of marine oils, the consumption of the hull volume by the gas fuel system, especially by LNG tanks, increases significantly. Moreover, at present, the LNG chain and infrastructure for LNG bunkering is still in the early stages of development, which increases LNG fuel delivery costs. Despite these disadvantages,

LNG is still considered to be ecological and economical fuel for present and future marine propulsion applications.

2. Dual-fuel (gas-Diesel) engines

The gas fuel design is strongly determined by the dual-fuel engine type. There are two types of engines: high-pressure, Diesel cycle type and low-pressure, Otto cycle type.

In the high-pressure engine the combustion air is compressed first, then the gas is injected to the cylinder. Next, the air-gas mixture is ignited by pilot liquid fuel (diesel) injection. In low-pressure engines, gas and air are mixed before compression, and as with high-pressure engines, the combustion of the compressed mixture is initialized by pilot fuel injection [4].

High-pressure dual-fuel engines require the supplying gas pressure to be as high as 250-300 bar, while minimum gas pressure for low-pressure engines need 5-7 bar only. An additional disadvantage of high-pressure engines is found in their required necessity of switching to pure oil fuel when operating at lower than 15-20 % of the engine load. Due to this, maintaining low emission limits in ports or close-to-shore areas becomes challenging.

In the case of low-pressure engines, the pilot fuel constitutes about 1% of the total energy and is quite constant over the whole range of operations, so high emission with low engine loads is not an issue[4]. On the other hand, low-pressure engines are at risk of unintended (knocking) ignition, which results in the strong reduction of engine power or even engine element destruction [5]. In order to avoid such combustion conditions, the ratio of combustion air excess is increased to the 2.0-2.2 range, and in the gas fuel mode, the engine operates at just up to 80% of its power.

3. Fuel gas system LNG tank types

There are two types of LNG tanks: integral with and independent of the hull structure [6].

In the case of integral tanks, only membrane type tanks are accepted for LNG storage. Such tanks are non-self-supporting tanks which consist of a thin layer (membrane) supported through insulation by the adjacent hull structure. Their Maximum Allowable Working Pressure (MAWP) is normally lower than 0.25 bar g, but if the hull structure is properly designed, the MAWP can be increased to 0.7 bar g. Because they are adjustable to hull shape, the ship's hull volume fulfillment is very effective. The membrane tanks offer very large LNG storage capacity: from 100 to 20,000 m³.

There are three categories of independent, self-supporting tanks: A, B and C. The A-type tanks are designed using the classical ship-structural analysis procedure. Due to the possibility of gas leakage in the case of a break in the tank structure, A-type tanks are required to have a full secondary barrier which is capable of collecting the leaking gas and transferring the gas vapor to a controlled area. As the design procedure is identical to the ship's structure, similarly to the membrane tanks, the MAWP is normally 0.25 bar g, or in the special design, up to 0.7 bar g. Comparable to the membrane tanks, A-type tanks can be well-fitted to the hull structure, but as they hold an independent support structure, the hull volume fulfillment effectiveness is slightly lower.

B-type tanks are similar to A-type tanks in MARP, but they are designed using model tests, refined analytical tools and methods of analyses to determine stress levels, fatigue life, and crack propagation characteristics. With such an approach to design, only small tank structure cracks and small gas leaks are expected. Therefore, only a partial secondary barrier, in the form of a drip tray to protect the hull structure against low temperatures, is required.

C-type independent tanks are tanks with an MARP higher than 0.7 bar g. Therefore, they are considered to be pressure vessels. Usually, the shape of C-type tanks is cylindrical (as gas transport vessels), but the variety of cross section shapes, which can be found in a number of implementations, ultimately increase the ship's hull volume fulfillment. An additional disadvantage of this type of tank is found in the LNG storage volume, which is presently limited to 500-600 m³. Nevertheless, future projects with C-type tanks with storage capacities up to 2,000 m³ are under consideration. The most important feature of C-type tanks is that they can not only be installed in new ships, but can also be

used for upgrading existing ships with fuel gas systems. In this case, LNG vessels are located at the ship's upper deck.

4. Fuel gas systems

Figure 2 presents different fuel gas system solutions [7]. As can be observed, no matter the system type, it is necessary to withdraw the liquefied gas from the vessels and warm it up to room temperature in a vaporizer (VAP) with the use of a glycol-water (WG) brine. An additional task of the gas fuel system is the compression of gas to the pressure required by the ship's engines.

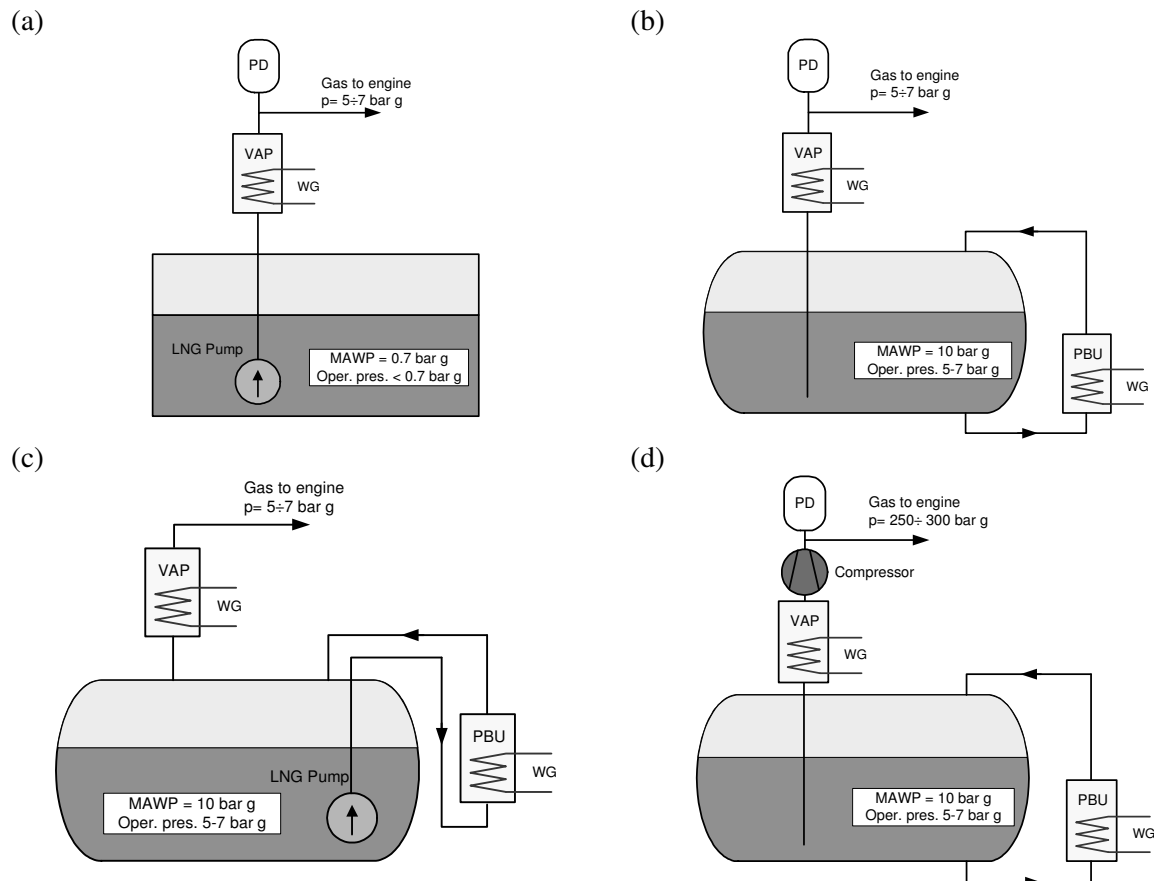


Figure 2. Different schemes of the gas fuel system - see description in the text, VAP - vaporizer, PBU - pressure built-up unit, WG- water-glycol brine, PD - gas pressure pulsation dumper

In non-pressure vessels (membrane type, A-type and B-type tanks), gas compression can be fulfilled with the gas compressor installed after the VAP, or as presented in figure 2(a), with the LNG centrifugal pump located inside the tank. Exploitation costs for the scheme with the LNG pump are lower, but the complexity of such a system, especially the installation of the pump inside the tank, is much higher. Thus, the system production costs are also higher. When the compression device is used, a gas pressure pulsation dumper (PD) needs to be considered to avoid high pressure variation at the engine inlet.

Figure 2 (b) represents the gas system with the pressure vessel. Such a scheme allows the compression of the fuel gas inside the LNG tank to reach the pressure required by the low-pressure engines. Gas compression is fulfilled with the pressure built-up unit (PBU), which evaporates the LNG with the help of the WG (as in the VAP) and returns vapor back to the LNG tank. In this scheme, the LNG flow is forced by the hydrostatic pressure difference between the top and the bottom of the LNG

tank. Therefore, it is crucial to locate the PBU below the LNG tank bottom level, which makes the operation of the PBU possible even when the level of LNG in the tank is very low. If it won't be possible, the LNG pump to supply the PBU will need to be used, as shown in figure 2 (c). Although in the figure 2 (b) scheme the compression device is not used for gas to the engine, but, due to LNG a turbulent evaporation in the VAP, gas pressure pulsation can be relatively high, and can affect engine operation. Therefore, the PD should also be considered for these types of systems. However, if the piping arrangement between the LNG tank and engine is complex enough, it is possible that the gas pulsation will be dumped by the gas pipes. Therefore, each system working in the scheme presented in figure 2 (b) should be analyzed to determine the necessity for the PD installation.

Figure 2 (c) presents a scheme where the gas-to-engine is withdrawn from the LNG tank in the form of vapor, and not liquid as in the other schemes. Therefore, due to a lack of any compression device and the turbulent evaporation process in the VAP, there is no pressure pulsation in the gas provided to the engine. A disadvantage of this scheme is found in the necessity of a much higher capacity of the PBU, which undertakes the gas-to-engine evaporation function here. Therefore, the gravity-based PBU (as shown in figure 2 (b)) can not be applied to this scheme.

The discussed fuel gas system schemes above are sufficient to compress the gas up to the pressure required by the low-pressure gas engine. In order to adapt those systems for high-pressure engines, the gas needs to be additionally compressed in a minimum two-stage compressor, located after VAP. An example of such a system, based on the scheme with the gravity-based PBU compressor, is presented in figure 2 (d).

5. Boil - off gas utilization

LNG tanks provided for marine applications are required to withstand the collision acceleration defined as 2g. Therefore, such tanks are characterized with relatively massive internal supports which are also the main sources of the heat flux to the internal (cryogenic) vessel. In comparison with onshore stationary cryogenic tanks, the evaporation rate for marine C-type tanks with vacuum-perlite insulation is 2-3 higher. In order to reduce the emission of greenhouse gases, IMO regulations require that gas is kept in the tank below the opening pressure of the tank safety valve without venting for a minimum of 15 days (except in emergency situations) when the fuel system is in stand-by mode (no gas is consumed by the engine). This requirement, in connection with the relatively large heat flux to the tank's internal vessel, implicates the necessity of the boil-off-gas (BOG) utilization realization. Figure 3 presents the BOG utilization methods that can be applied in the fuel gas systems [7].

The easiest method is found in the connection of the gas vapor phase from the tank with the liquid withdrawn line before the system VAP, as presented in figure 3 (a). Then, the BOG can be utilized by one or more of the ship's engines. However, it should be noted that the amount of gas to be utilized is low in comparison with nominal gas consumption. In addition, the dual-fuel engine in gas mode can't operate at lower than 25% of its load. Therefore, if the gas stream is too low, the engine will need to be switched off. Its restart in gas mode is possible if the engine temperature is high enough, which would require that the engine warm-up with the oil fuel. Consequently, when the BOG stream is insufficient to run the engine with its minimum operation load, this gas utilization method cannot be applied.

The other BOG utilization method is to use the gas combustion unit (GCU), as presented in figure 3 (b). Before gas vapor is provided into the GCU, it needs to be warmed-up to room temperature in the VAP2 heat exchanger. The heat generated in the GCU can be transferred into the ship's other system that requires heating, such as domestic hot water or WG systems for example.

Instead of GCU, the BOG can be compressed and stored in the high pressure gas tank (figure 3c), and then provided to the engine after its restart.

In the case of low-pressure tanks, the BOG can be also utilized with GCU or supplied to the engine with using of the gas compressor after the VAP2 - compare figure 3d.

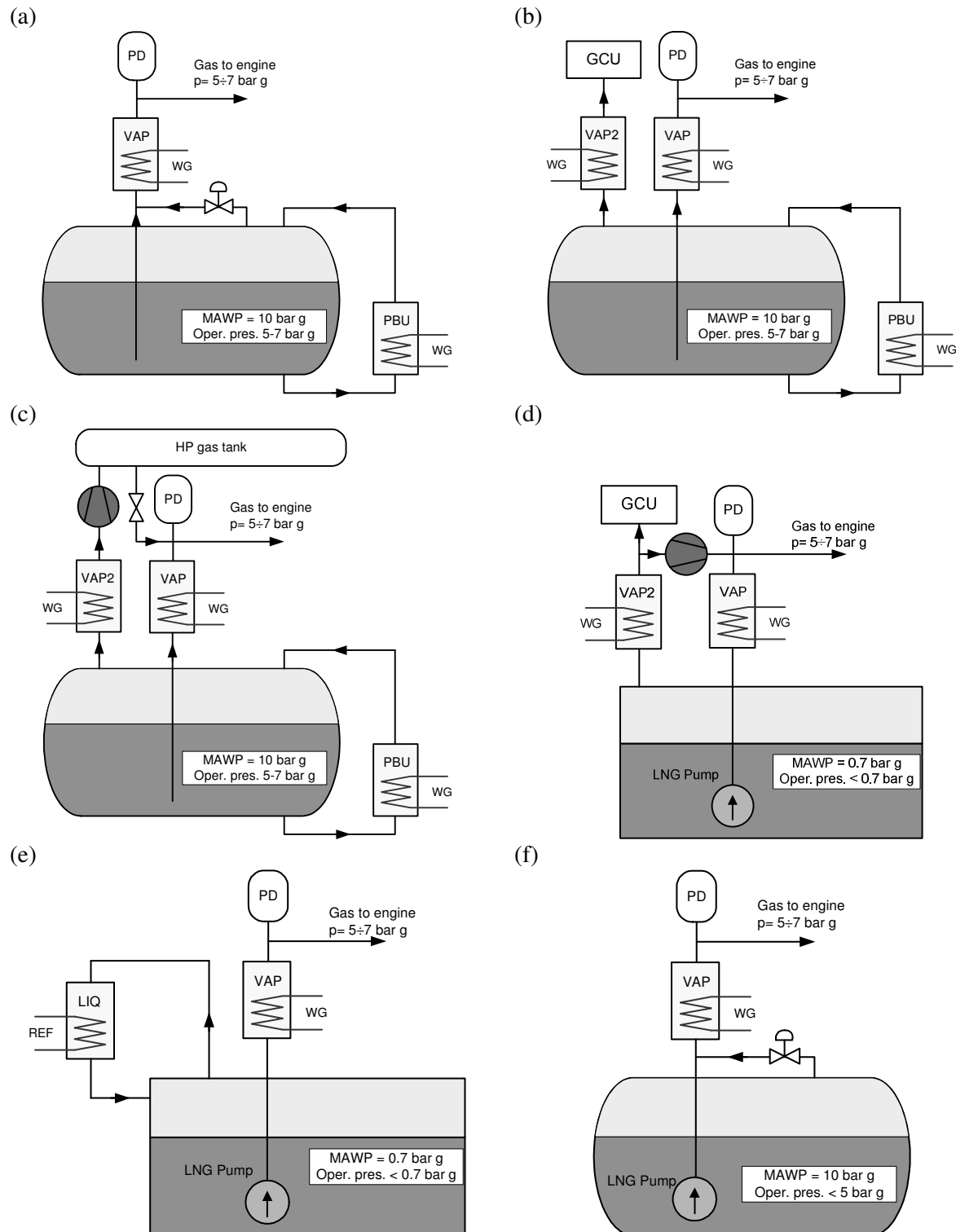


Figure 3. Boil-off gas (BOG) utilization methods - see description in the text.

The next method is the BOG re-liquefaction with the help of the cryogenic refrigerator, and then returning the liquid to the LNG tank - see figure 3e. It is economically justified to use such a system in the case of very large BOG streams, as with low-pressure LNG tanks.

The last method discussed in this paper, shown in figure 3f, is the use of the high-pressure tank which normally operates in the low-pressure tank scheme (compare figure 2a). In this case, the operating pressure is lower than the pressure required by the low-pressure engines. Thus, the pressure increase margin inside the tank is much higher than in other high-pressure tanks. As such, the BOG can be collected inside the LNG tank, and after the engine restart, it can be provided to the engine through the by-pass line before the LNG pump start. In this way, pressure inside the tank can be reduced to the nominal level.

6. Samsø Ferry fuel gas system

Between 2013 and 2015, Wrocław University of Technology, in collaboration with Remontowa LNG Systems Ltd (former FUE Rumia) and Kriosystem Ltd., has developed, designed, produced, installed and successfully commissioned the first Polish fuel gas system for four Wärtsilä 6L20DF low-pressure dual fuel engines. The system was installed on the Samsø Ferry, ordered by the Danish Samsø island commune in the Remontowa Shipyard S.A. Figure 4 presents a view of the LNG tank and the tank connection space (TCS) production, transportation and installation in the ship.

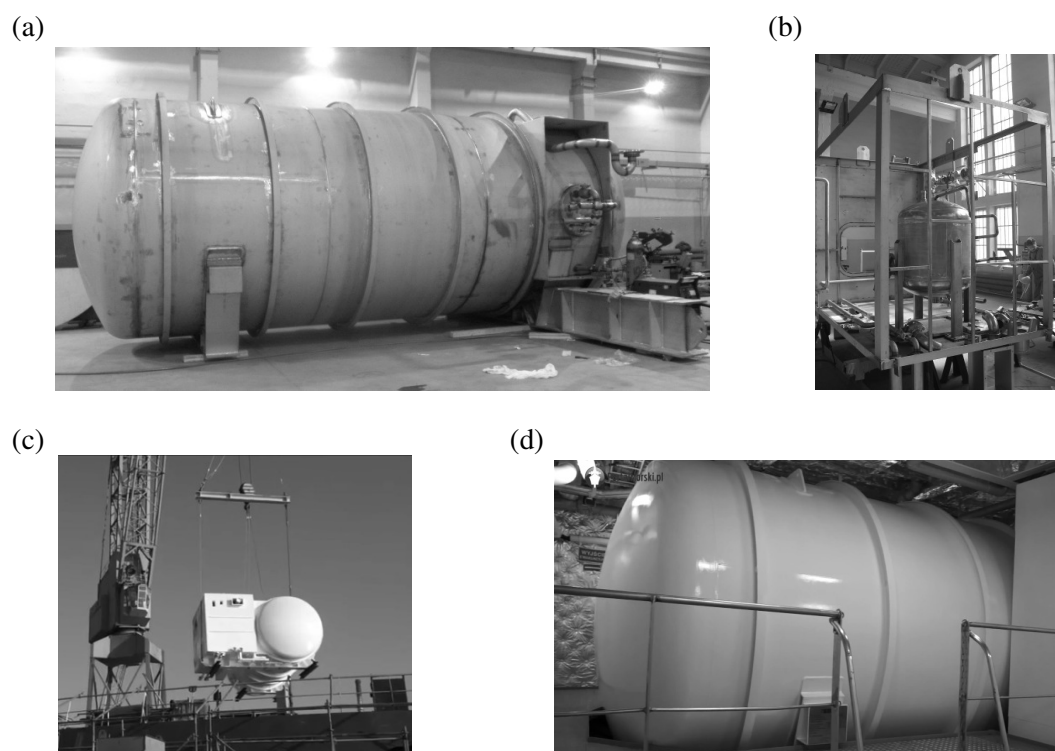


Figure 4. Samsø Ferry fuel gas system LNG tank with TCS, (a) LNG tank production, (b) TCS production, (c) LNG tank transportation in to the ship, (d) view of the LNG tank in the ship

The system operates with the scheme presented in figure 2(b), while its simplified flow scheme is presented in figure 5.

The Samsø Ferry fuel gas system is designed to provide 1300 Nm³/h of gas to the ship's engines. The gas pressure at the engine inlet is required to be higher than 6.7 bar g and its temperature should be in the range of 0-60 °C. The LNG is stored in the 40m³ volume, vacuum - perlite thermal insulated, 9 bar g design pressure, independent C-type LNG tank. The LNG Tank is bunkered from an LNG onshore facility through the vacuum insulated bunkering line. The pressure in the LNG tank during the bunkering process can be controlled by switching between the top and the bottom filling. The connection of the bunkering to the onshore bunkering facility is placed in the bunkering station, located on the ship's starboard.

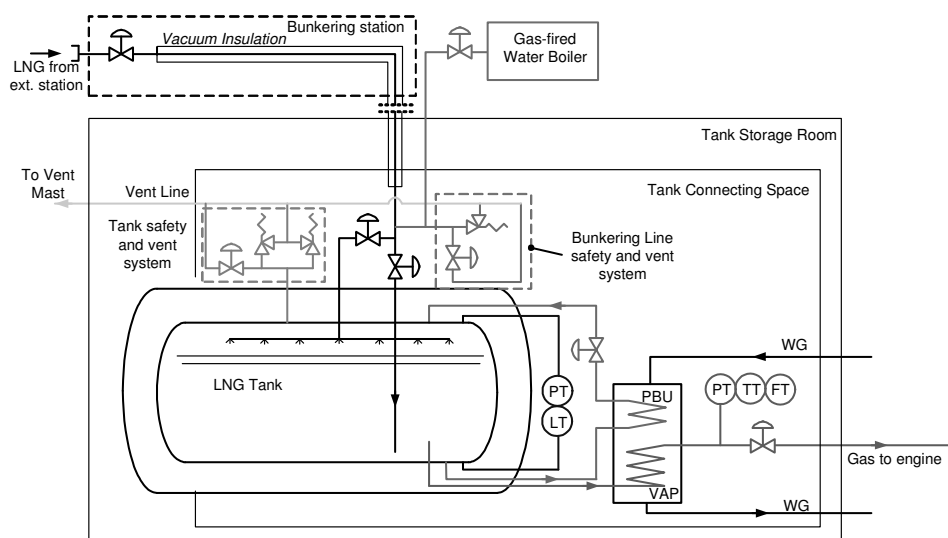


Figure 5. Simplified flow scheme of the Samsø Ferry fuel gas system.

All connections to the LNG tank as well as the VAP, the PBU, the LNG tank pressure relief system, tank instrumentation and all process valves are housed by the TCS, located on the side of the LNG tank. The TCS is gas-tight, which creates the secondary barrier for all pipes and equipment located in the TCS. In addition, the TCS floor acts as a drip tray for liquid gas in the case of a gas system connection failure. Due to relatively low BOG generation, the Samsø Ferry fuel gas system consists of a gas-fired water boiler for BOG utilization. The water boiler is combined with the ship's domestic hot water system.

7. Conclusions

In order to reduce the global emission of pollution from ships, the International Marine Organization IMO has established more restrictive emission levels. LNG is considered to be an ecological and economical fuel for present and future marine propulsion applications. In this paper, the authors provide and discuss some of the most important issues concerning fuel gas system schemes. It can be concluded that the type of fuel gas system to be installed in a particular ship should be chosen with respect to a number of parameters, such as: ship size, design and application, gas engine type, as well as the expected sailing range in gas mode.

Acknowledgments

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