Two-stroke engines

LNGC-optimised designs of ME-GI engines and fuel gas supply systems

MAN Energy Solutions
Future in the making

Future in the making

Contents

The environmentally beneficial ME-GI concept sets the new industrial standard for two-stroke propulsion engines in liquefied natural gas carriers (LNGC) and other aspects of commercial shipping.

The rapidly increasing operating hours of the ME-GI engines (at the time of writing more than 1,000,000 hours) provide robust, substantial, and reliable data. MAN Energy Solutions (MAN ES) continuously improves and optimises the ME-GI engine based on the vital operating data and customer feedback. The keywords in the process of research and design are performance improvements and cost optimisation to improve the ME-GI competiveness further and at the same time safeguard the strong reliability from the HFO burning two-stroke engine. The most recent ME-GI engine design specifically tailored for LNGC is based on the novel S70 or G70 engine design.

Introduction

A stable and reliable supply of fuel gas is vital for maximising the gas running time and increase the economic benefit of the owner. The ME-GI engine design inherently handles varying gas qualities in combination with the lowest fuel gas consumption. The gas quality depends on the bunker supplier and the position of bunkering, but also, at least for LNG carriers, the fuel gas quality will fluctuate depending on the specific point in time of the ship's voyage, for example is it loaded or in ballast. The superior characteristic of the diesel-type combustion of the ME-GI engine combined with the well-proven high-pressure (HP) gas supply system gives MAN B&W two-stroke engines the highly flexible nature regarding the calorific value of the gas and the ability to run on almost any fuel gas quality with no or limited decrease in efficiency. The ME-GI engine is thus not sensitive to varying gas qualities or a low methane number.

The ME-GI engine is designed and optimised for operation in three different modes to obtain a high degree of fuel flexibility. These modes are:

- Dual fuel mode, in which the amount of fuel gas is maximised and the pilot oil consumption minimised
- Specified fuel gas mode, where almost any mixture of compliant fuel and gas can be specified
- Compliant fuel only mode.

Whenever the vessel enters either a harbour or an emission-restricted zone, the multi-fuelled ME-GI engine changes reliably and seamlessly between operating on fuel gas and compliant fuel. Furthermore, service experience confirms the largest benefit of the ME-GI engine, namely that it maintains its high efficiency without any methane slip during load changes and during variations in ambient air conditions. These results and the more than 100 ME-GI engines in service and 300 on order confirm the legacy of the two-stroke engine in the ME-GI execution. The most recent addition to the ME-GI technology is the ME-GI Mk. 2 platform.

Some of the challenges and decisions required to make a fuel gas ready vessel are often related to the design of the fuel gas supply system (FGSS). MAN Energy Solutions is continuously involved in designing reliable and cost-optimised FGSS solutions for both

LNG carriers and LNG-fuelled ships. The FGSS must match the discharge pressure with the instantaneous fuel demand of the optimised ME-GI engine. When the ME-GI engine is combined with MAN dual-fuelled GenSets, or other dual-fuelled (DF) gensets, to cover the electrical consumption on board, the FGSS must match the fuel gas demands of both engine types. This includes handling the fuel gas supply variables, that is, tank pressure, boil-off gas (BOG) rate under varying conditions, gas composition, suction and discharge temperature.

Since LNG carriers already have LNG on board, the prevailing challenge is to design an efficient FGSS capable of handling and supplying BOG to the ME-GI engine and for example DF gensets and/or auxiliary boilers under varying operating conditions.

As a part of the ME-GI optimisation, which focuses on the entire engine and engine-related systems, the design of the FGSS has also been scrutinised to further increase performance and cost optimise the system. Different applications call for different FGSS solutions and MAN ES is cooperating closely with industry partners to ensure cost-effective solutions for ME-GI fuel gas supply systems.

The wide range of pump vaporiser units (PVUs) from MAN ES matches the requirements for supply of HP LNG and ethane to the ME-GI engine. The optimised MAN PVU has redefined previous FGSSs with its low installation costs, less space requirement, redundancy, and direct integration with the ME-GI engine control system.

MAN Cryo, owned by MAN ES, is a specialist in LNG fuel gas supply systems with more than 20 years of experience within the field. MAN Cryo has system designs developed to suit the ME-GI performance.

Engine technology development

The optimised Mk. 10 engine design is the result of extensive research and design considerations with the purpose of optimising individual engine components with a size and weight reduction of the engine as the goal.

Mk. 10 engine design

The optimised engine design platform described in Fig. 1, has resulted in a lighter engine, as the overall length, width, and height of the engine are reduced.

The optimised and lighter engine is the result of an extensive process:

- Combustion space improvements: The piston skirt height is reduced and the hydraulic nuts are exchanged with smaller torque-tightened bolts. These improvements opened up for a reduction of the top land height and a reduction of the thickness of the cylinder cover deck. The weight of the cylinder liner has also been reduced by shortening the cooling jacket and reducing the cylinder liner thickness.

- New connecting rod: the Flex-Rod has been designed with a more even force distribution on the main bearing. This has enabled changes in the bedplate design and a reduction of the bedplate weight.

- New and more flexible main bearing support design.

- Introduction of the weight-reduced wide-pad crosshead bearing design.

- Reduced cylinder distance, which has allowed a reduction of the cylinder frame and bedplate size.

Introduction of the top-controlled exhaust valve (TCEV) and the fuel booster injection valve (FBIV) means that the fuel injection system and exhaust valve actuation are more flexible, simplified, and cost efficient. The fuel booster and the injector valve have been combined in one unit to create a more simple system, and the exhaust valve actuator has been integrated in the exhaust valve. By doing so, the long fuel pipes and hydraulic pipes on top of the engine have been removed. The distributor block placed on the exhaust valve distributes HP hydraulic oil to the exhaust actuator on top of the exhaust valve and to the booster function in the FBIV.

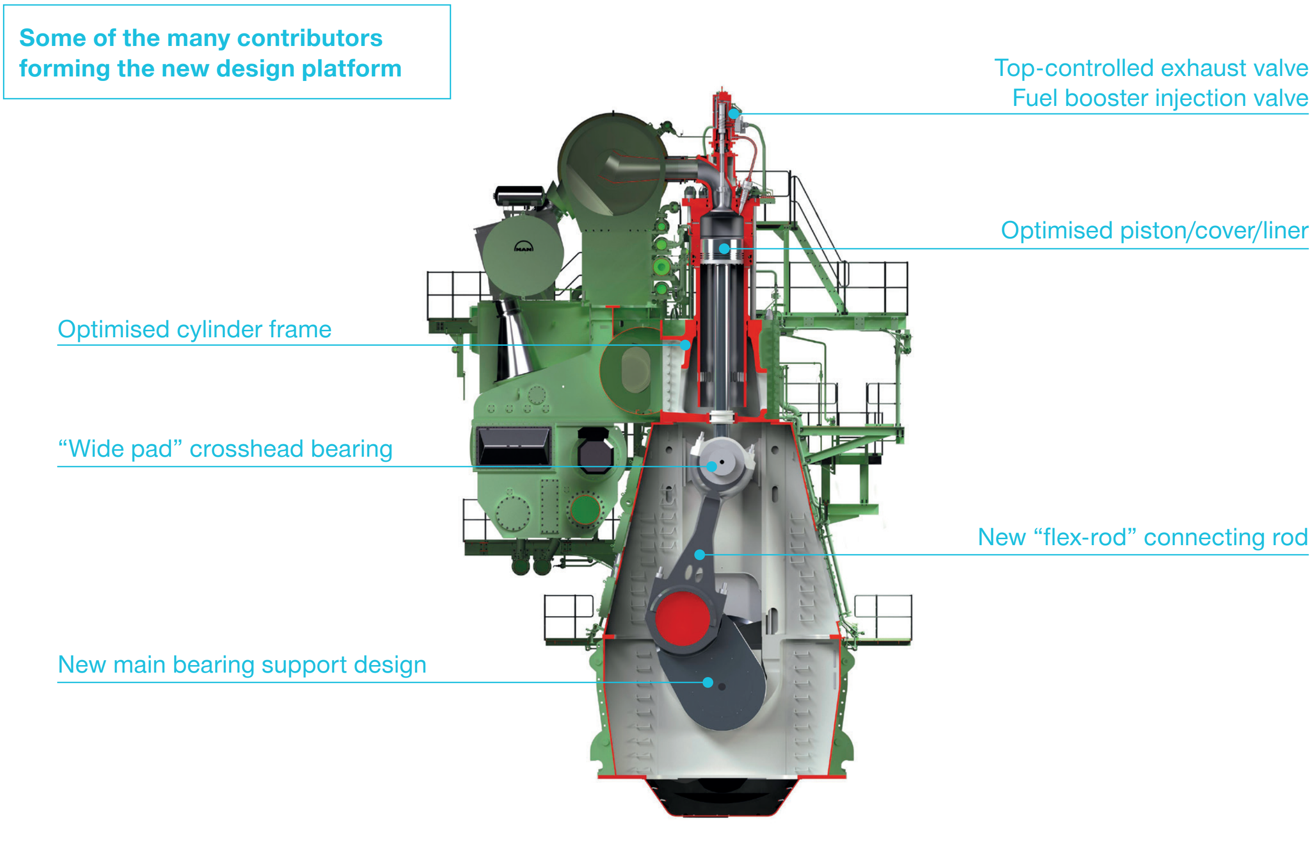

Fig. 1: The optimised parts of the Mk. 10 engine platform

The engine control system fully controls the combustion process by electronic control of fuel injection and exhaust valve opening according to the instantaneous crankshaft position.

The introduction of the Mk. 10 design also includes a considerable reduction of specific gas consumption (SGC) in dual-fuel mode with the dual-fuel gas-optimised performance tuning, see Fig. 2. In addition to the significant 10% reduction of engine mass and the reduced size, it makes the Mk. 10.5 a competitive choice.

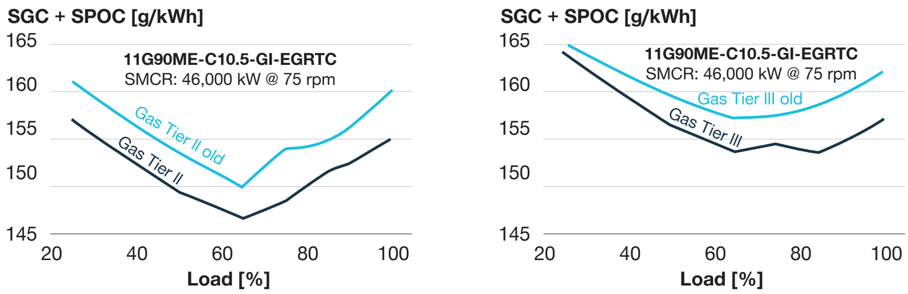

Fig. 2: 11G90ME-C10.5-GI-EGRTC, dual-fuel gas-optimised performance tuning

ME-GI improvements

In constant pursuit of reduced operating expenditure (opex) and reduced manufacturing and installation costs, a number of improvements have been made to the ME-GI top cover and the injection system.

Dual-fuel operation requires injection of both pilot fuel oil and gas. The FBIVs operate as main injection valves, when the engine operates in compliant fuel only mode and as pilot oil injectors, when the engine operates in dual-fuel mode. This means that the engine does not require additional or special pilot oil valves. In this scenario, the FBIV must perform reliably across a large range of injection amounts, from injecting the low pilot oil amount to the needed compliant fuel amount at maximum continuous rating (MCR). Research and design improvements have resulted in the part-load optimised nozzle designed for the lower compliant fuel consumption at part load and 1.5% pilot oil consumption.

The most recent design improvement is the new pilot injection valve (PIV) principle shown in Fig. 3 and the new pilot fuel injection principle. This principle addresses the different injection profiles required by the ME-GI (and the FBIVs) by applying adaptable nozzle size configurations.

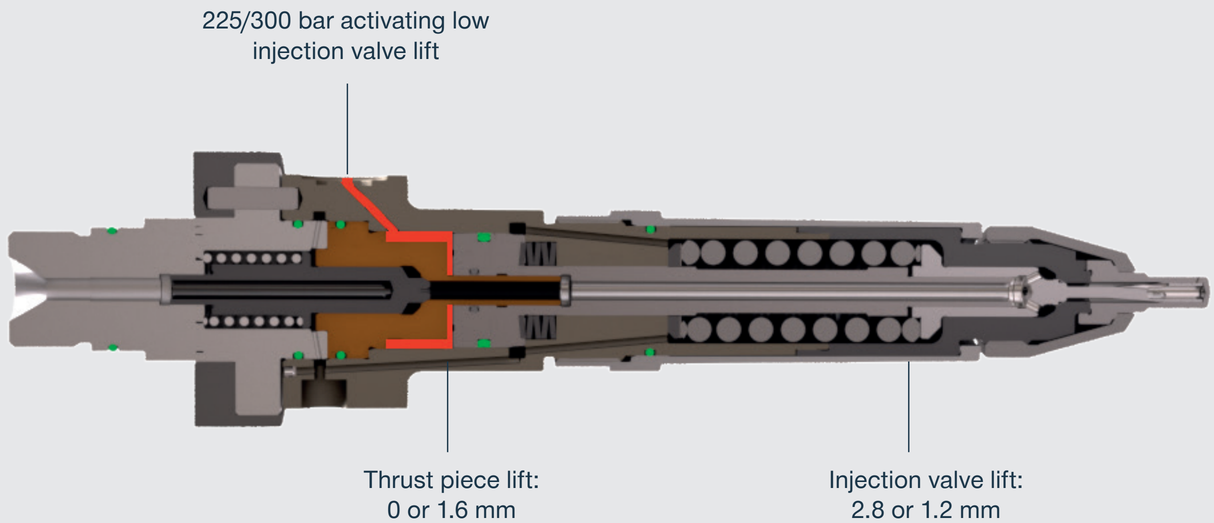

Fig. 3: Cross section of the new pilot injection valve

This means that the size of the nozzle injection bores can be adjusted to match the individual ME-GI mode as illustrated in Fig. 4, both the small pilot oil injection amount in dual fuel operation and the injection amount at MCR in compliant fuel only mode. Furthermore, the pilot oil injection has been improved by implementing a dedicated pilot oil injection profile.

The gas injection system on the ME-GI engine is of the common rail type, where the pressure in the gas supply system is constant equal to the gas injection pressure. HP gas is distributed via a chain of double-walled pipes connected to each cylinder, where the gas enters the gas distribution block and, eventually, the gas valves via the gas distribution channel in the cylinder cover.

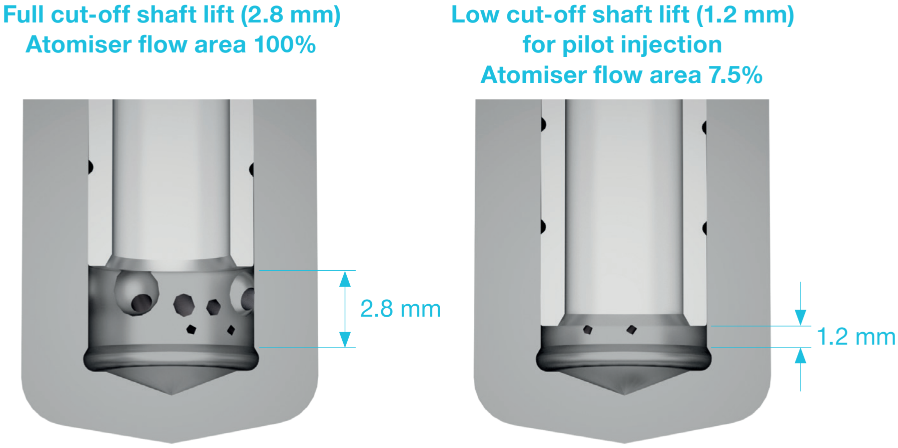

Fig. 4: Close-up view of the fuel nozzle concept in compliant fuel only mode (left) and in dual fuel mode (right)

ME-GI Mk. 2

To simplify and reduce installation costs several improvements have been implemented to the top cover and the double-walled chain pipe:

- the blow-off pipe is omitted and the supply and blow-off pipes have been combined into one double-walled chain pipe, see Fig. 5A/B
- the pipes for sealing oil and hydraulic actuation oil have been removed from the top cover and replaced by internal channels in the cover
- separate gas block and accumulator
- new gas injection valves accommodating the new sealing oil and actuation oil channels in the top cover

The ME-GI control and safety system is designed to fail to safe condition. Incidents occurring during fuel gas running result in a fuel gas stop and an immediate automatic changeover to operation on compliant fuel.

As part of the optimisation, gas in the HP fuel gas pipes and the fuel gas auxiliary system can now optionally be returned to the service or cargo tank.

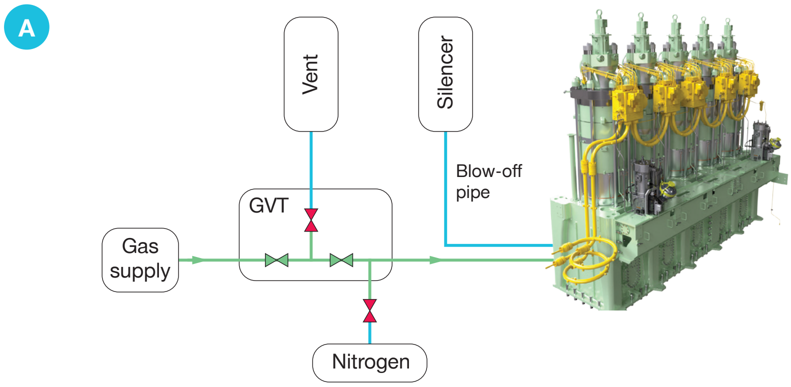

Fig. 5A: ME-GI Mk. 1 system layout with blow-off pipe and nitrogen connection in the gas valve train (GVT)

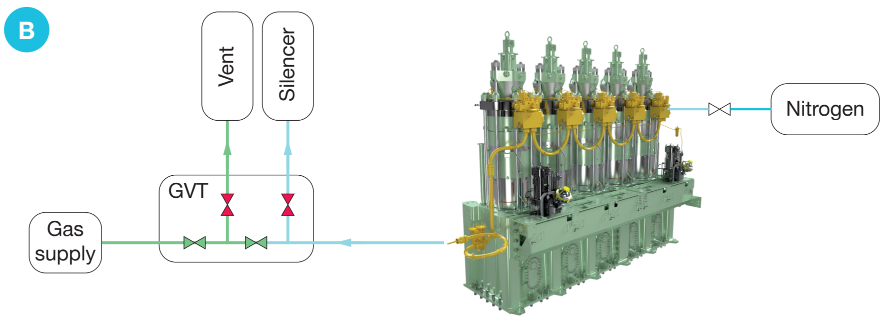

Fig. 5B: ME-GI Mk. 2 system layout showing gas operation

The changeover to fuel oil mode is always done without any engine power loss.

Previously, if a fault occurred on a single cylinder gas operation had to be stopped. The new Mk. 2 design has been optimised, as illustrated in Fig. 6, so one cylinder can be withdrawn from gas operation, while the engine continues in gas operation on the remaining cylinders. The cylinder not operating on gas may continue on the compliant fuel with unchanged load and performance depending on the nature of the fault.

Compared to the Otto cycle operating principle, the ME-GI concepts give the lowest gas consumption, the lowest methane slip and a superior engine performance not dependent on ambient conditions and gas composition.

The low methane slip is a vital parameter, compared to CO_2 the methane slip has a 100-year global warming potential (GWP) weighted factor of 28 [1].

According to IMO, the focus in the coming years will be the methane slip due to the significant environmental impact. A potential implementation of a global CO_2 tax will not affect the owner who chose the ME-GI technology as the propulsion solution.

If you need further detailed information about our engine types, our engine programme can be found by following the link given in [2].

Besides, our Computerised Engine Application System (CEAS) gives access to performance data and lists of capacities, see [3]. Based on input containing the overall desired engine layout, CEAS provides important engine and performance characteristics gathered in the CEAS engine data report.

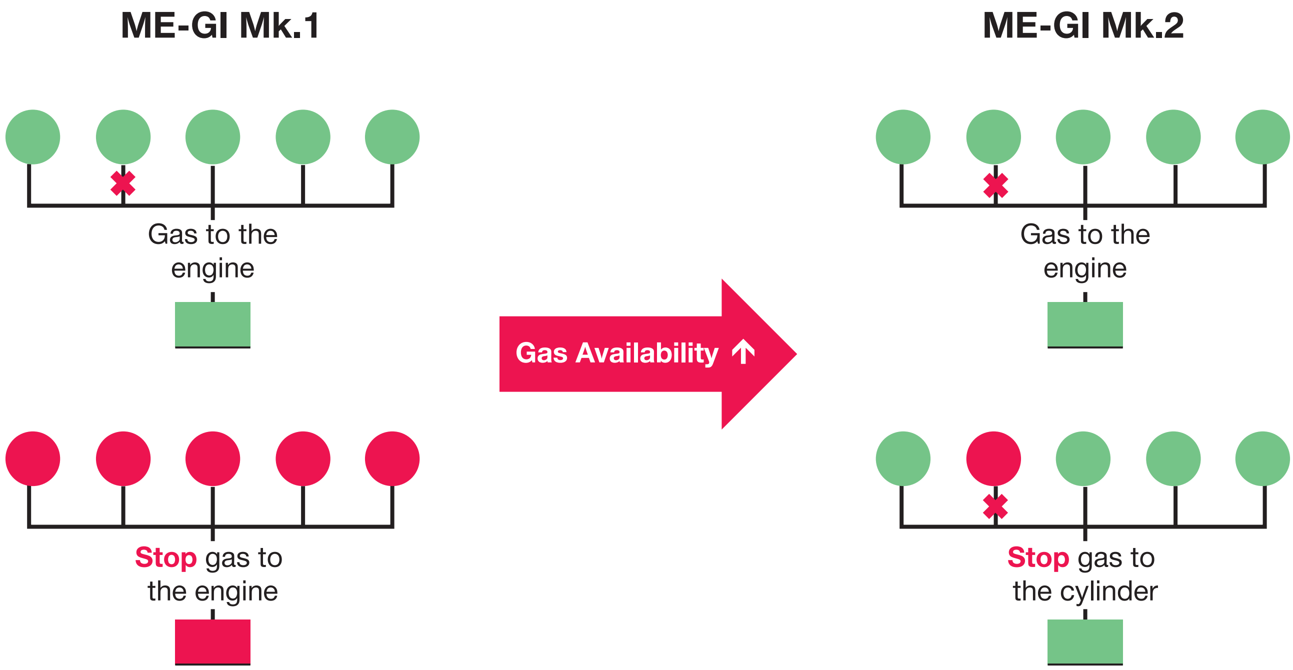

Fig. 6: Comparison of a failure in the gas injection system for ME-GI Mk. 1 and Mk. 2

Properties of LNG

On ships, natural gas (NG) is normally stored in the liquefied state (LNG) close to atmospheric pressure, thereby reducing the volume to 1/600th of the original volume. When stored on board, the continuous heat influx from the surroundings results in the development of BOG and an increase in tank pressure over time. Furthermore, handling of the LNG, for example during bunkering, generates excessive BOG in the tank. Means of controlling or reducing the tank pressure must be installed regardless of the ship type.

LNG characteristics

Some of the physical-chemical characteristics of LNG will be briefly discussed in the following section. Highlighting some of the properties of LNG will reveal characteristic differences defining the possible ways of storing, treating and handling the LNG on its way to the engine. The LNG figures in Table 1 are from CEAS [3].

Two of the important characteristics of LNG are the boiling point and the fact that the chemical composition and methane number (knocking tendency) vary with the composition of natural gas (NG) and the applied liquefaction process at the refinery.

The largest LNG production is seen at lower methane numbers, see Fig. 7.

Fig. 7 shows that an engine requiring LNG with a methane number of minimum 70 (AVL) can combust 90% of the global LNG supply. An engine requiring a methane number of minimum 80 (AVL) can use only 38% of the global supply. The great advantage of the ME-GI engine is that it combusts all LNG qualities, because it is based on the Diesel principle. Lower methane numbers may for engines using the Otto combustion process (air - gas premix) require derating of the maximum power.

NG, which has a high percentage of methane, consists of a mixture of various hydrocarbon gases, methane

Table 1: Fuel gas properties and requirements to fuel gas supply pressure and temperature for the ME-GI engine and MAN gensets [3]

Fuel gas	LNG
Lower heating value (MJ/kg)	**50.0**
Boiling temperature (°C at 1 bar)	**-162**
Supply pressure at main engine (bar)	**300 bar at 45°C±10°C**
Supply pressure at gensets (bar)	**6 bar at 0-60°C**

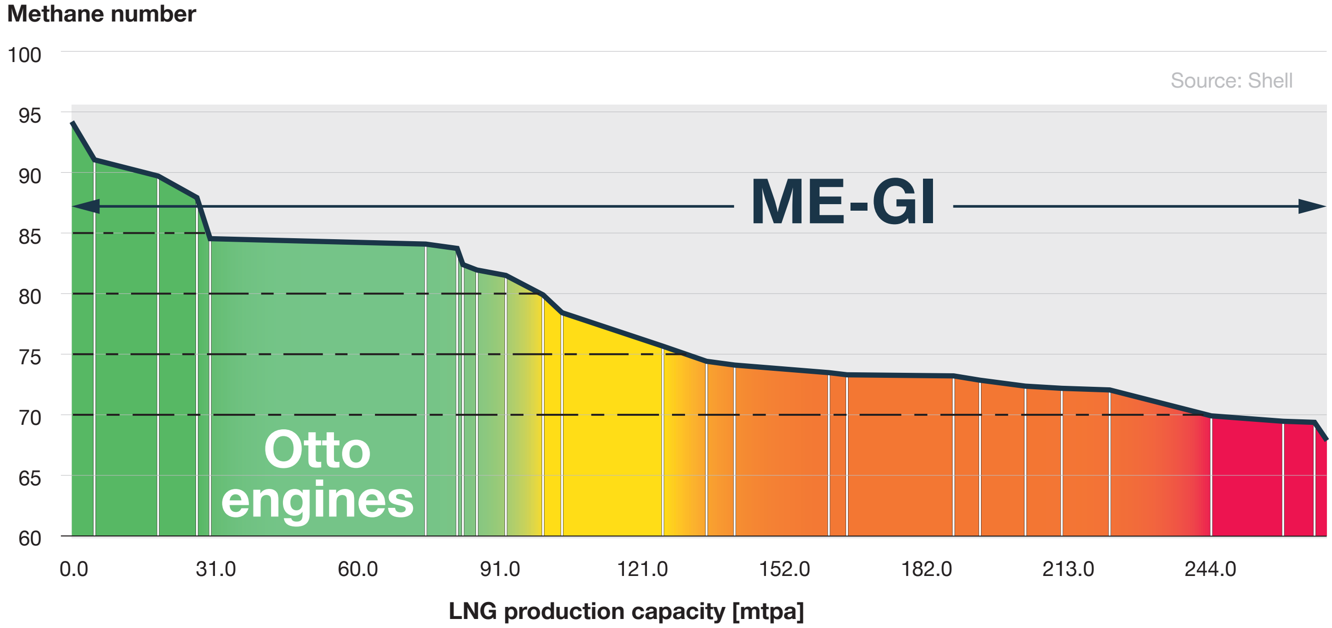

Fig. 7: Methane numbers of the global LNG production, the ME-GI engine operates on all methane numbers without derating

(CH_4), ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}) and pentane (C_5H_{12}), as well as carbon dioxide (CO_2), nitrogen (N_2) and hydrogen sulphide (H_2S). Typically, methane constitutes 85 to 95%, along with a few per cent of ethane, even less propane and butane, and trace amounts of nitrogen. As mentioned, the exact composition varies according to source and processing history. At the refinery, gas impurities, sulphur (S_2) and CO_2, are removed and the gas is cooled to its boiling point (–162°C) at atmospheric pressure [4, 5].

Another important characteristic is the nonhomogeneous vaporisation of LNG over time due to the different boiling points of the gasses. The boiling point of nitrogen at atmospheric pressure is –196°C that of methane is –161°C and ethane –89°C. As the components with lowest boiling point evaporates faster, the chemical composition and the heating value of the BOG changes. The energy content of LNG depends on the chemical composition, temperature and nitrogen content. For most LNG, the nitrogen content is limited to approximately one per cent. In BOG, as much as 20% nitrogen can be observed and the large amount of nitrogen dilutes the total energy content and needs to be taken into consideration when sizing the FGSS.

As over time, first nitrogen and later methane are the primary BOGs, the composition of LNG in the tank changes to contain more of the heavier hydrocarbons, an effect called aging.

Another reason for the change of LNG composition is that the content of the tank may stratify, i.e. the heavier hydrocarbons sink to the bottom of the tank. The LNG supply to the engine will have a different composition compared to the bunkered LNG, since the supply pump sucks from the bottom of the tank.

Tank types

When choosing the LNG tank type, the essential parameters are the tank size and the design pressure, the amount of BOG, and for how long excess BOG must be retained in the tank. This places demands on how variations in temperature and pressure are handled during bunkering operations and engine operation and on the investment in equipment utilising excessive BOG or in reliquefaction plants.

The characteristics of the LNG tank types classified by IMO are:

1. Integrated tanks, also termed membrane tanks: low-pressure (0,25-0,7 bara) tanks. The hull forms part of and supports the tank structure, and the tanks make efficient use of the space on board, but are vulnerable to sloshing. It is the dominating type for cargo tanks on LNGCs but they are also introduced on large container vessels. Manufacturers: Gaztransport & Technigaz and Hyundai Heavy Industries (HHI).

2. Freestanding or independent self-supporting tank types (not part of the hull). The independent tank types are subdivided into:

   A. IMO Type A: Non-pressurised tank of prismatic design with full secondary barrier. The tank is not vulnerable to sloshing and it has a great volume efficiency since the tank can fit the shape of the hull. Often it is a stainless steel tank held in position by stainless steel supports and the internal walls of the space accommodating the tank are insulated with a high thermal-efficiency system of insulation panels. This design gives a low BOG rate and potentially up to 30-50% greater volume efficiencies than IMO Type C tanks. The Type A tank is often used on small LNGCs and recently in container vessels. Manufacturers: Gaztransport & Technigaz, Torgy LNG, LNG New Technology and others.

   B. IMO Type B: Non-pressurised tank of a self-supporting spherical (Moss type) or prismatic design with a partial secondary barrier. The tank type is often used on larger LNGCs. Manufacturers: Moss Maritime, IHI Corporation, DSME, Kawasaki Heavy Industries (KHI), Braemer LNG PV, Torgy, LGM Engineering, NHI Innovation and others.

   C. IMO Type C: Pressurised tank (up to 20 bar) integrated in the hull, the volume efficiency is not great due to the roundish shape (single or bi-lobe design) and the space around the tanks is often not utilised. The large benefit of these tanks is the possibility of pressurising with up to 20 bar. The tank type is often used in smaller LNGCs and container vessels. Manufacturers: MAN Cryo, AC Inox, TGE Marine Gas Engineering, LGM Engineering, Aker Engineering and others.

The IMO tank Type C was for many years the preferred tank type, since BOG management is not as critical as for the other tank types. The benefit of using one of the other tank types is the design pressure above atmospheric pressure. For the Type B prismatic tank type, BOG management has to ensure that the pressure does not build up during bunkering and on sea voyages.

Generally, storing and supplying LNG requires approximately 3-4 times the volume compared to HFO if tank Type C is chosen. However, an IMO Type A tank occupying about the same space as an IMO Type C tank can hold up to 50% more LNG. A more in-depth explanation of the different tank types can be found on for example the IMO webpage or on the webpages of the different tank manufacturers.

The centrifugal pump submerged in the LNG tank in Fig. 8 (LNG supply pump) has several functions. The pump may be part of a spraying system, and as Fig. 9 shows, it supplies LNG at approximately 6 bar and −162°C to the suction side of the MAN PVU HP pump.

By installing a spraying system in the top of the tank, the tank can be cooled and the pressure controlled by distributing cold LNG with the spraying system. A recent trend in tank design is to lower the BOG rate by improving the tank insulation technology and thus, minimising heat ingress. One of our recent papers goes through the principles of calculating the tank size for a container vessel [6].

Reliquefaction of boil-off gas

An onboard reliquefaction plant liquefies surplus BOG from the LNG cargo tanks and returns it to the tanks, which is a way to control the LNG tank pressure on long and short voyages and during unloading in port. In port, requirements to cargo tank pressure must be met and if the pressure is too high it must be lowered through the gas combustion unit (GCU) or reliquefied.

Two frequently applied reliquefaction system designs are full and partial reliquefaction systems (FRS and PRS). The two systems are offered in many different configurations and from different manufacturers.

The fundamental difference between applying FRS and PRS is the definition of the vessel speed (consumption) at which mass balance equilibrium is achieved. Both PRS and FRS can be designed with an additional cooling cycle or they can be based on the Joule-Thomson effect. A widely used refrigeration cycle is the reverse Brayton Cycle. The refrigeration cycle can be of an open or closed loop type.

The refrigerant in the additional cooling cycle is often nitrogen, but it can also be a mixture of refrigerants to tailor the cooling capacity to different needs. A mixed refrigerant system (MRS) uses a mixture of refrigerants instead of several pure refrigerants with different boiling points as in conventional cascade refrigeration systems. Reliquefaction systems have also been developed which directly compresses, expands and liquefies BOG [7, 8].

Non-condensable components, mainly nitrogen, are removed in a separator.

Full reliquefaction system
Fig. 8 illustrates the principles behind an optional full reliquefaction system and the integration of gas supply to the ME-GI engine.

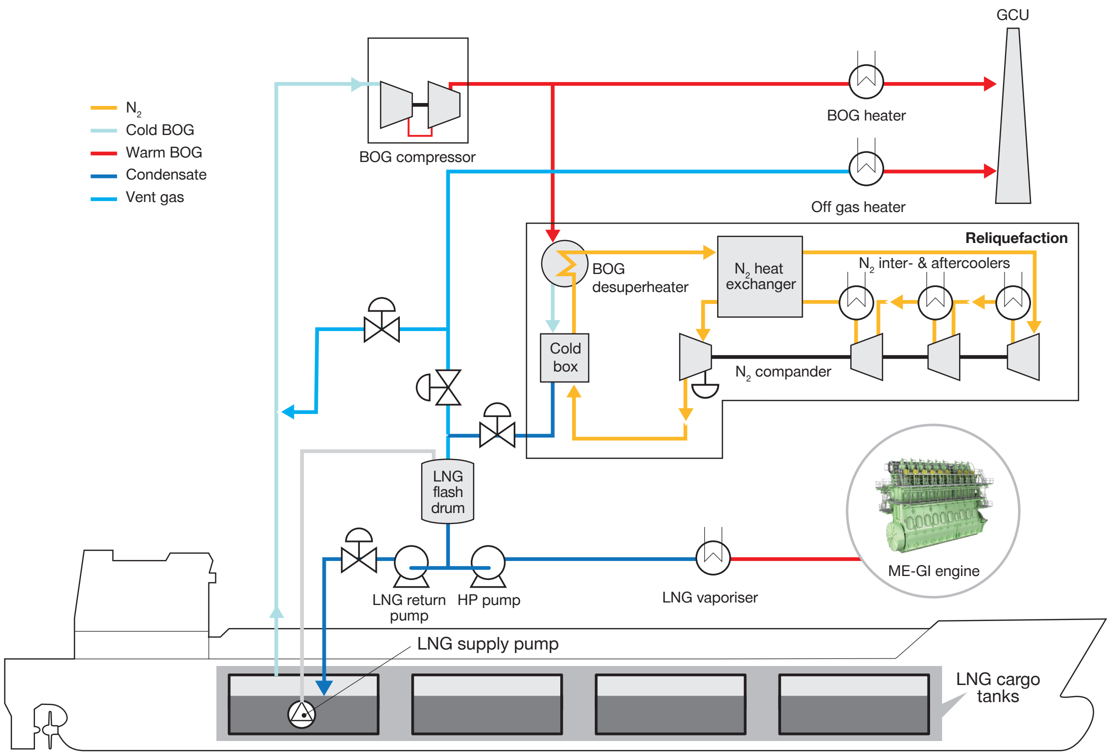

Fig. 8: FGSS with evaporated reliquefaction by heat exchanging with cold nitrogen (N_2)

The main components of the system in Fig. 8 are:

1. BOG compressor
2. Cold box – heat exchanger
3. Flash drum – separates gas and liquid
4. Nitrogen cooling loop including a compander, inter- and after coolers and a heat exchanger

The BOG compressor supplies excess BOG at 300 bar and 45°C to the BOG desuperheater, where it is cooled to approximately −90 to −100°C @ 5-6 bar. Next, the cold BOG enters the cold box, where it is cooled to approximately LNG tank temperature, i.e. −162°C @ 1 bar, and liquefied.

The principle applied in the reliquefaction plant is the reverse Brayton refrigeration cycle, where nitrogen by means of successive compression and expansion cycles removes heat from the BOG. The reliquefaction process involves a closed nitrogen loop with a three-stage compressor, where the last stage is coupled to an expander for energy savings, and a cryogenic heat exchanger (cold box). The cold box has multiple streams; one is cold BOG from the desuperheater and another is LP nitrogen from the expander, which provides the cooling effect. The nitrogen loop also incorporates a heat exchanger, which improves the efficiency of the nitrogen loop.

Partial reliquefaction

Fig. 9 illustrates the principles behind a partial reliquefaction system combined with the integration of the gas supply to the ME-GI engine and the gensets.

The BOG compressor supplies excess hot BOG at 300 bar and 45°C to the

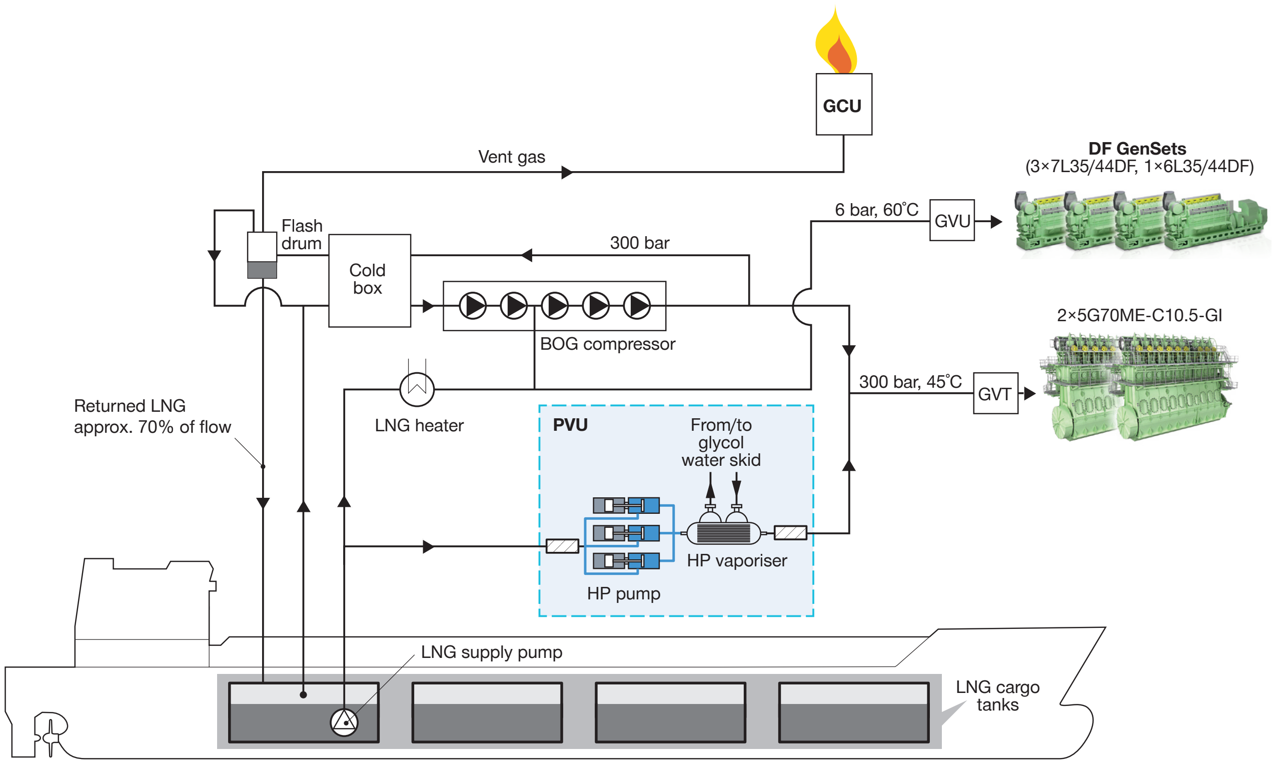

Fig. 9: FGSS with a partial reliquefaction system based on the Joule-Thomson effect

cold box, where the colder BOG from the cargo tank precools it. Next, the gas enters the Joule-Thomson valve and undergoes expansion to approximately 2 to 3 bar pressure. This causes the gas temperature to drop to approximately the LNG tank temperature, i.e. −162°C, and liquefy. Precooling of the BOG leads to a larger temperature drop in the Joule-Thomson valve and a larger efficiency of the system.

The Joule-Thomson (J-T) valve is a throttle valve, where the pressure drops from 300 bar to 2 bar as the gas passes the valve. The resulting temperature change of the gas from approximately −85°C to approximately −162°C is termed the Joule-Thomson effect. This effect depends on the Joule-Thomson coefficient, which is a gas property.

Reliquefaction systems
To illustrate the diversity of solutions for regulating the LNG tank pressure, Figs. 10-13 show four different systems.

Full reliquefaction solution

The principles of an FGSS with an integrated full reliquefaction system are shown in Fig. 10.

By applying the this full reliquefaction system, the relative cost, total installation cost, and electrical power consumption are increased compared to a PRS, because there is an additional compressor.

However, the advantage is that you can achieve a lower service speed, where the gas is not wasted as BOG in the GCU.

In principle, the owner buys an insurance with an additional cost to keep the gas in the tank for longer periods.

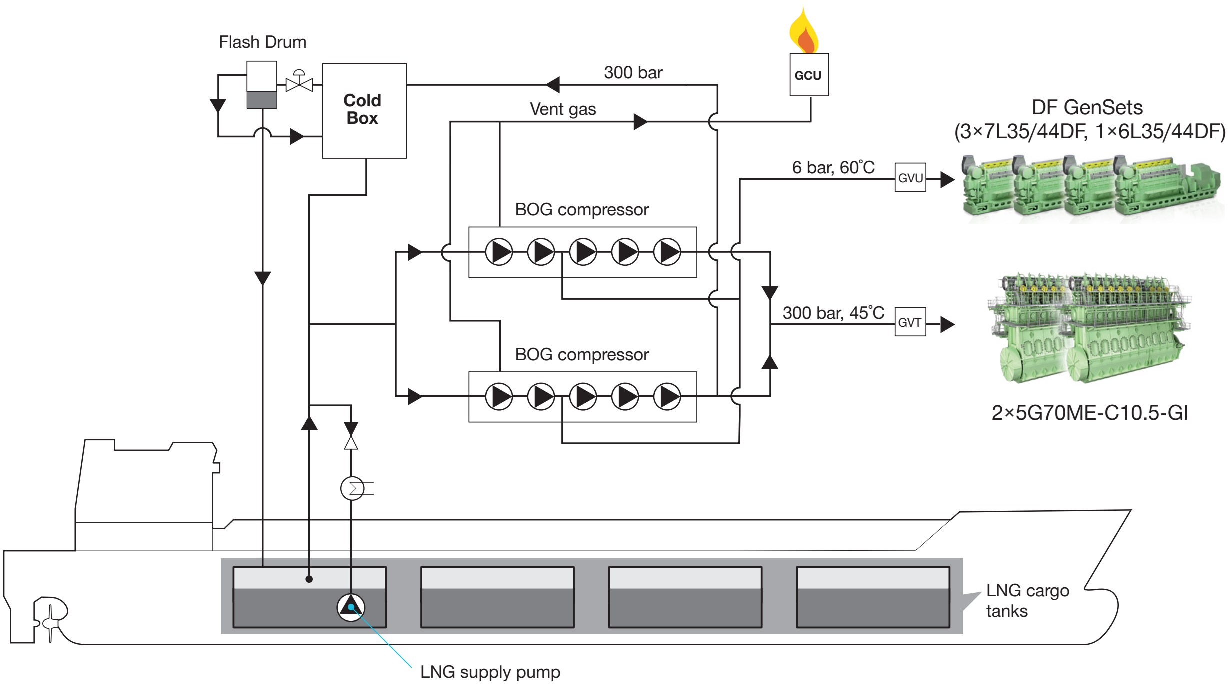

Fig. 10: FGSS with an integrated full reliquefaction system

Reliquefaction and optimiser

The system shown in Fig. 11 is a full reliquefaction system also equipped with an advanced nitrogen cooling cycle, where an optimiser has been integrated to increase the efficiency.

The main components of the system are:

1. Two BOG compressor skids

2. BOG preheater

3. Two nitrogen compander modules

4. Cold box or cryogenic heat exchanger

5. Flash drum or separator

The BOG is removed from the cargo tanks by a three-stage compressor with cooling after each stage, heated in the preheater, and supplied to the cooling circuit and the cold box where it is condensed to LNG. The cryogenic temperature in the cold box is produced by a nitrogen compression-expansion cycle. From the separator, the LNG is returned to the cargo tanks by the differential pressure of the system. The fundamental mode of operation of the system is described in detail in [9].

In the LNG vaporiser, the cold duty is removed from the LNG while it is heated to the ME-GI engine requirement. The main objective is to utilise the cold duty taken out, before the LNG reaches the evaporator, and use it to cool the BOG reliquefaction system. This heat exchange is performed in the optimiser, which operates in parallel to the cold box. This has the effect that part of the nitrogen is cooled by heat exchanging with the pressurised LNG.

The optimiser is only in operation when the BOG reliquefaction system is working and the engine is fuelled with LNG. If the reliquefaction system is stopped or the optimiser is not heating the LNG sufficiently, the vaporisation system will heat the gas sufficiently before it enters the engine.

Subcooling

The system shown in Fig. 12 extracts heat by subcooling LNG with a nitrogen loop, which means the resulting LNG temperature is lower than the condensation temperature.

LNG is pumped from the bottom of the tank to the reverse Turbo-Brayton unit, where the LNG is subcooled by several degrees with nitrogen (depending on

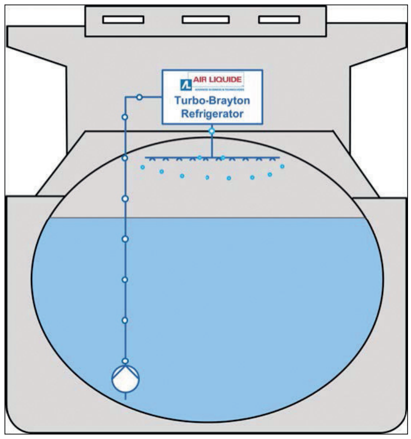

Fig. 12: Subcooling system

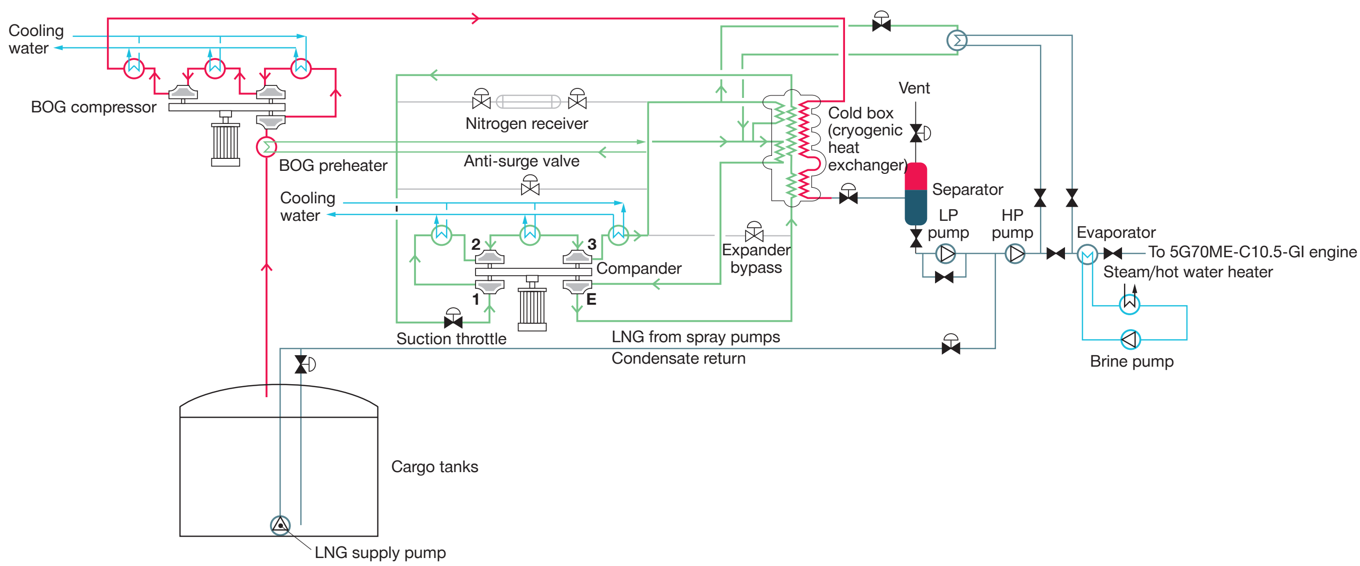

Fig. 11: Integration of the ME-GI fuel gas supply system and a reliquefaction system with optimiser

the flow rate of the pump) and sprayed out in the top of the tank. Spraying the subcooled liquid is a way to regulate the BOG pressure in the tank.

Cascade reliquefaction

Fig. 13 shows an eductor-based cascade reliquefaction system.

In the reliquefaction system shown in Fig. 13 the BOG is compressed to approximately 12 bar and led to the gas booster unit via the aftercooler.

In the booster unit, a multistage compressor compresses the BOG to 200 bar @ 40°C, next the compressed BOG enters the cryogenic cold box, where it is precooled by BOG from the LNG storage tank.

The HP gas is expanded in the eductor, and a mixture of gas and condensate is generated which is separated in the condensate receiver from which the condensate is transferred to the LNG storage tank. BOG generated in the cargo tank is drawn out by the eductor, fed to the gas booster compressor, and is mixed with feed gas for continuous refrigeration.

Integration of MAN PVU and reliquefaction systems

Currently, MAN ES researches the possibility of transferring energy between the MAN PVU vaporiser, where heat is needed to evaporate the HP LNG and the liquefaction system, as partly described in Fig. 11. This solution will not depend on the type of reliquefaction system.

The cold duty removed from the LNG during evaporation can be transferred to the reliquefaction system. The amount of cold heat available for the reliquefaction system depends on the engine load and, therefore, the fuel mass flow. The potential is smaller compressors and expander in the reliquefaction cooling cycle, or complete elimination of both. The total cost of the system will be reduced by utilising the cold duty of the LNG, which is otherwise wasted, and the efficiency of the reliquefaction system will be increased by 15 to 20%.

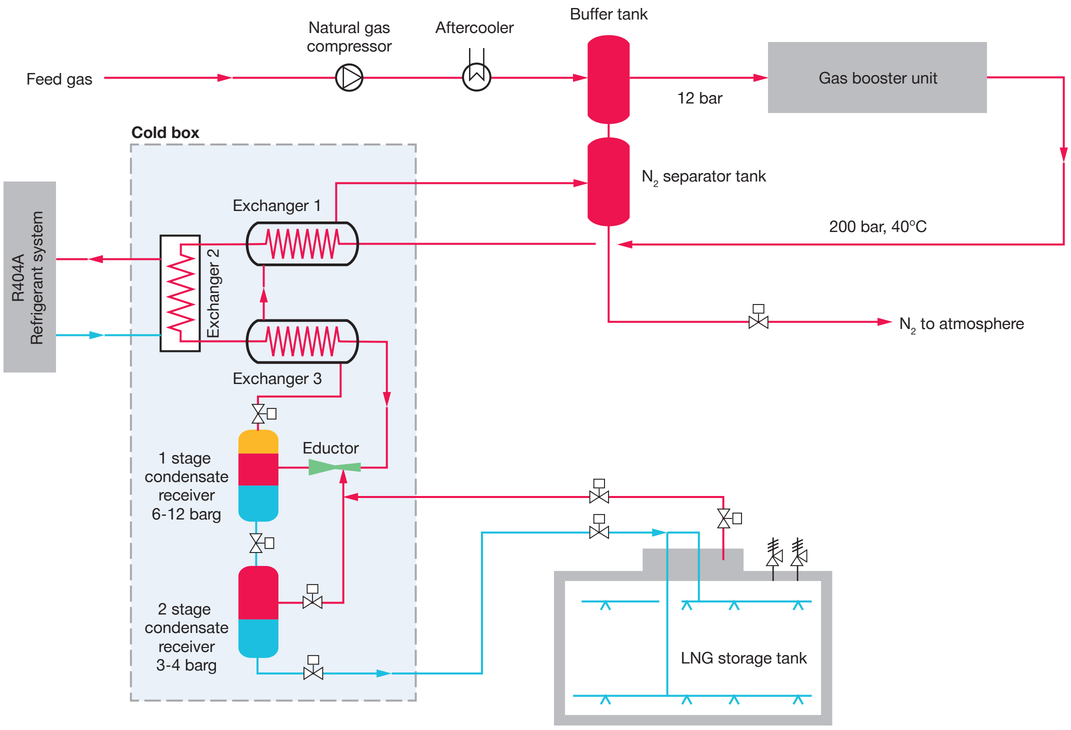

Fig. 13: Cascade reliquefaction system

LNGC and ME-GI dedicated fuel gas supply systems

If the ME-GI engine is combined with dual-fuelled MAN GenSets (or other DF gensets) to cover the electrical consumption, the FGSS must match the fuel gas demands of both engine types. Beyond that, the choices to consider related to the type of FGSS technology and components are numerous, some of the most important being:

1. Operation profile, including for example the time spent in emission restricted areas and restrictions in general
2. Tank size, type and gas holding time
3. BOG amount and the equipment utilising BOG, for example an auxiliary boiler or genset(s) running on BOG
4. BOG compressor
5. Reliquefaction plant
6. Electricity demand and consumption, electricity production, power take out/in (PTO/PTI), genset(s) and DF genset(s)
7. Steam production and consumption
8. Redundancy in FGSS.

The FGSS must supply fuel to all engines taking into consideration all gas supply variables. The engine requirements to gas supply pressure and temperature when operating on LNG are:

- for the ME-GI engine: HP gas at 300 bar, 45°C and
- for the dual-fuel gensets: low-pressure (LP) gas at 6-12 bar, 0-60°C

The amount of gas available in dual-fuel mode depends on the amount available from the FGSS, i.e. on the charter and voyage type and tank conditions. The engine control system (ME-ECS) receives information from the FGSS control system about the available amount of fuel gas, based on this it calculates the required amount of compliant fuel.

When designing an FGSS for LNG carriers, in particular the amount of BOG has a large impact. A BOG rate in the range of 0.08 to 0.135% per day must be handled continuously in loaded condition. Today, the trend goes towards lower BOG rates as the tank insulation technology improves. Presently, FGSS optimisation is given a lot of focus and, in particular, the ability to handle BOG in a cost and environmentally optimised way. MAN Cryo and MAN ES can support the optimisation of a design concerning the above topics in order to find the most optimal way to handle BOG and optimise the size and placement of the LNG fuel tanks.

Often, the design of the FGSS on LNGCs with a relatively large BOG amount is based on either a BOG compressor, delivering 300 bar supply pressure to the ME-GI engine, or on an HP cryogenic pump and vaporiser solution. However, the well-proven technologies of these FGSSs have a cost. MAN ES is constantly evaluating cost reduction possibilities of BOG handling systems together with compressor suppliers and the shipyards involved.

Although, the FGSS is designed according to application, there is quite a large number of factors to consider. The possibilities to optimise an FGSS to match these are increasing. This is reflected in the FGSS layouts:

- BOG compressor, MAN PVU, and partial reliquefaction
- LNG HP pumps and vaporiser, BOG compressor and partial reliquefaction system improved with an intermediate refrigerant recycle
- MAN PVU and reversed Turbo-Brayton unit
- Five-stage twin-compressor system
- Standard high-pressure CT-D twin-compressor system
- MAN Cryo fuel gas supply system

The layouts of these systems are described in more detail in the following sections.

BOG compressor, MAN PVU, and partial reliquefaction

The FGSS in Fig. 14 for larger LNGCs is based on a BOG compressor, an MAN PVU in parallel, and partial reliquefaction.

The BOG compressor and/or the MAN PVU supplies gas to the main engine and gensets. The system has a high degree of fuel flexibility, and the BOG handling efficiency is optimised by installing a reliquefaction plant.

In the flash drum, gas is separated from LNG. Approximately 70% of the flow returns to the cargo tank as LNG and the remaining gas is compressed and combusted. The GCU provides a method to burn off excessive gas in an emergency with a critically rising tank pressure. A suction drum is not needed because LNG is recirculated through the MAN PVU HP pumps.
The FGSS in Fig. 14 is designed with partial reliquefaction, but optionally the BOG compressor can also feed a full reliquefaction system (N_2 cooling system). However, it is not an ME-GI engine requirement.

Boil-off gas compressor

As mentioned, several parameters must be considered when designing an efficient FGSS. One of these is the total amount of BOG, which is highly dependent on the ship operation cycle (loaded or ballast voyage) and the tank pressure level.

If the FGSS is designed with a BOG compressor, the design pressure of the LNG tank can be reduced. The compressor is designed to feed BOG to the ME-GI engine with a pressure at between 200–300 bar depending on the engine load, while simultaneously feeding DF gensets with 6–12 bar gas pressure.

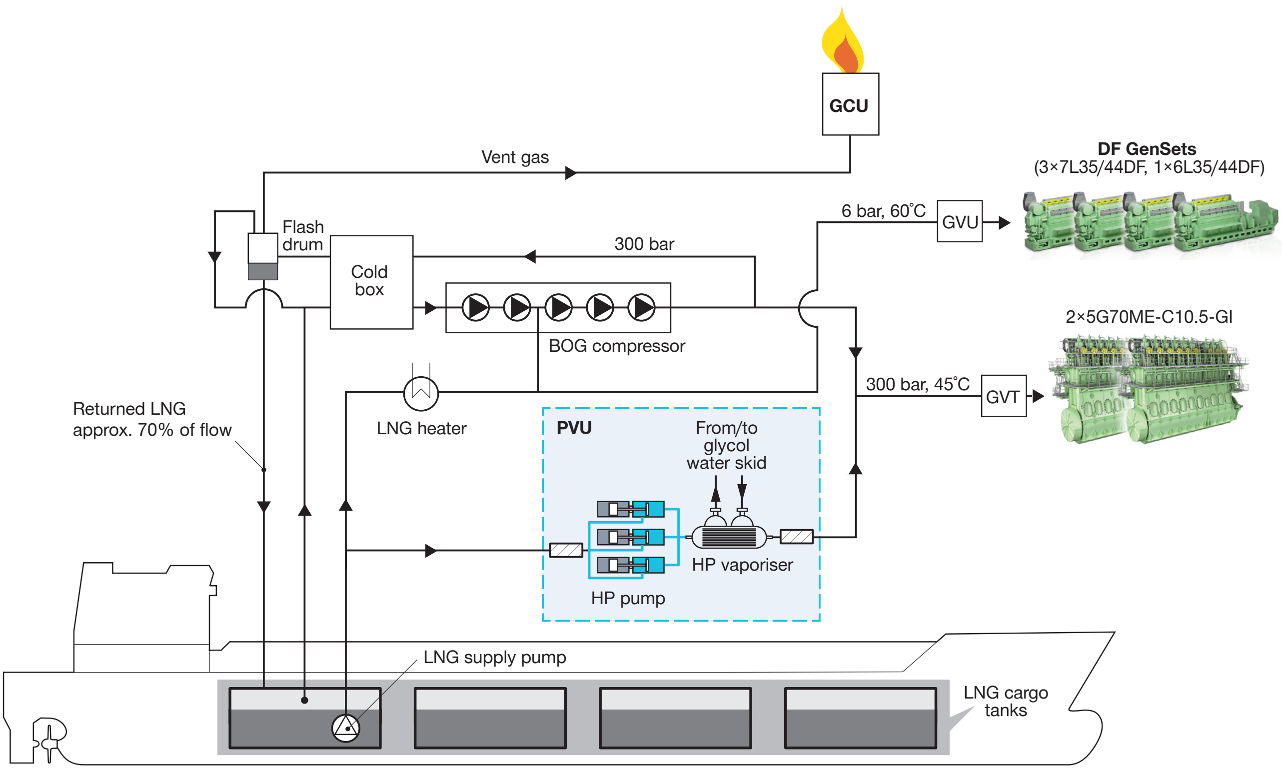

Fig. 14: FGSS based on BOG compressor, MAN PVU, and partial reliquefaction

Figs. 15A–D show examples of BOG compressors from Burckhardt Compression, Kobelco and Mitsui.

The BOG compressor is often exposed to extreme conditions, for example ultra-cold to warm start-ups. The fuel gas compressor is designed for low suction temperatures and has a gas-tight compressor casing. Often the thermal design and material selection means that it is not necessary to precool the compressor or to heat the fuel gas prior to start-up.

As the temperature typically increases 150–200°C between the stages, each compressor stage can be designed with an intercooler to fully control the inlet temperature to the following stage.

Bypass valves can be installed for some of the pressure stages to regulate the flow through the compressor according to the supply pressure required by the engine. The fuel gas supplied to the gensets is taken from one of the early stages and the ME-GI supply after the last stage.

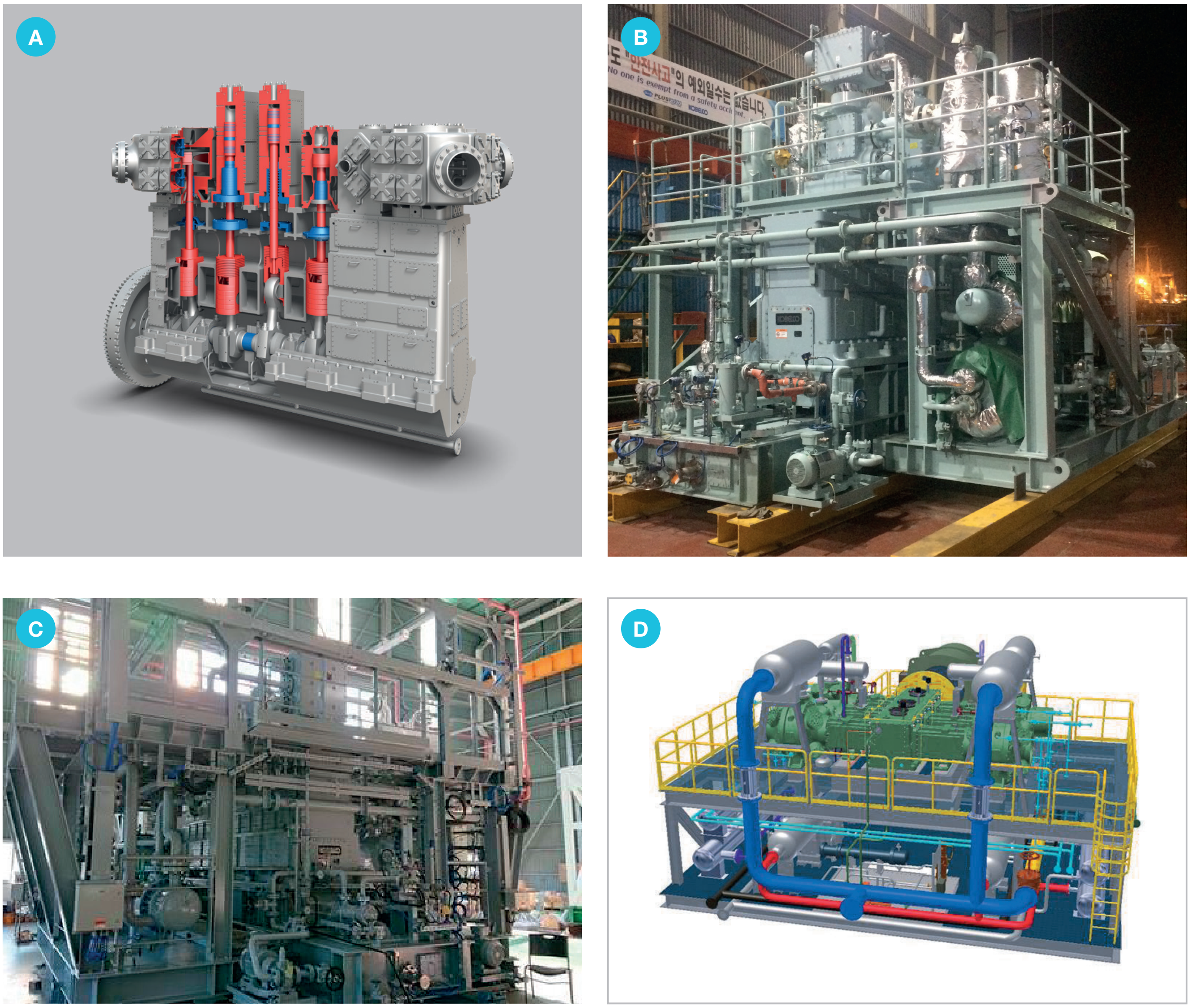

Fig. 15: Examples of BOG compressors for the LNGC application A) Burckhardt Compression, B and C) Kobelco and D) Mitsui – courtesy of Burckhardt Compression, Kobelco and Mitsui

MAN pump vaporiser unit

The MAN PVU is designed to supply LNG with the pressure and temperature required by the ME-GI engine.

The MAN PVU sizes currently available for LNG are shown in Table 2.

As an example, Fig. 16 shows the MAN PVU-7000.

The PVU receives cryogenic LNG supplied by a cryogenic centrifugal pump, and subsequently the HP reciprocating pump pressurises the LNG. The HP pump shown in Fig. 17 has three cylinders actuated by linear hydraulic pistons.

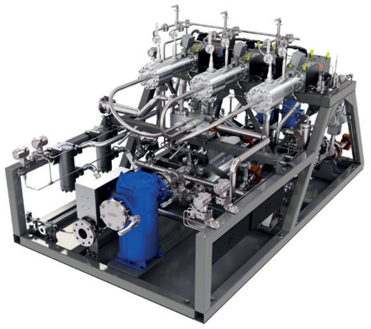

Fig. 16: The ME-GI PVU designed by MAN Energy Solutions (PVU-7000)

The pressurised LNG flows through a compact printed circuit heat exchanger in which it is heated by warm glycol water. A HP filter catches fine particles present in the gas before the gas is directed towards the GVT and the engines.

The gas pressure delivered to the engines is controlled by the hydraulic flow control of the pump. The individual control of the three cryogenic pump heads, each with 50% capacity of full engine load, means that the MAN PVU can still provide full capacity with only two cold ends in service. This means that one pump cylinder can be taken out of service for overhaul while the remaining two are operational and still supplying 100% of the required capacity.

The engine gas pressure and mass flow demands are instantly transferred to the PVU control system and further to the pump module. This results in a very stable and precise gas pressure control, which secures efficient ramp up and down in all operating conditions.

The simplifications implemented in the MAN PVU design result in a reduced number of sub-systems and components, and the compact design introduces considerable savings in the complete FGSS.

Gas valve train

The recent cost-optimised GVT Mk. 4 in Fig. 18 controls the safe admission of gas to the ME-GI engine via the commands from the ME-GI ECS.

As Fig. 14 shows, the GVT is installed between the FGSS and the ME-GI engine to provide a double block-and-bleed function, when the engine is not running on gas or whenever the ME-GI ECS requests a gas stop. In reality, it means that the volume between the block-and-bleed valves depressurises when the gas system is out of operation.

Table 2: MAN PVU line-up for methane

Type of PVU	LNG (kg/h)	Engine power (MW)	Length x width x height (mm)	Weight (kg)
PVU - 1,000	Up to 1400	Up to 9.0	(3,700 x 2,240 x 2,000)	2,500 - 3,500
PVU - 3,000	1,401 - 2,900	9.1 - 18.4	(3,700 x 2,240 x 2,000)	3,500 - 4,500
PVU - 5,000	2,801 - 6,800	18.5 - 30.3	(3,700 x 2,240 x 2,000)	4,000 - 5,000
PVU - 7,000	4,701 - 6,800	30.4 - 44.0	(4,800 x 2,240 x 2,000)	5,500 - 6,000
PVU - 10,000	7,601 - 9,500	49.6 - 61.9	(4,800 x 2,240 x 2,000)	5,500 - 6,000

Fig. 17: MAN PVU HP pump

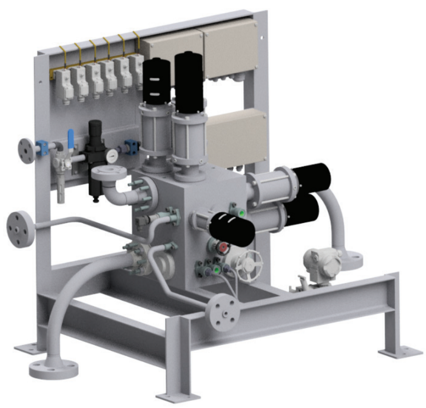

Fig. 18: The gas valve train Mk. 4

The GVT is designed with slow-opening valves to ensure that HP gas is admitted slowly in order to avoid pressure shocks on the seals.

LNG high-pressure pumps and vaporiser, BOG compressor and partial reliquefaction improved with an intermediate refrigerant cycle

Fig. 19 shows a conventional FGSS where two LNG HP pumps, a vaporiser and a BOG compressor in parallel supply gas to the ME-GI engine.

The cargo tanks are equipped with in-tank pump(s) to feed the HP system and the heaters in the LP system for the gensets.

The HP pumps, vaporiser and heater are utilised here to achieve the required 300 bar pressure level. The pumps must cover the range from minimum fuel gas load to maximum load. The electric motors for the LNG HP pumps can be controlled by a variable frequency drive (VFD).

A suction drum has to be incorporated in the design to ensure that there is a large LNG volume on the suction side of the LNG HP pump, which secures cold suction temperatures and prevents cavitation.

The FGSS can be optimised by improving the partial reliquefaction system by precooling the gas in an intermediate refrigerant recycle level (intercooler), where the gas is cooled prior to expansion in the cold box. In this way, the pressurised gas is precooled before the expansion and the efficiency of the overall process is increased.

LNG high-pressure pumps and vaporiser

The HP pumps and vaporiser can be arranged on a skid for easy installation.

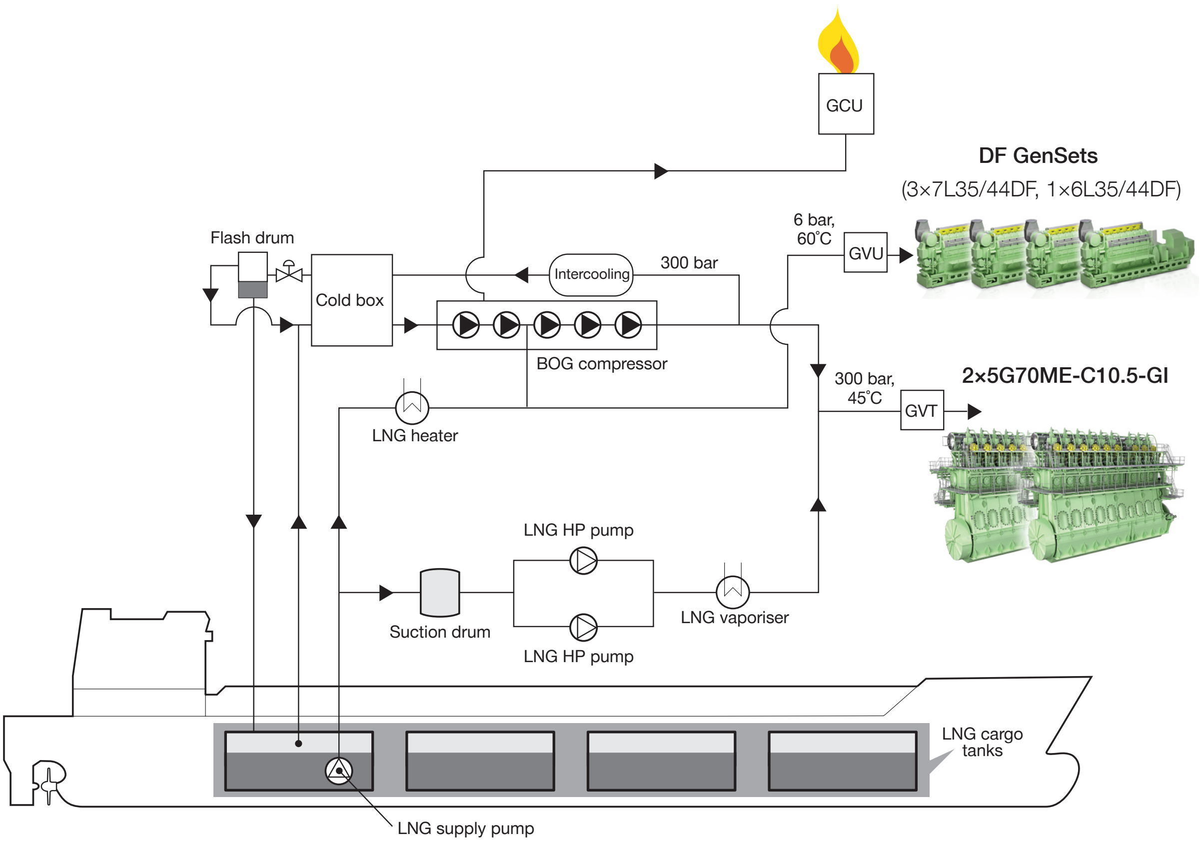

Fig. 19: FGSS based on LNG HP pumps, vaporiser, BOG compressor and partial reliquefaction

MAN PVU and a reverse Turbo-Brayton unit

The new FGSS solution in Fig. 20 combines the MAN PVU and a sub-cooling unit based on the reverse Turbo-Brayton cycle.

The principle behind this solution is that the sub-cooling system draws liquid LNG from the tanks, cools it to a temperature below the LNG temperature in the tank and returns the sub-cooled LNG to the tank utilising the built-in spray system in top of the tank.

As the LNG in the tank becomes sub-cooled, the BOG rate is minimised to a steady-mass equilibrium depending on the gas consumption.

The sub-cooling process does not alter the LNG composition in the tank and the minimised BOG combustion necessary does not change the composition considerably.

In this FGSS, the fuel gas supply for the ME-GI engine comes from the MAN PVU, and a BOG compressor is not needed.

Five-stage twin-compressor system

For owners and charterers requiring full redundancy of BOG delivery, a simplified and cost-optimised system based on two fuel gas compressors has been proposed, leaving out the conventional cryogenic pump and vaporiser.

The operating conditions for an LNG carrier are surplus BOG in loaded condition and approximately 50% BOG (of the cargo tank content) in ballast condition, if a 10% heel is maintained. This allows the vessel to operate on boil-off gas 75% of the time. The short period (approx. 25%) of operation on LNG does not allow a reasonable payback time covering the capital expenditure (capex) of the LNG cryogenic pump.

The layout can be designed as previously shown in Fig. 10 with a submerged LNG supply pump and two compressor strings delivering simultaneously HP fuel gas to the ME-GI and LP fuel gas to DF gensets.

Two fuel gas compressors each capable of handling 100% of the BOG are installed. The power consumption of the compressor is six times that of the cryogenic pump, when delivering the same flow to the main engine. The main compressor will be operating continuously to ensure full redundancy, and the second compressor unit can be started manually in case of a malfunction. Studies show that two compressors handling 75% of the BOG each can be sufficient in most cases. Furthermore, it is important to look at the inlet temperature of BOG to the gas compressor. If the temperature can be lowered, a smaller compressor size can be chosen. Insulation of LNG tanks and BOG pipes on deck have often been discussed as a way to lower the temperature.

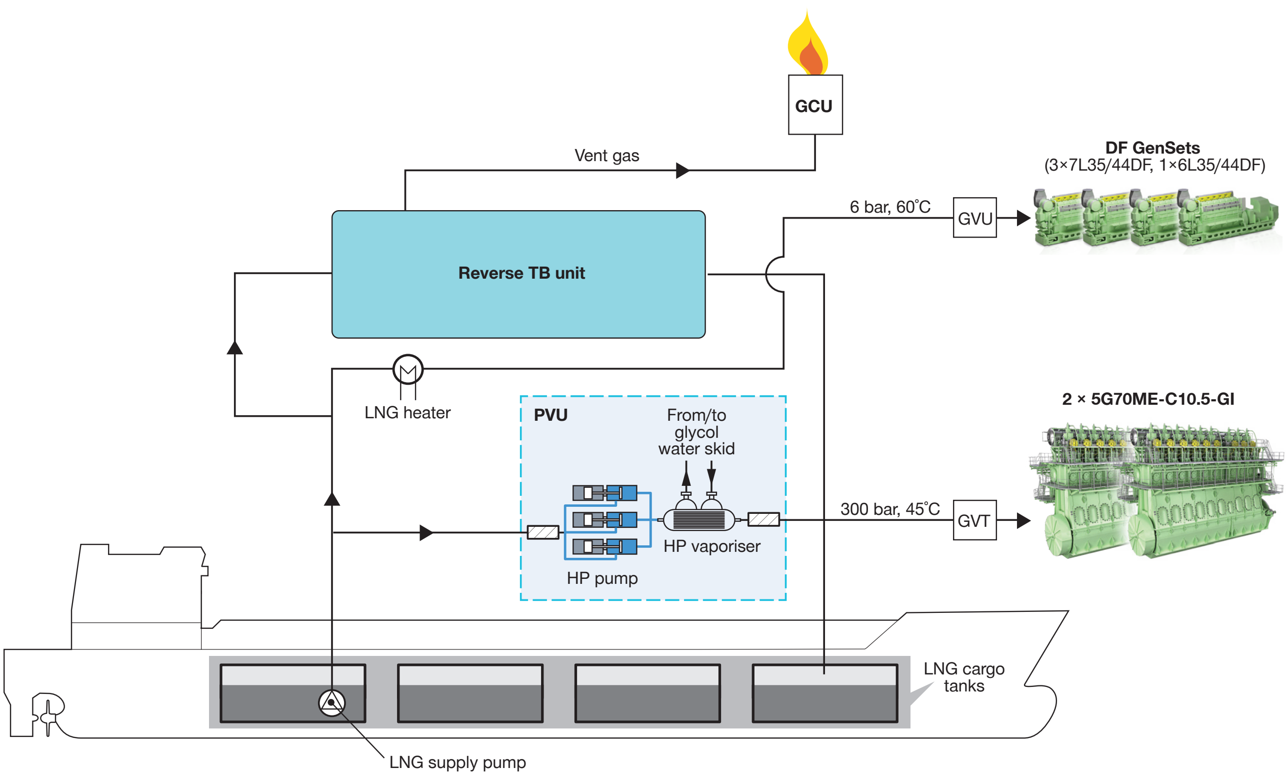

Fig. 20: FGSS layout with MAN PVU and a reverse Turbo-Brayton unit

Compressor

The Burckhardt compressor pressure range of 150-300 bar covers the required fuel gas delivery pressure in the load range of the ME-GI engines. However, several makers, for example Mitsui Engineering & Shipbuilding, Kobelco and General Electric produce reliable piston compressors applicable in this FGSS design. The GE compressor requires preheating of the fuel gas.

Standard high-pressure CT-D twin-compressor system

Since shipowners increasingly demand cost-optimised solutions, MAN ES and Burckhardt Compression have developed a simple FGSS for both ME-GI powered small LNG carriers as well as other ME-GI powered vessels. As an example, Fig. 21 shows the FGSS for a 30 kcum LNG carrier based on two small and compact compressor units.

For this purpose, Burckhardt Compression developed a CT-D compressor design solution based on the well-proven trunk piston technology. Depending on the specific setup and as an alternative to the Laby®-GI, the CT-D design can contribute to a tangible capex reduction of the complete propulsion system.

The standard HP range compressors from Burckhardt Compression with a discharge pressure up to 310 bar are divided into four compressor types with flow capacities from 24 kg/h up to 500 kg/h for the CT compressor shown in Figs. 22 and 23, and 675 kg/h for the CX compressor.

The FGSS solution shown in Fig. 21 is based on two CT-D compressor units, where each unit with two CT compressors driven by a common electric motor delivers 1000 kg/h. The application of multiple compressors opens interesting partial redundancy options. Full redundancy is obtained if three CT-D compressors are installed.

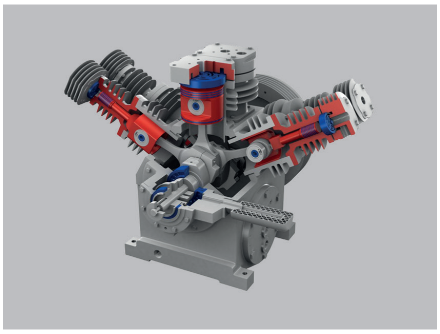

Fig. 22: Cross section of the CT compressor

Fig. 23: Installation of the complete CT-compressor solution

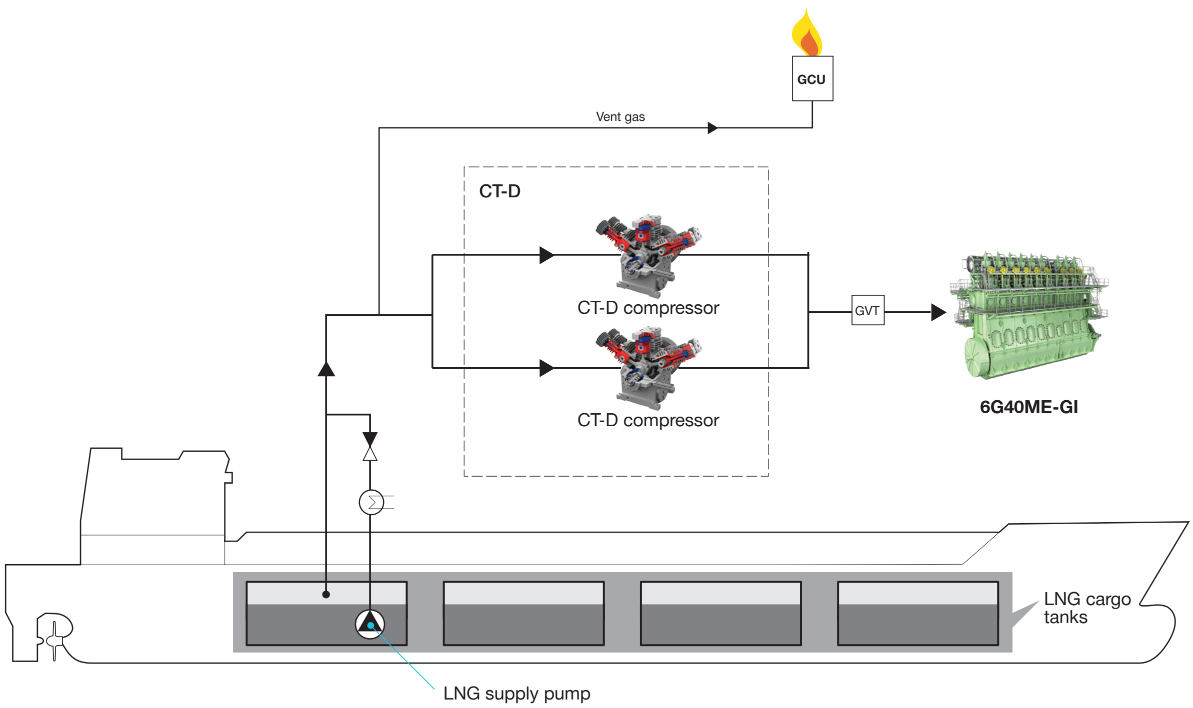

Fig. 21: FGSS solution with two CT-D compressors

The system provides efficient part-load operation, where one compressor unit can be taken out of operation when the load drops.

Further benefits are the simplified installation of the small unit, see Fig. 23, and the slightly reduced or comparable power consumption compared to the Laby®-GI. As with the Laby®-GI solution, a partial reliquefaction system based on a common cold box and suction drum can be built in without requiring an additional compressor.

Compressor characteristics

The CT-D compressor is built with an inter-cooler between the five stages to fully control the inlet temperature to the next stage. Since the FGSS is based on multiple smaller compressors, the smaller rating of the electric motor enables the use of less expensive and less complicated variable frequency drives than for the larger motors. The electric motor and the variable frequency drive must be ATEX approved. The use of a variable frequency drive gives the optimum turn-down power curve shown in Fig. 24.

Fig. 24 shows a comparison of relative shaft power (shaft power/shaft power$_{MAX}$) as a function of relative flow (flow/flow$_{MAX}$) for the CT compressor operated with variable frequency drive (ideal curve) and for the conventional compressor bypass (blue curve).

The engineers on board can perform normal in-between maintenance work on the CT compressors. The maintenance cycle of the CT compressor is higher than for the Laby®-GI, though still manageable, which makes this design an attractive alternative.

MAN Cryo fuel gas supply system

A reliable and safe operation of LNG-fuelled vessels is necessary. MAN ES offers a complete propulsion package including LNG fuel gas supply systems via MAN Cryo.

MAN ES took over fuel-gas specialist Cryo AB in 2015 and fully integrated it into its business. Under the brand MAN Cryo, the company offers systems for storage, distribution and handling of liquefied gases within the marine segment.

To get an LNG fuel gas system with both optimised operation and investment costs, it is important to understand the nature of LNG, BOG handling and the operation pattern of the ship. With more than 20 years of experience in LNG fuel gas systems, MAN Cryo is known for its high quality standard and reliable LNG system designs.

MAN Cryo offers FGSS solutions for LNG including C-type tanks, BOG handling and compressors, glycol water handling, LNG bunkering and the MAN PVU for ME-GI engines.
MAN Cryo also has a close cooperation with Gaztransport & Technigaz about membrane tanks solutions. Hence, MAN Cryo offers a complete LNG fuel gas system optimised for the ME-GI.

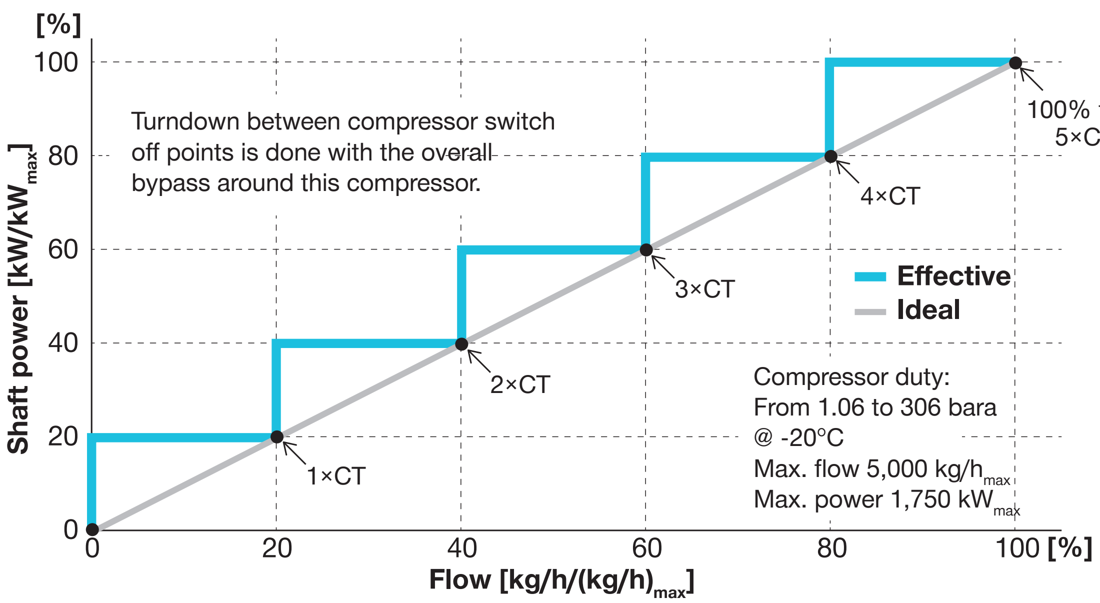

Fig. 24: Turn-down curve for 5 CT compressors and a compressor with bypass for comparison

Summary

The advantages of combining the ME-GI engine with the different FGSS configurations described in this paper are highly efficient and cost competitive propulsion solutions.

The most recent edition of the ME-GI engine offers advantages related to all major aspects of vessel propulsion, operation, greener environment and costs. The Diesel principle applied for the ME-GI engine ensures reliable and cost-optimised operation on almost any fuel and in all conceivable weather conditions in the most environmentally safe way. The advantages of the novel weight and performance optimised Mk. 10 engine layout have been integrated into the ME-GI engine together with the ME-GI Mk. 2 improvements.

When combined with one of the MAN PVU-based fuel gas supply solutions, the most reliable and dependable propulsion systems to date are available for LNG carriers. The MAN PVU is a turnkey FGSS solution, continuously optimised to suit the different needs by improving the performance, the overall layout, and by reducing the number of components in the installation. MAN Cryo offers a complete LNG fuel gas supply system package including the PVU.

The FGSS solutions are optimised with the different requirements from individual ship types in mind. The intention has also been to utilise the capabilities of the individual components fully without compromising part-load operation or redundancy, which can be integrated into the system in more ways than previously.

Besides recent developments within LNG tank technology, insulation technology and reliquefaction systems have to be considered when designing the FGSS.

A flexible engine room layout of this kind offers the most fuel-flexible and environmentally safe solution. The flexibility in designing the engine room layout as desired will give the shipowner and yard the most cost and efficiency optimised solution on the market.

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Acronyms and Abbreviations

ATEX	Atmosphères Explosibles
AVL	Anstalt für Verbrennungskraftmaschinen List
BOG	boil-off gas
CAPEX	capital expenditure
CEAS	computerised engine application system
DF	dual fuel
DSME	Daewoo Shipbuilding & Marine Engineering
EGR	exhaust gas recirculation
EGRBP	exhaust gas recirculation bypass
ECS	engine control system
FBIV	fuel booster injection valve
FGSS	fuel gas supply system
FRS	full reliquefaction system
GCU	gas combustion unit
GWP	global warming potential
GVT	gas valve train
HFO	heavy fuel oil
HHI	Hyundai Heavy Industries
HP	high pressure
IMO	International Maritime Organization
J-T	Joule-Thomson
KHI	Kawasaki Heavy Industries (KHI)
LNG	liquefied natural gas
LNGC	liquefied natural gas carriers
LP	low pressure
MCR	maximum continuous rating
MRS	mixed refrigerant system
MTPA	metric tonnes per annum
NG	natural gas
OPEX	operating expenditure
PIV	pilot injection valve
PRS	partial reliquefaction system
PVU	pump vaporiser unit
SGC	specific gas consumption
TCEV	top controlled exhaust valve
VFD	variable frequency drive

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