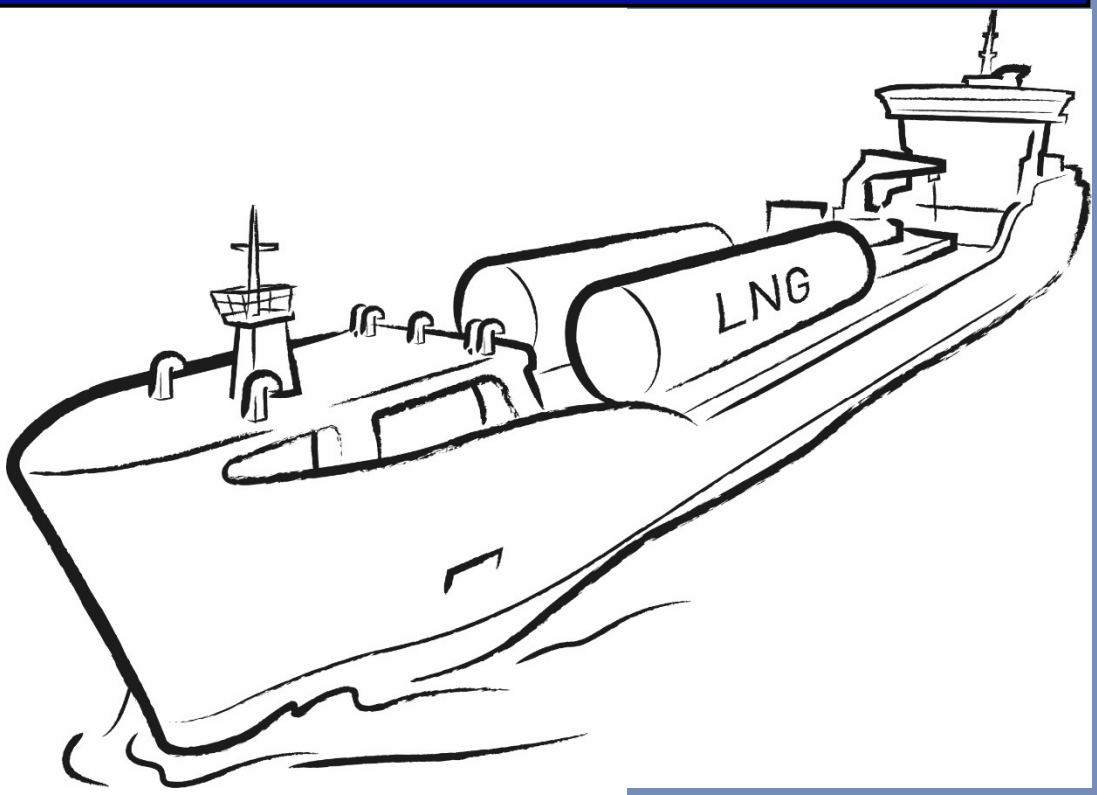
WIN GD
Winterthur Gas & Diesel

Application of WinGD X-DF engines for LNG fuelled vessels



Winterthur Gas & Diesel Ltd.

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Executive summary

The increasingly stringent regulations concerning the sulphur content in fuels and related SO_X emissions, along with requirements to reduce CO_2 emissions, are increasing the attractiveness of LNG as a clean fuel and valid alternative to conventional fuel oils.

With the International Maritime Organization's (IMO) worldwide fuel sulphur cap being lowered to 0.5 % from 2020 onwards, the use of LNG fuel can benefit not only ships sailing in ECA areas but essentially all merchant vessels.

At the same time the global LNG infrastructure is rapidly being expanded to enable continuous operation with LNG, while fuel price levels can offer an additional advantage to vessels operating on LNG fuel.

Winterthur Gas and Diesel (WinGD) has launched the X-DF engine series, the only marine low-speed engines able to operate with low-pressure natural gas. In comparison to the high-pressure natural gas application, the low-pressure dual-fuel technology applied in the WinGD X-DF engines not only guarantees the significant benefits in reduced sulphur and CO_2 emissions by application of LNG as fuel, but additionally reduces particulates by more than 85 %. Importantly, the low-pressure gas technology enables the engine to comply with the IMO Tier III NO_X limits without the need of any cost intensive after-treatment system.

In LNG fuelled vessels, the fuel gas supply system (FGSS) requires special attention. The different components are described in this paper. The choice of the low-pressure dual-fuel technology has a beneficial impact. By choosing the WinGD X-DF engine, using low-pressure gas only up to 16 bar, the FGSS is both cheaper and safer than an installation with an engine requiring high pressure LNG of up to approximately 300 bar. In operation, the low pressure gas installation needs less energy and involves lower maintenance efforts and costs.

This paper gives an overview of the layout of an LNG fuelled vessel, including a more detailed description of the X-DF engine technology, the related fuel gas supply system layout possibilities for merchant vessels, as well as the derived operational and commercial benefits.

1 Introduction – LNG as a fuel for marine propulsion

Natural gas has gained increasing interest as an alternative fuel to marine diesel and heavy fuel oils (HFO) for merchant shipping.

This development is primarily driven by its potential to reduce emissions of:

- Carbon Dioxide (CO_2)
- Nitrogen oxides (NO_X)
- Sulphur oxides (SO_X)
- Particulate matter (PM)

The IMO has lately enforced or introduced new emission regulations for CO_2 and the sulphur content of fuel.

Newly built ships need to be in compliance with EEDI (Energy Efficiency Design Index) limits, which will be further reduced in 2020 and 2025. The use of LNG as fuel is one possible measure to reduce the CO_2 footprint at the same energy output.

The maximum allowed fuel sulphur content is being reduced step by step. Following the implementation of the 0.1 % limit in Emissions Control Areas (ECAs) from 2015, and a global cap of 3.5 % from 2012, the IMO has decided upon a globally effective limit of 0.5 % from 1. January 2020. The use of expensive low sulphur fuels or the installation of scrubbers can be avoided by operating the vessels on LNG fuel.

Eventually the first low-speed gas engines ordered exploit the benefits of natural gas during vessel operation in IMO ECAs or other areas with stringent national emission limits. With the new worldwide fuel sulphur cap set at 0.5 % from 2020, LNG becomes attractive also for vessels operating continuously outside ECAs.

In the long term, it is expected that natural gas will be readily available worldwide in ports with a competitive price level compared to oil based fuels, and this serves as a real incentive to apply gas as engine fuel on any kind of seagoing vessel.

To meet the demand for engines capable to run on natural gas, WinGD developed the low-pressure dual-fuel technology for the low-speed X-DF engines. It is derived from the low-pressure gas technology successfully introduced on four-stroke medium-speed engines, which has become the industry standard gas combustion technology in this range of applications.

One important advantage of the low-pressure natural gas technology is the capability to meet emissions limits that are considerably below the IMO Tier III level in ECAs without expensive NO_X exhaust gas after treatment systems or engine internal measures. Engines designed to operate with high pressure natural gas (around 300 bar) do require such after treatment systems.

An important aspect in the use of natural gas in marine vessels is the detailed layout of the fuel gas supply system. For diesel oils, the fuel treatment systems are well known and over the years have become highly optimized. Conversely, the storage and handling of gas for marine propulsion still involve selecting from many variants that impact financial and operational aspects. These different solutions are highly influenced by the choice between engines with either low-pressure or high-pressure gas technology.

2 The move from fuel oil to LNG operated vessels

2.1 LNG as a competitive opportunity

The decision to equip a new vessel with LNG instead of oil based fuels as main fuel is linked to either emission compliance issues or commercial advantages, or both. The initial investment into a LNG propulsion system can add an additional 20 % to 30 % to the vessel price. The main driver for making such an investment is therefore the expected benefit derived from the reduction in fuel operating costs.

In SO_X Emission Control Areas (SECAs), LNG competes with MGO or ultra-low sulphur fuels. Outside these areas, HFO may remain as the main competing fuel, albeit from the year 2020 in combination with a SO_X scrubber system.

The prices for LNG are usually published in US$/mmBTU, which corresponds to approximately 38 to 41 US$/ton for fuel oil, depending on the actual compared gas or fuel qualities. A common natural gas price reference is the Henry Hub index price, which indicates the price of natural gas in the pipeline system in the USA. To transport gas worldwide and to use it as marine fuel, the natural gas has to be liquefied and distributed via a dedicated logistics system, which increases the price of LNG by about 3 to 5 US$/mmBTU.

Below Figure 1 shows the price development of LNG from 2013 to mid-2016. It can be seen that still today, a substantial economic advantage can be achieved with LNG driven vessels operated in SECAs, where MGO is the reference fuel. With LNG being 6 US$/mmBTU cheaper, savings of 2.4 Mio US$ per year can be achieved by vessels operating at an output of 10 MW.

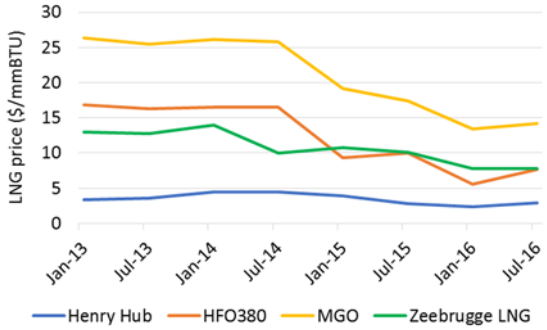


Figure 1: Fuel price development from 2013 to 2016. (Zeebrugge LNG price is shown including a 3 US$/mmBTU markup for liquefaction to the natural gas price)

Outside SECAs, the savings in 2013 would have been close to 4 US$/mmBTU with LNG from Zeebrugge (Belgium) compared to HFO, but declined to a similar price level mid of 2016. Thus, the potential savings varied between zero and 1.6 Mio US per year at an average operating power of 10,000 kW.

However, the general expectation is that oil prices will pick up again and the cost attractiveness of LNG will reincrease accordingly.

2.2 Ensuring the availability of LNG for LNG fuelled vessels

LNG as a clean energy source for electric power, heat generation and mobility, has received increased global attention. As a consequence, all over the world LNG import or export infrastructures, including liquefaction and/or regasification plants for natural gas supplied by LNG carriers or pipelines, are available. As the continuously increasing fleet of large LNG carriers prove, this LNG supply chain will continue to grow. Until now, most of this infrastructure built up has been targeted for land-based applications of natural gas. For marine application the infrastructure is just starting to be built up.

The LNG bunkering for vessels can be carried out in various ways, by direct vessel to vessel bunkering at sea or in port, from a land-based fixed tank, or from trucks.

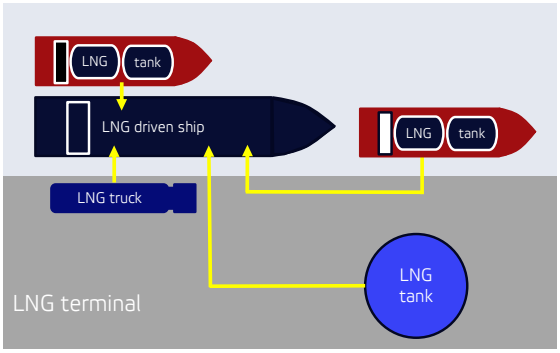


Figure 2: LNG bunkering possibilities: ship or barge to ship, truck to ship (up to 60 cbm/truck), tank to ship

The highest concentration of bunkering terminals, mainly for small LNG fuelled vessels, is currently located around the Baltic Sea (Figure 4).

For larger vessels with 1000 cbm or more LNG tank capacity, the most suitable bunkering solution is expected to become bunker ships having several thousand cbm capacities. Many of the existing large LNG terminals being supplied by LNG carriers on a regular basis are capable of loading these LNG bunker vessels, which can in turn supply ships at different locations.



Figure 3: Ship to ship bunkering of LNG. (Picture: Port of Gothenburg)



Figure 4: The developing LNG supply infrastructure in Europe. A snapshot of existing (large black), planned (dark blue), or proposed (small, light blue) LNG supply points. (Source: DNV-GL LNG report, Jan. 2015)

During 2017 and 2018 many projects will be realized along the Northern European and North American coasts, as well as in Singapore and China, thus multiplying the bunkering facilities for vessels with tank capacities of more than 1000 cbm worldwide. It is also important to note that several bunkering vessels with capacities of between 5000 and 7000 cbm have been ordered for delivery between 2016 and 2018. These ships will be used to transfer LNG from large terminals to LNG fuelled ships.

2.3 Vessel design

Worldwide small and large shipyards are investing in the design of LNG fuelled vessels.

One key element to be considered when moving from diesel to LNG fuel is that of the tanks (see description in chapter 4.3). Due to the lower density of LNG, which is less than half that of HFO, and the additional isolation requirement, LNG tanks including the installation room require about double (large tanks) or four times (small tanks) the space compared to an HFO tank. This additional space requirement imposes the need for new and innovative ship designs that enable the same cargo capacity for similar vessels.

Fuel gas handling and related operational matters, such as bunkering, boil-off handling, and safety issues, also demand additional design considerations for the shipyards (see chapter 4).

3 Low-pressure X-DF engine technology

3.1 LNG combustion technology

LNG can be burned in gas form after injection into the combustion chamber with low or with high pressure.

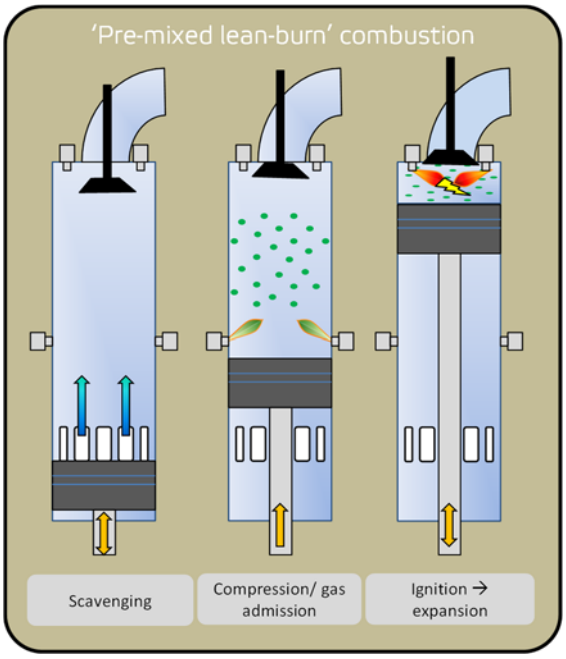


Figure 5: Low-pressure gas injection with lean-burn Otto cycle combustion process as implemented with WinGD low speed X-DF dual-fuel engines

With low-pressure injection, the lean-burn pre-mixed combustion concept can be applied. This so-called Otto cycle is characterized by a fast combustion at low maximum combustion temperatures, leading to very low NO_X emissions that are below the IMO Tier III level.

High-pressure gas injection is required to follow the known Diesel cycle. The gas combustion, despite the assistance of pilot fuel injection, is slower than with fuel oil. But, due to the characteristic diffusion flame, the maximum combustion chamber temperature remains very high, leading to high NO_X emissions that are closer to the level of standard diesel engine.

3.1.1 Gas injection

When injecting gas into the closed combustion chamber at the beginning or during the first phase of the compression phase (piston close to bottom dead centre), the pressure in the combustion chamber is low. This allows the gas to be injected at low pressure. After injection, the gas mixes with air before igniting close to the top dead centre position of the piston. Due to the homogeneous mixture, the so-called lean-combustion follows the Otto cycle.

On the other hand, when injecting the gas close to the top dead centre, the compression pressure can reach pressures of more than 150 bar. This means that gas pressures of about 300 bar or more are required to ensure a quick introduction, good mixing with air and finally efficient combustion following the Diesel cycle.

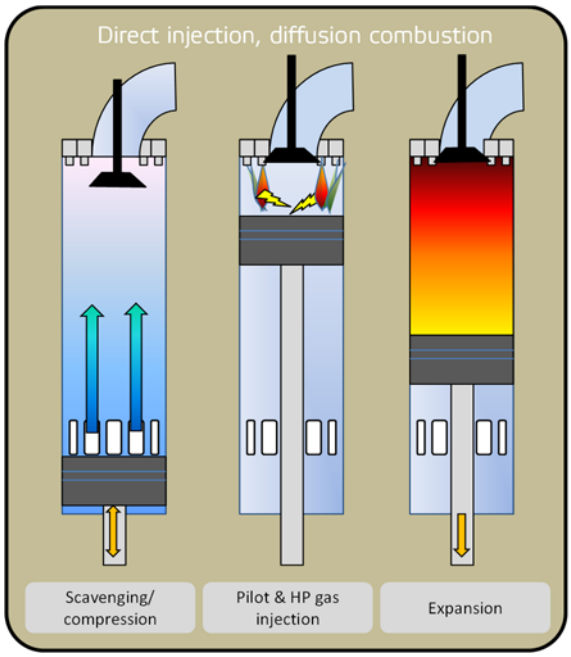


Figure 6: High-pressure gas injection with Diesel cycle combustion process

3.1.2 Gas combustion

With the low-pressure gas injection, the pre-mixed gas and air need a support to start the combustion. Ignition can be stimulated by different energy sources, the most common being:

- an electro-magnetic spark (spark ignition)
- a fuel oil pilot injection, with the amount of fuel as low as 0.5 % of the total injected fuel (gas and fuel oil)

Intensive research and development on large low-speed marine engines has revealed that the pilot injection is the most suitable technology for the low-pressure gas engine. It reduces the required quantity of pilot fuel oil to levels below 1 %, achieves high efficiency, and ensures

compliance with the IMO NO_X Tier III limits without any after treatment system.

With high-pressure injection the gas can, in principle, burn directly after injection through a diffusion flame. But the burning speed would be too slow without any additional combustion support. Commonly, therefore, the gas combustion is supported by an additional fuel oil pilot injection, thus increasing both heat and turbulence to accelerate the gas combustion. The required fuel oil pilot with high-pressure gas injection can represent 5 % to 10 % of the total injected fuel energy. This impacts emissions and may prevent the possibility of operating on gas at less than 10 % engine load. Tier III compliance can only be achieved by installing expensive exhaust gas after treatment capability, or an exhaust gas recirculation (EGR) system.

3.2 Benefits of the low-pressure dual-fuel technology

The low-pressure gas injection and combustion process applied in WinGD low-speed X-DF engines provides the following benefits:

- NO_X emissions compliant with IMO Tier III limits in ECAs without any need for after treatment systems
- Sulphur oxide (SO_X) and particulate emissions reduced to almost zero
- Low-pressure gas supply and injection system with low investment and maintenance costs
- Stable operation on gas across the entire load range makes the use of gas fuel possible for port-to-port operation and manoeuvring.
- Low operating costs thanks to low auxiliary power consumption for the low-pressure system
- Minimal fuel oil need, the pilot fuel quantity remaining below 1 % of the total heat release

3.3 The WinGD X-DF low pressure dual-fuel engines

3.3.1 Basic engine design

WinGD low-pressure X-DF engines are based on the existing RT-flex and X- diesel engine series. Except for the newly developed gas and pilot injection system, all components are of the same design.

Few parts need to be adapted for specific additional installation requirements to be able to operate the engine not only with fuel oil, but also with low-pressure gas.

The X-DF dual-fuel engines therefore benefit from reliable and proven technologies relating to the engine structure, bearings, combustion chamber design, lubrication systems, and electronic control system.

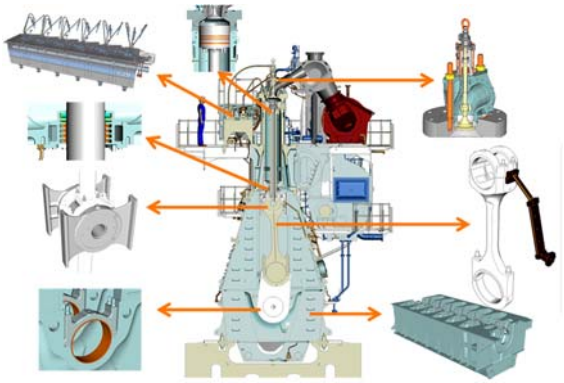


Figure 7: Proven technologies from the RT-flex and X-engines applied for the WinGD X-DF engines

3.3.2 Gas and pilot injection technology

To bring the low-pressure gas from the vessel's gas supply system into the engine combustion chamber, the following main parts had to be adapted or added to the diesel engine:

- Gas admission piping system
- Gas admission valve (GAV) on the cylinder liner to inject the gas into the combustion chamber
- Cylinder liner modified for GAV installation
- Pilot injection system consisting of pilot fuel pump, piping system and pilot injector
- Pre-chamber for pilot injection combustion
- Adapted cylinder cover to accommodate the pilot injectors with the pre-chamber

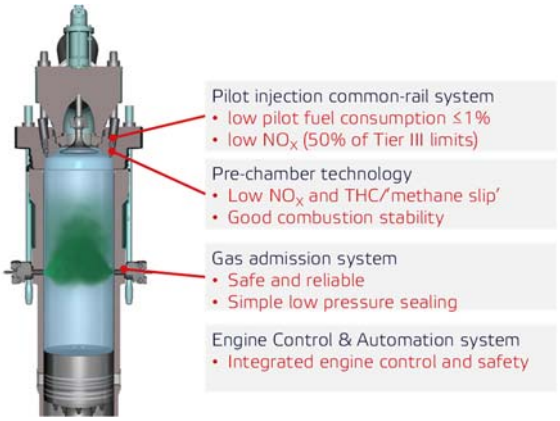


Figure 8: Key gas combustion systems components of the low-pressure dual-fuel engine

Gas piping system

The proven double wall pipe design used also in standard diesel engines is applied for the main and pilot fuel high-pressure pipes. The proper layout and dimensioning ensure that pressure losses and dynamic pressure fluctuations, which could disturb proper operation of the system, are kept low.

All gas distribution pipes on the engine feature a double wall design, and are made of stainless steel in order to comply with existing safety rules. Additionally, the safety relevant shut-off and vent valves in the piping are integrated into the double wall design.

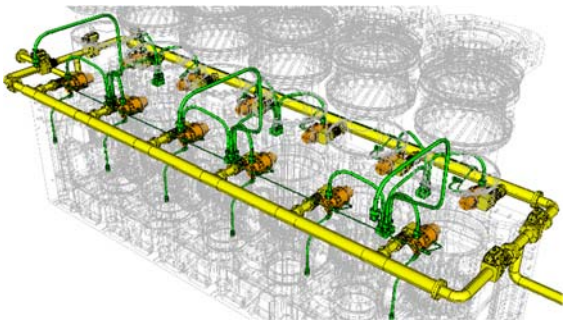


Figure 9: Gas admission system related piping

Gas admission valves (GAV)

To satisfy the specific requirements of the low-speed engines, an entirely new gas admission valve was developed (Figure 10).

The poppet valve concept maximises reliability and ensures ready maintainability. A space efficient hydraulic actuation system allows the outline dimensions of the valve to be kept as small as possible. The necessary hydraulic power supply is taken from the existing servo-oil system, which also actuates the exhaust valve as with the original diesel engine.

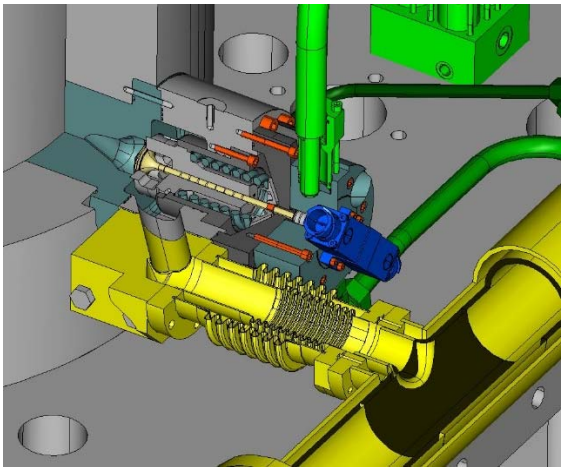


Figure 10: The gas admission valve arrangement

For increased operational safety, the gas admission valves are equipped with a stroke measurement sensor, which allows the engine control system to take immediate action in case of a valve or related control signal malfunction.

After passing through the gas admission valve, the gas fuel is introduced into the cylinder via gas admission bores which pass through the cylinder liner wall. The detailed design of the admission bores in terms of dimensioning and geometry is chosen to achieve best mixture homogeneity and to optimize the engine performance.

Pilot fuel ignition system

With a pilot injector, the pilot fuel is injected into a pre-chamber. This pre-chamber makes it possible to considerably reduce the amount of pilot fuel, thus guaranteeing ignition stability and low NO_X formation levels.

Figure 11 shows where the two pre-chambers per cylinder are added to the cylinder cover, while the main fuel injectors are still located in their original positions.

The water-cooled pre-chamber inserts are manufactured from hot gas corrosion-resistant material, and the pre-chamber tips can be replaced separately. Cooling water channels in the cylinder covers cool the pre-chamber using the existing cooling water circuit for cylinder liner, cover, and exhaust valve.

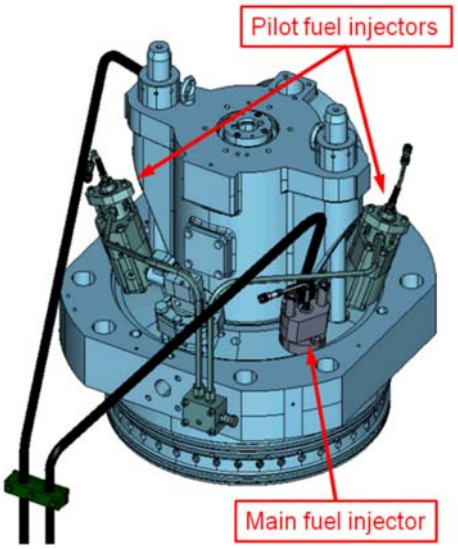


Figure 11: Main and pilot fuel injector arrangement on cylinder cover

At reference full load conditions, the amount of pilot fuel accounts for less than 1 % of the energy input, a level lower than any other system available on the market. When the engine is operated in pure diesel mode, the pilot fuel injectors are activated with a further reduced injection volume, which prevents the formation of excessive deposits on the injector tip and in the pre-chamber.

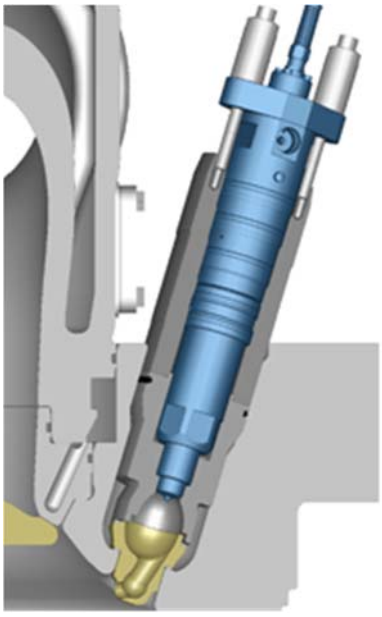


Figure 12: Cut through pilot injector and pre-chamber located in the cylinder cover

Pilot fuel supply system

The pilot fuel pump unit supplies pilot fuel oil to the injectors at a pressure of up to 1200 bar. The unit consists of an electrically-driven high-pressure pump with a pressure regulation device, fine fuel filters, and an overpressure safety valve.

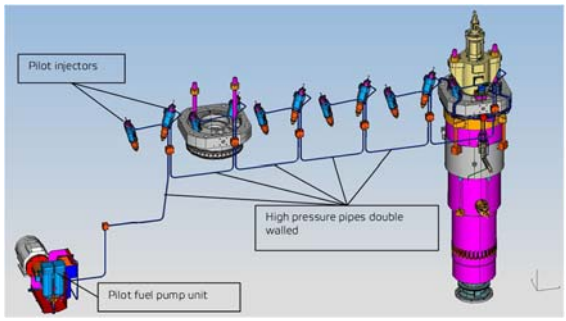


Figure 13: Pilot fuel supply system with one pump for the complete engine, piping, and two pilot injectors per cylinder

Electronic engine control system

WinGD low-pressure X-DF engines are operated by a UNIC-based engine control system. The UNIC control system is an embedded engine management system with a modular design. It is applied with various diesel engines in the Generation X-engine series. For dual-fuel engines, the system is extended with the following additional main functionalities for gas operation:

- Fuel mode transfer to change from liquid to gas mode and vice-versa during engine operation
- Adjustment of gas admission and pilot fuel injection timing, duration, and pressure
- Exhaust waste-gate control to adjust scavenge air pressure and air flow
- Knock and misfire detection and control, for combustion control and engine safety
- Firing and compression pressure balancing of individual cylinders to improve engine performance
- Safety related functionalities

Besides the standard cylinder control module for controlling actuators related to diesel operation, a second module is added to every cylinder to serve the input and output signals required for gas operation.

3.4 Engine Performance and emissions data

3.4.1 Efficiency

The performance behaviour over load of a low-pressure gas engine following the Otto cycle differs from that of a Diesel cycle engine. With the Otto cycle, the best fuel consumption is achievable closer to full load, and is closer or better than the achievable fuel consumption of the Diesel cycle with fuel oil.

Towards lower loads, the Diesel cycle allows an improvement in fuel consumption, whereas the Otto cycle has a flatter curve with a slight increase towards low load.

Figure 14 shows a comparison between the achievable specific energy consumption behaviour of a Diesel Cycle and an Otto Cycle engine over load.

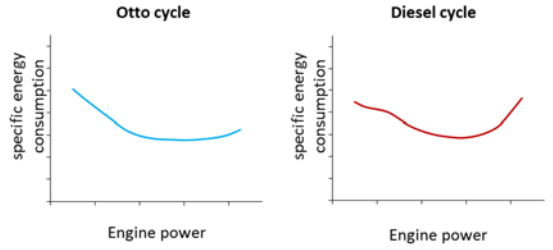


Figure 14: Typical specific energy consumption curves over load for the Otto ad Diesel cycles.

3.4.2 Emissions

The most notable advantage of the low-pressure X-DF engine is the low level of emissions of any exhaust gas element.

CO_2

In natural gas a large portion of the fuel gas is methane, which contains less carbon than fuel oils. The beneficial consequence of this is that less carbon is involved in the combustion process to achieve the same amount of energy. This results in the CO_2 emission levels being approximately 1/3 lower than those from diesel.

NO_X

As the low-pressure X-DF engine has a pre-mixed homogeneous high air to fuel ratio in the combustion chamber, the flame temperatures are relatively low. This results in low levels of NOx production. Conversely, with high-pressure gas injection, the temperature levels in the diffusion flame are much higher. The net difference is that the low-pressure gas engine has NOx emissions that are 80 % to 90 % lower than the equivalent high-pressure diesel or gas engine, and needs no cost intensive after treatment system to operate in IMO NECAs (NO_X emission control areas).

Sulphuric oxides

The minimal levels of sulphuric oxide emissions are related to the small pilot injection. With the pilot fuel being less than 1 % of the total fuel, the sulphur emissions are reduced by more than 99 %. With the higher pilot fuel injection, the sulphuric oxide emissions of a high-pressure gas engine can be 5 to 10 times greater.

Particulates

The creation of particulates is strongly linked to the diffusion flame in a high-pressure injection combustion. In the pre-mixed flame of the low-pressure X-DF engine, however, particulates are virtually non-existent. Only the very small pilot fuel injection, which is still a diffusion flame, creates some particulates.

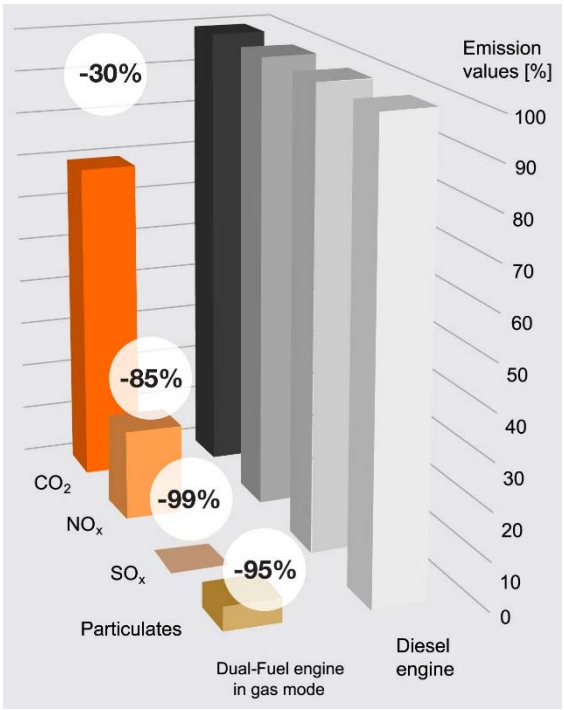


Figure 15: Typical emission figures for low-pressure gas and high-pressure diesel modes. The low-pressure engine is NOx IMO Tier III compliant without an after treatment system

Unburned hydrocarbons - methane slip

As with the diesel engine, neither low-pressure nor high-pressure gas engines are able to burn completely the injected fuel. The amount in the low-pressure engine is about 3 times higher, but nevertheless the unburned portion is at a low level of below 3 g/kWh.

Methane is considered a contributor to global warming as CO_2. The methane emission levels per g/kWh are about 100 to 150 times smaller than those of CO_2. On the other hand, methane has a stronger effect on global warming. Overall the equivalent global warming effect of the low-pressure gas engine, taking into account the CO_2 as well as the methane emissions, remains about 20 % below the level of a comparable diesel engine.

3.5 Operation of WinGD X-DF engines

3.5.1 Gas and diesel operation

The WinGD low-pressure X-DF engine is designed to operate with either gas or fuel oil at any load continuously. In gas mode, there is no limitation to operating at loads below 5 % as is the case for engines with high-pressure gas injection.

In harbour manoeuvring conditions, classifications societies request that any gas engines should switch over to diesel. This rule has been introduced to reduce risks related to gas handling in harbour regions.

Once in open waters, the changeover from diesel to gas operation is possible within about 2 minutes, which is the time needed to cover the filling of the gas pipes and the gradual replacement of fuel oil by gas injection.

Should it be necessary, for example because of damage to the vessel's fuel gas supply system or the engine's gas injection and ignition system, the dual-fuel engine can switch over from gas to diesel operation within one crankshaft revolution:

1. Gas injection is immediately stopped and replaced by fuel oil injection from the main fuel injection system
2. Venting the gas supply lines in the vessel and the engine.

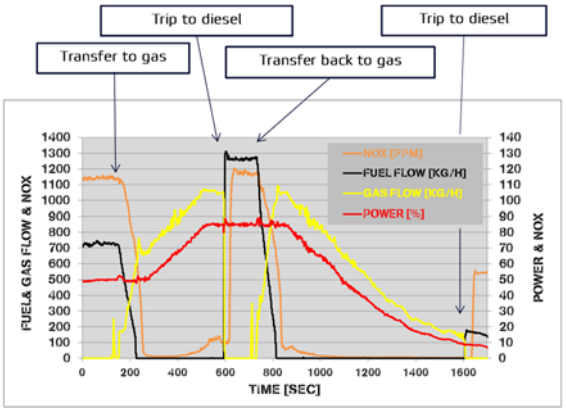


Figure 16: Smooth transfers from diesel to gas operation and back to diesel

The transfer from gas to diesel can occur at any load and is controlled in such a way to keep the vessel speed constant.

3.5.2 Poor quality LNG fuel and tropical conditions

The bunkered LNG may have different ignition qualities, characterized by the methane number (MN). At lower methane number, the resistance to self-ignition is reduced. With the low-pressure X-DF technology, this can become relevant when operating above 80 % engine load, whereas in low loads the combustion is stable also with very low methane numbers. To overcome this physical boundary condition, WinGD has developed the DCC (Dynamic Combustion Control) technology. By carefully adjusting the amount of injected liquid fuel, the lean burn gas combustion is kept stable even at high loads with low methane number fuel, and full availability of the vessel is ensured.

The DCC technology has also shown to be advantageous when operating in wet tropical conditions. The high ambient temperatures and very high humidity impact turbocharging efficiency and, eventually also, combustion quality at high loads. Also in these conditions, DCC ensures the full operability of the engine over the full load range (see Figure 17).

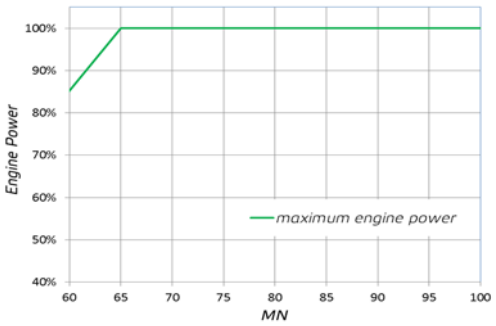


Figure 17: Achievable engine load with different LNG qualities at any ambient condition.

DCC is designed so, that the advantage of the X-DF low pressure gas engine technology in regard to compliance with the IMO Tier III NOx limits without any after treatment system is maintained.

3.5.3 Maintenance of the low-pressure X-DF engine

Since the majority of components of the engine are the same as those of a diesel engine, the same maintenance work and intervals can be applied for the low-pressure X-DF engine's main components.

When operating continuously on gas, extended intervals between overhauls for the main injectors and fuel nozzle tips for fuel oil may be applied.

The following parts related to gas and pilot fuel injection will demand regular service:

- Pilot fuel injectors (nozzle tip and pre-combustion chamber)
- Pilot fuel pump
- Gas injectors
- Gas admission valves

3.6 Engine room safety concept

The use of LNG on board a vessel requires special measures to ensure the safety of operations, the vessel, and human life.

The most important rules are:

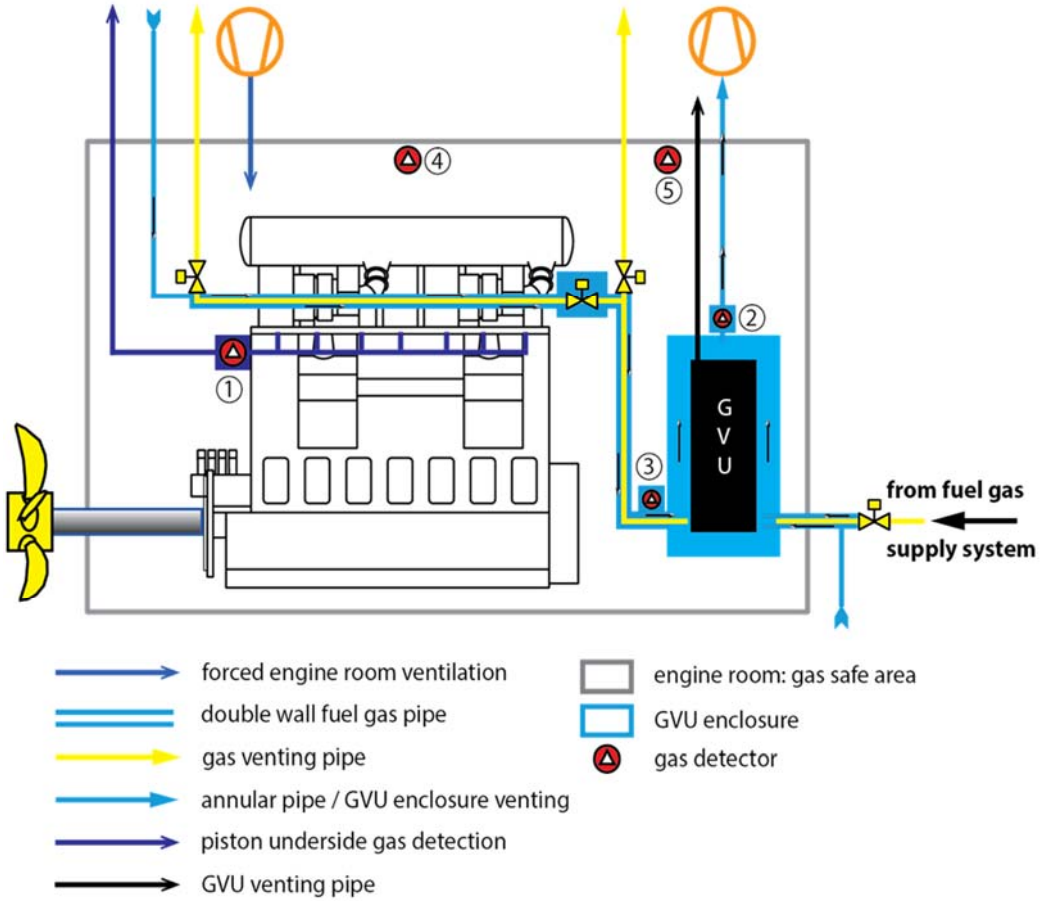


Figure 18: Safety system for the dual-fuel low-pressure engine embracing sensors and venting devices for main injection lines, double wall pipe outer rings, air and exhaust flow path, engine room

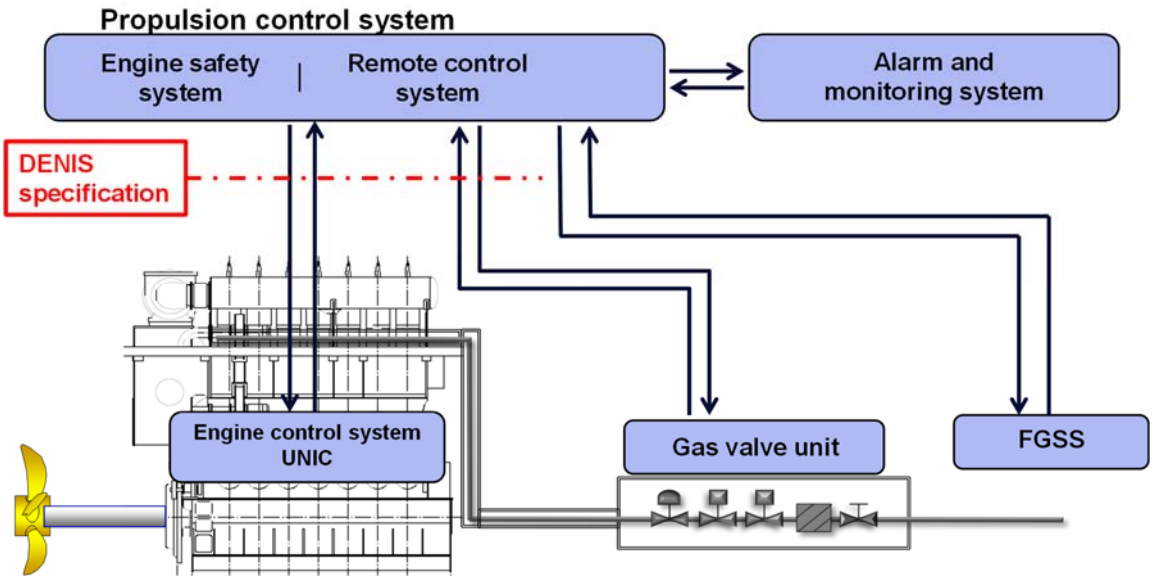


Figure 19: Control systems for the FGSS and the engine

- Classification society rules for the layout of the FGSS
- The IGC and IGF code of the IMO (International code for construction and equipment of ships carrying liquefied gases in bulk & International Code of Safety for Ships using Gases or other Low-flashpoint Fuels)

The safety concept (Figure 18) adheres largely to the established concept for marine low-pressure gas medium speed engines. It is ready to be applied for the HAZID (Hazard Identification) and HAZOP (Hazard and Operability) study for new vessel designs.

To avoid gas entering the engine room, all parts have a gas safe design and gas is supplied in double wall pipes. This allows early detection of gas leakages after primary damage, venting of the system, and the shutting off of gas operations before the gas can enter the machinery space.

Air is supplied for venting of the complete engine room and the outer space of the double wall pipes, while inert gas (nitrogen) is supplied for venting the gas valve unit and the double wall pipe inner rings.
As specified by the IMO IGC & IGF codes, the exhaust gas pipes for any gas engine need to be equipped with gas explosion or relief valves.

3.7 Management systems for the engine and FGSS

Several control systems are connected for the control and monitoring of the fuel gas supply and engine load, as well as the operation. All need to be linked to the vessels control, alarm and monitoring system (Figure 19).

4 The fuel gas supply system (FGSS)

The specific requirements and the possible variants for preparing the liquid gas for injection as gas into the engine are described in the following paragraphs.

4.1 Gas Valve Unit (GVU) at the engine inlet

Before entering the engine, the liquid LNG is evaporated and pressurized. The compressed gas passes through the gas valve unit (GVU). The GVU is the specified interface between the engine and the fuel gas supply system (FGSS).

The gas valve unit has several important functions:

- Adjustment of the gas injection pressure: although the pressure can be partly adjusted by the main gas compressor or the cryogenic pumps, the final adjustment is made in the GVU

- Quantity of gas: By controlling the pressure, the quantity of supplied gas is also controlled
- Gas filter
- Safety system: The gas valve unit takes over the safety function to vent leaking gas from the double walls on the engines. It also provides safety for the complete piping when switching off the gas operation because of a standard change to diesel or a complete operational stop.

Due to the different valves, pipes and sensors installed, the GVU itself has to be in a gas safe environment. The GVU can be as a closed stand-alone solution, or as an open design; the latter requires that the equipment is located in a gas safe containment/room.



Figure 20: A closed gas valve unit (GVU)

The basic maximum required pressure at the GVU inlet is 16 bar. As the engine operate with lower gas pressures at low load operation, there is a potential to save compression energy by lowering the GVU inlet pressure.

The engine itself works with gas pressures between approximately 5 to 16 bar. Higher level gas pressure is required at high loads to inject the gas within the available time frame and mix it well with the air. At low loads with lower speed and lower gas quantities, less pressure is required. The lower heat value (LHV) of the gas also influences the actual required gas flow at any given power.

The gas pressure at the GVU inlet may, therefore, be adjusted according to the actual need at the engine inlet, which is represented in Figure 21.

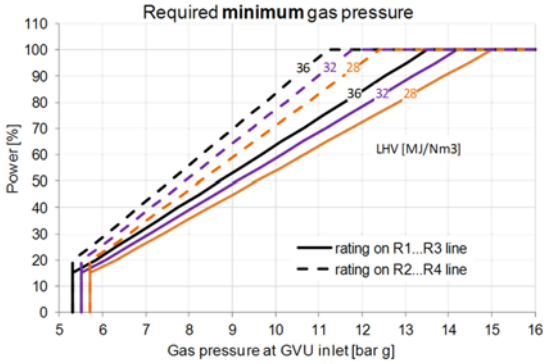


Figure 21: Typical gas supply pressure depending on the engine load and the lower heating value (LHV) of the gas

The gas temperature at the GVU engine inlet is kept between 0 ºC and 60 ºC under dry, and between 20 ºC and 60 ºC under tropical conditions to avoid any water condensation.

4.2 Basic layout of the FGSS

The fuel gas supply system design requires attention to meet both, the operational needs, as well as the official technical safety requirements specified by the regulatory bodies and classification societies.

There are basically two means of moving the gas from the storage tank to the engine:

1. Forced boil-off: The liquid natural gas is pressurized to the required level with pumps, and is then evaporated to meet the engine inlet conditions. 0 % to 100 % of the needed gas can be produced.

2. Natural boil-off (BOG): Due to heat passing through the tank walls, part of the LNG in the tank is evaporated. If the tank is designed to withstand high pressure, the BOG can be kept in the tank until the pressure limit is reached. Alternatively, the BOG can be compressed and used as fuel for the main or auxiliary engines or for a boiler. The energy required for compression is higher than for the forced boil off gas, which is compressed in liquid form, whereas the BOG needs to be compressed in the more energy intensive gas form. Depending on the tank size and type and the actual engine load, the evaporated quantity may cover 5 % (large merchant vessels) to 60 % (LNG carrier) of the gas quantity needed by the engines at full load.

The resulting key elements of the fuel gas supply system are:

1. LNG (Liquid Natural Gas) storage tank
2. Cryogenic pump and heat exchanger for compression and evaporation of the liquid gas
3. BOG handling concept: High pressure tanks, gas compressor, reliquefaction plant or gas combustion unit
4. Piping between the components
5. Gas valve unit (GVU) as the interface to the engine, regulating the gas quantity and pressure supplied to the engine

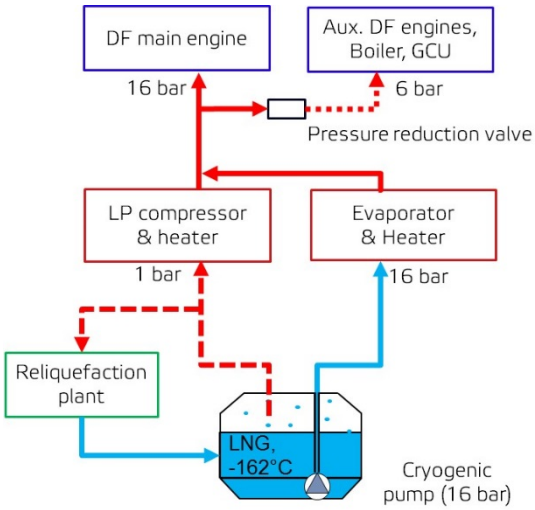


Figure 22: Basic layout of a low-pressure fuel gas supply system for main and auxiliary engines (red: gas, blue: liquid, dotted line <6 bar, full line: 16 bar)

The low-pressure fuel gas supply system has several advantages compared to the high-pressure solution. In the first place, the low-pressure gas system requires fewer safety precautions. Furthermore, the system component costs are clearly lower, more proven solutions are available on the market, and less energy is needed to reach the required pressures. As a consequence, maintenance work and costs are also minimized throughout the vessel's lifecycle.

4.3 LNG tanks

Natural gas is stored in liquid form, i.e. liquid natural gas (LNG). At atmospheric pressure, gas is liquefied at temperature below -162 ºC (at below -182 ºC it becomes solid). This low temperature level is required by the methane content, being the lightest component. The other gas elements in natural gas become liquid at higher temperatures.

4.3.1 Tank volume

When changing from oil based fuels to LNG, a larger tank will be required. As a rule of thumb, the tank size needs to be doubled:

- The density of LNG, being around 450 kg/m3, is less than half that of HFO which has a density of about 1000 kg/m3. This gives a tank increase factor of about 2.2.
- On the other hand, the heat value of LNG is larger by a factor of 1.2, which means a potential reduction of the LNG tank size by a factor of 0.84
- Isolation and the need for free tank space when full may, however, increase the size again by a factor of 1.2

In total this gives a capacity increase requirement for the LNG tank of a minimum factor of 2 so as to ensure operation with the same independence as with fuel oil.

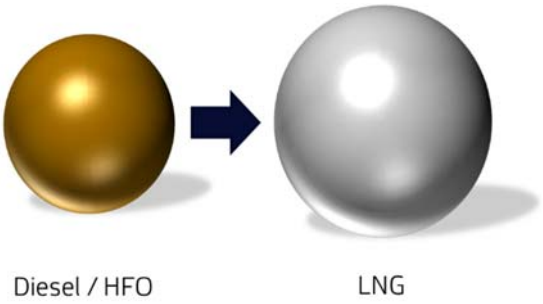


Figure 23: Doubling of the tank size from fuel oil to LNG. Depending on the tank design and location, additional space may be required around the tank

Depending on the tank design and location, even more vessel space may be needed to accommodate the LNG tank, which for small vessels can result in a space requirement more than 3 times larger than that of the original HFO tank.

Therefore, the replacement of the fuel oil tank with an LNG tank might reduce the overall loading capacity of the vessel.

The reduction of the cargo volume puts into question the often considered full fuel flexibility: in order to maintain the flexibility to run at any time on either LNG or fuel oil, the vessel's overall tank capacity (fuel oil tank plus LNG tank) would need to be at least tripled rather than doubled, meaning that the cargo capacity would be reduced accordingly.

4.3.2 Tank types

Depending from the surface to volume ratio (lower with larger tanks) and the applied isolation more or less gas in the tank is being evaporated, the boil-off gas (BOG). The quantity of evaporated BOG in the tank is usually given as the boil-off rate (BOR), which can reach between 0.06 % per day of the total stored gas for very large storage tanks and up to 0.4 % for smaller tanks.

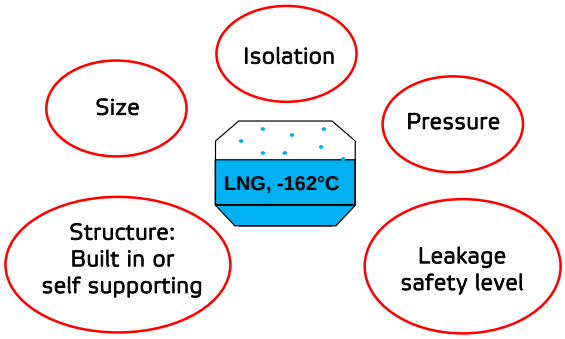


Figure 24: Key tank characterisation parameters

The available tank designs are differentiated by:

- the achievable maximum pressure
- the applied isolation (vacuum, polyurethane, etc.) influencing the achievable BOG rate
- the possible size/volume
- being either self-supporting, or supported by the ship's hull (membrane tanks are supported by the hull).
- the need for either a total or partial gas tight and isolated secondary barrier, meaning an outer containment able to intercept cold LNG leakages from the primary containment without risk of cracks

Membrane tanks and independent (self-supporting) type A, B and C tanks that follow the IMO IGC code can be applied:

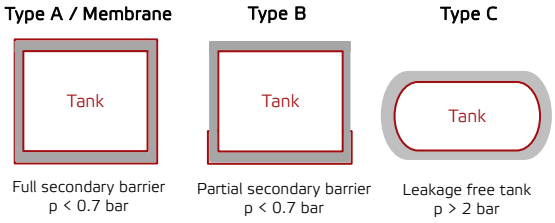


Figure 25: LNG tank types classified by the application of larger or smaller secondary barriers and operational pressures

"Type A tanks" with a prismatic shape and membrane tanks can hold up to 0.7 bar. The cargo is usually kept below 0.25 bar. The outer surfaces are straight planes. BOG rates of between 0.06 % and 0.2 %/day have been reached.

First barrier leakages may occur as the material and design used are not crack propagation resistant. Therefore, a full secondary gas tight and isolated barrier is required.

"Membrane tanks" are commonly used for the large tanks in LNG carriers. For other merchant ships they need to be considered if bigger volumes of LNG are required. The required additional space is the lowest of all tank types.



Figure 26: Inside of a large membrane tank integrated in the hull of an LNG carrier vessel (Source: GTT)

"Type B tanks" are very similar to A tanks, holding pressures up to 0.7 bar, but are characterized by the use of only a partial 2nd barrier (drip tank) to prevent, in the unlikely case of leakage, cold LNG from cooling the hull structure leading to cracks. The structure can have a self-supporting prismatic shape with straight planes. Another design option is to have spherical tanks (Moss tanks).

BOG rates between 0.07 % and 0.2 %/day have been reached.

"Type C tanks" withstand pressures of typically up to 8 bar, but may also reach 10 bar, the maximum allowed by the IMO. To withstand such pressures, they are usually of cylindrical or spherical shape. They represent the preferred solutions for merchant vessels with tank sizes of up to 1000 or 2000 m^3 because of the easier handling of BOG than with the other tank types.

Despite the smaller tank size with a higher surface to volume ratio that produces higher

BOG rates of 0.2 to 0.6 %/day, long storage times without the need for extra treatment of the BOG can be achieved.

No secondary barrier is required for type C tanks, as structural stresses are kept low and the design has been proven against cracks.



Figure 27: Two type C tanks installed on the deck of the M/T Ternsund owned by Terntank – the first vessel in operation with a WinGD low pressure DF engine

4.4 Pressurizing LNG in its liquid state with cryogenic pumps

For merchant vessels with small tanks, the natural boil-off gas rate is too low to be able to operate the engine at higher load. Therefore, with low-pressure dual-fuel engines, the liquid gas from the tank needs to be pressurized by cryogenic pumps up to the required 16 bar (or lower for lower load operation) and then evaporated in a vaporizer.

Cryogenic pumps can be placed in two different ways.

1. Either the LNG is guided through a pipe to the cryogenic pumps located outside the tank, or
2. The cryogenic pumps are submerged within the LNG tank

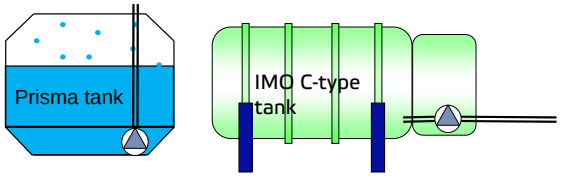


Figure 28: Cryogenic pumps submerged within the LNG tank (example left in a prismatic tank type A), or positioned outside the tank (example right in a type C tank). Both positions are possible for any kind of tank.

4.5 Natural boil-off gas (BOG)

Even if the LNG tanks are isolated, some heat will enter the tank and some proportion of the liquid natural gas will evaporate. Depending on the tank's size and isolation, the boil off gas rate can vary between 0.06 %/day to 0.3 %/day.

Generally, on merchant vessels, the BOG may typically cover up to 5 % to 10 % of the installed power. On LNG carriers 60 % of the power may be covered by BOG.

4.5.1 BOG handling possibilities

There are the following possibilities for handling this natural BOG:

1. Compressing it for use in auxiliary and main engine
2. Storing it for as long as possible in the tank by increasing the pressure to the tank's allowed level.
3. Reliquefying the gas through a reliquefaction plant and refilling it back into the tank
4. Burning the natural BOG in the Gas Combustion Unit (GCU) or boiler

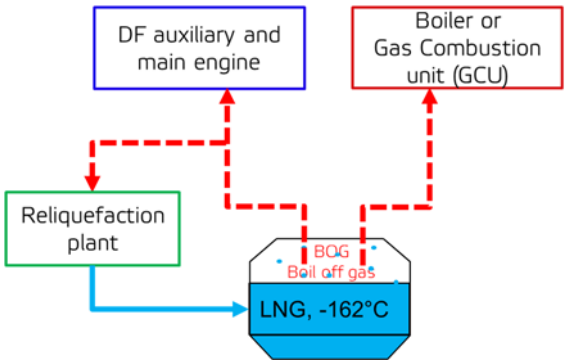


Figure 29: Possible handling and use of natural BOG

4.5.2 Gas compression

Many different types of gas compressors are available for the low-pressure gas engine with up to 16 bar. These include centrifugal, screw or piston compressors. In contrast, for the high-pressure gas engine with 300 bar, only piston compressors from a limited number of suppliers, are currently available.

The compressors now available on the market may typically cover the pressure and quantity levels as indicated in Figure 30.

The different compressor types may be roughly characterized as in Table 1.

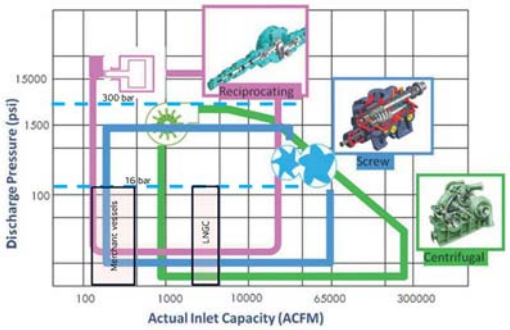


Figure 30: The pressure and capacity range of different compressor technologies (centrifugal, screw or piston compressor) offered by Kobelco (Choosing the right compressor, Isao "Zac" Zukeran et al., LNG Industry, June, 2015)

Table 1: Typical compressor type characteristics

	Screw	Centri-fugal	Piston
Achievable pressure	medium	medium	high
Energy efficiency	low	low	high
Energy versus capacity	linear	Linear above 70% load	quasi linear
Size	small	small	large
lubrication	oil	oil free	oil / oil free

The electrical power demand for operating the compressors is significantly different when comparing the low- and high-pressure gas concepts. The energy needed to compress the BOG to 300 bar requires about 4 to 5 % of the engine power. This is about 3 times more than the 1 to 2 % engine power for 16 bar (see also Figure 31). This higher electrical power needs to be taken into consideration in practice. Low compressor efficiencies can actually increase the total energy demand by a factor of 1.5 to 3 compared to the theoretical compression energy need.

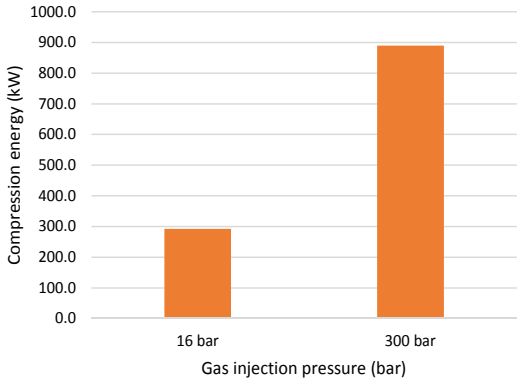


Figure 31: Comparison of the theoretical compression energy demand for natural gas compression to 16 bar or 300 bar for 20000 kW engine power (without consideration of compressor losses, which in reality may increase the demand difference)

4.5.3 BOG Reliquefaction

Excess levels of natural BOG that exceed the quantity needed on board may also be reliquefied and put back into the LNG tank.

There are different technical solutions for cooling the gas. These are known as the Joule Thomson (JT), Mixed refrigerant (MR), and Brayton, Stirling solutions.

All these processes have one basic common thermodynamic process for cooling a gas, namely the expansion of a gas after compression and first cooling it through a heat exchanger. The expansion may happen through an orifice (Joule Thomson), a turbine (adiabatic expansion), or by a piston (Sterling).

The BOG may be expanded directly (only by the Joule Thomson process passing through an orifice) or it can be cooled through a heat exchanger. This involves exchanging heat with another gas having been cooled by expansion (for example nitrogen or other hydrocarbon gases).

Cooling and reliquefying gas via an intermediate media

Most cooling processes available usually cool the gas through a heat exchanger exchanging heat with a liquid that has been cooled via any kind of compression-expansion cooling process. To achieve temperatures below -162 ºC, nitrogen is the primary choice of cooling liquid, saturating at ambient pressure at –196 ºC. But other fluids can also be used. In the mixed refrigerant (MR) process, several liquids with different saturation temperature levels are applied (propane, butane, nitrogen, etc.), which allows the required total

energy needed to liquefy the gas to be reduced. Some designs add a JT step to the process of cooling through heat exchangers to get to the required -162 ºC.

The Brayton process expands the gas through a turbine connected either to a generator or a compressor wheel in order to partially recover the energy used for compression.

The most energy efficient solution is the Stirling process. This is able to cut energy consumption by half. Helium is used as the coolant, and expansion takes place over a piston. However, this solution is available only for the liquefaction of smaller quantities of gas.

Direct expansion of BOG using the Joule Thomson (JT) process

When cooling the boil-off gas directly, the Joule Thomson process exploits the effect that the gas is automatically cooled to -162 ºC and will partly liquefy when expanded through an orifice when starting from the right pressure (>100 bar) and temperature level. To realize this effect, the natural gas has to be compressed to 100 bar at a temperature below -80 ºC. A higher pressure is possible as well, but this requires more energy and does not give any reliquefaction rate advantage. The benefit of the JT process is its relative simplicity and, therefore, also its lower investment cost. The disadvantages are the limited rate of achievable reliquefaction, and the requirement for strong compression of the gas.

The reliquefaction technology choice

The solution chosen impacts the overall energy required to reliquefy the gas, as well as the required investment for the plant.

Table 2: Typical characteristics for the different reliquefaction processes

	Joule Thomson	Mixed refri-gerant (MR)	Brayton	Stirling cycle
Cooling gas	Gas itself	Propan, Ethan, Butan	Nitroge n	Helium
Expansion by/through	orifice	orifice	turbine	piston
CAPEX	low	medium	medium - high	high
Energy	high	medium	medium	low

Since the capital cost of reliquefaction plants is rather important, the economic benefit of the solution needs to be evaluated in a detailed study for each specific vessel.

4.5.4 Burning BOG in a boiler or in the gas combustion unit (GCU)

Another possibility is to burn the BOG in a boiler so as to supply heat for the vessel. If the amount of BOG is higher than the demand, the excess can be burnt in a gas combustion unit (GCU), which represents an actual loss of energy. It is, therefore, the least recommendable solution and is often installed only as a safety device, and used only if other BOG treatment devices are out of order.

5 Commercial benefits of the X-DF engine

There exists great interest in the use of LNG as fuel, particularly when sailing within ECA areas. The possibility to apply LNG instead of expensive low sulphur fuel provides a financial incentive. With the sulphur cap of 0.1 % due to come into force in 2020, all merchant vessels can thus benefit from using LNG as fuel.

For a comparison of the different solutions, the type of FGSS (fuel gas supply system) to be installed has to be considered. The FGSS layout is largely driven by the following major factors, which are partly linked to each other:

- the gas tank size,
- the quantity of BOG and
- the related possible handling of BOG.

For small and medium size merchant vessels, type C tank are likely to be the best solution. The high pressure resistance of up to 10 bar allows tank storage holding times up to one month, which allow a safe standstill without special need for BOG treatment.

On large merchant vessels requiring tank sizes of more than 1000 or 2000 cbm, membrane or type A or B tanks will be applied. The BOG needs to be released from the tank and must either be used or reliquefied. The following analysis is submitted for these two types of vessel.

5.1 Merchant vessels with C-type tanks

With the capability of the C-type tank to store large amounts of BOG, the BOG can be used solely to run either the auxiliary engines or an additional boiler. A GCU (gas combustion unit) might be considered for those extreme occasions when high quantities of BOG cannot be utilised. Similarly, the installation of a compressor might be avoided by installing a tank able to release BOG at 6 bar pressure suitable for operating the auxiliary engine or boiler.

The FGSS layout can look as presented in Figure 32.

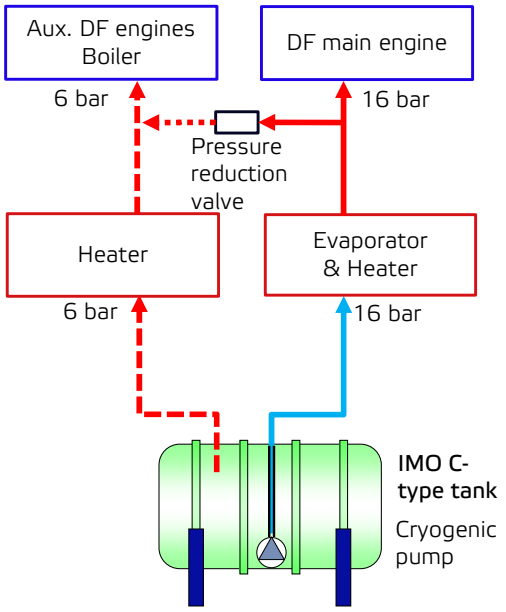


Figure 32: Possible layout of the FGSS for an LNG fuelled merchant vessel with a low-pressure X-DF engine and C-type tank (red: gas form, blue: liquid, dotted: <6 bar, full line: 16 bar)

The low pressure gas technology reveals large commercial benefits. By avoiding the need to operate an energy consuming NOx reducing system when sailing in ECA areas, the fuel costs of an engine with low pressure gas technology are maintained at the same level as those of an engine with a high-pressure gas technology solution.

Combined with the lower investments needed for the low-pressure technology and the FGSS, the low-pressure gas engine is the solution of choice.

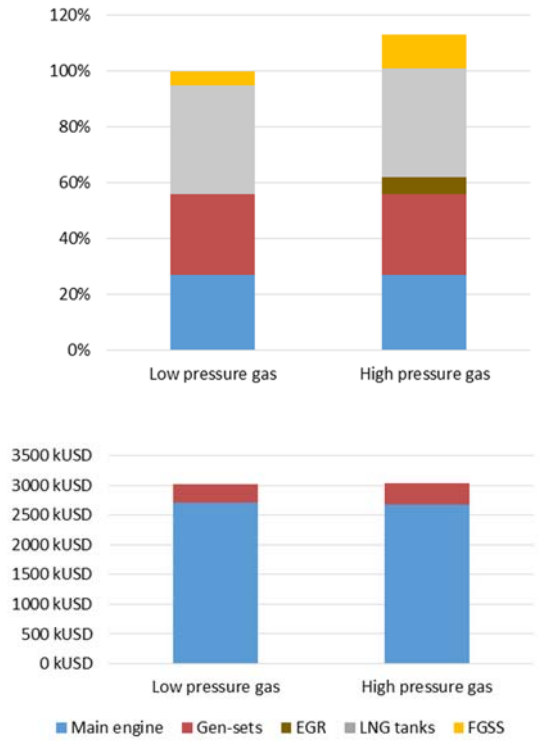


Figure 33: CAPEX (top) and annual fuel costs for an LNG fuelled vessel with 10000 kW operating mostly in ECA areas equipped with either a low-pressure X-DF or a high-pressure gas dual-fuel engine

5.2 Merchant vessels with large tanks (membrane or IMO Type A/B tanks)

For large LNG storage capacities of above 1000 – 2000 m^3, the tanks are usually not designed to hold high pressures. Therefore, consideration should be given to either the immediate use of the BOG or reliquefaction.

For very large container vessels, for example those with expected tank sizes of around 10'000 m^3, a starting layout as for small C-type vessels in Figure 32 may be considered. However, compressors have to be included in order to burn BOG in the auxiliary and/or main engines, or in boilers (see Figure 22).

If these consumers do not fully exploit the available BOG, an additional GCU or a small reliquefaction plant might need to be considered.

The extreme case is represented by LNG carriers having storage capacities that are more than ten times higher than the actual fuel needed. The BOG can, therefore, supply the main engine LNG demand at up to 60 % load.

For all these applications, the low-pressure dual-fuel engine concept enables the use of a more robust low-pressure gas system with much lower investment costs. For compressing the BOG to a maximum 16 bar, all technologies currently on the market, including centrifugal, screw and piston type compressors, can be applied to shape the solution for the operational need. With the alternative high-pressure gas engine concept, cost intensive piston type compressors would be needed in order to reach the 300 bar level.

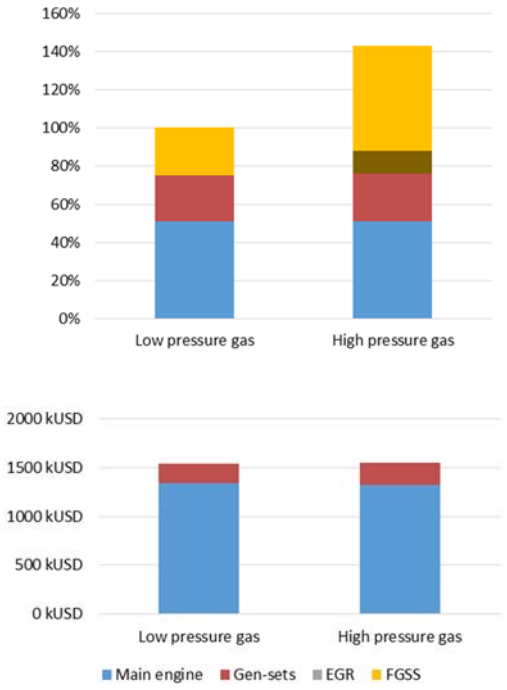


Figure 34: CAPEX (top) and OPEX costs (one Asia – USA tour) for low pressure X-DF and high-pressure gas dual fuel engine installations in an LNG carrier with 25000 kW power

Should reliquefaction be considered, any of the solutions described in chapter 4.5.3 can be applied. For example, the compressor might be designed to enable compression of the unused BOG at up to 100 bar to run an energy intensive Joule Thomson process. Alternatively, other more energy efficient solutions using Brayton, MR or Sterling technologies, could be considered.

Case studies for LNG carriers comparing low and high-pressure dual-fuel engine solutions show, that while achieving the same performance in relation to the overall fuel consumption, important investment cost savings can be realised with the low-pressure technology. A major factor in this comes from the energy savings achieved through compressing the BOG up to 16 bar only, instead of 300 bar (Figure 31).

For both large and small vessels, the use of the low-pressure engine avoids the need for any NO_X reducing equipment, since the engine is IMO NOx Tier III compliant.

6 Summary

With more stringent regulations soon to be applied for the fuel sulphur content and CO_2 emissions in international waters, LNG will become of interest to owners of any seagoing merchant vessel. The worldwide LNG infrastructure is growing and fuel price levels can give a commercial advantage to vessels operating on LNG instead of fuel oil (MDO/HFO).

The WinGD X-DF low-speed engine series has been designed to meet the increasing demand for LNG fuelled vessels.

When operating on LNG, the low-pressure dual-fuel technology applied in the WinGD X-DF engine series reduces sulphur emissions by up to 99 % and particulates by more than 85 % compared to conventional marine fuel oils. It is also the only technology able to reduce NOx emission to comply with the latest IMO Tier III NO_X limits without cost intensive after treatment systems or complex engine technologies, such as EGR.

Due to the higher fuel cost benefits, LNG fuelled ships operating in ECA areas and LNG carriers worldwide are currently the primary application focus. However, the upcoming worldwide fuel sulphur cap of a maximum 0.5 % from 2020 onwards will broaden the attractiveness for every seagoing vessel.

The choice between the low or high-pressure dual-fuel technology has a major impact on the fuel gas supply system layout (FGSS). By choosing the WinGD X-DF engine, the low-pressure solution makes the installation cheaper and safer. Furthermore, in operation it needs less energy and involves lower maintenance efforts and costs.

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