



# The Methanol- fuelled MAN B&W LGIM Engine

**MAN Energy Solutions**

Future in the making

Application, service experience  
and latest development of the  
ME-LGIM engine



# Future in the making



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**The MAN B&W LGIM engine is the methanol-burning version of our dual-fuel solution for liquid injection of fuels, the ME-LGI engine. This paper describes the service experience from the two generations of ME-LGIM engines, which have accumulated almost 90,000 running hours in total.**

**In the further development of the LGIM engine, a methanol-and-water blending concept has been introduced to the LGIM-W engine, which has passed Tier III compliance tests.**

**For the LGIM-engine, methanol as a drop-in fuel is readily achieved by blending increasing amounts of green or blue methanol with grey methanol. A net carbon-neutral solution that may co-evolve with an increasing production of green or blue methanol.**

**This provides fuel flexibility for the ME-LGIM engine, and combined with the ability to burn green methanol, when available, the engine becomes advantageous for other vessel types as well and not only methanol carriers having the methanol on board already.**

## Developing dual-fuel MAN B&W ME-LGIM engines

In 2012, MAN Diesel & Turbo decided to expand its dual-fuel engine portfolio by looking at low-flashpoint fuels and, as a result, the ME-LGI engine series were introduced. The MAN B&W ME-LGI engine is the dual-fuel solution for low-flashpoint liquid fuels injected in liquid form into the engine. Fig. 1 shows the development milestones of the methanol-burning version of the ME-LGI engine, the ME-LGIM engine.

Since 2012, 26 engines have been ordered for new methanol carriers. Moreover, 88,000 operating hours on methanol have been obtained with positive results for the shipowners and operators.

Like all MAN B&W GI and LGI engines, the LGIM engine is based on the Diesel combustion principle. Utilising the Diesel principle ensures the methanol burning engine the same power output and efficiency as the ME-C fuel oil burning engine. In addition, the benefits apply in both methanol (dual-fuel mode) and diesel oil (compliant fuel only mode) operating modes. The engine power output is not affected by ambient conditions, and it is only slightly sensitive to the quality of methanol, which is currently benchmarked to IMPCA (International

Methanol Producers & Consumers Association) [1]

All teething pains have been dealt with, and a new Mk. II version has been developed with optimised component designs. To comply with Tier III regulations of the International Maritime Organization (IMO), a simple methanol-and-water blending system has been introduced to lower the NO<sub>x</sub> level for Tier III compliance. Water for the blending system can be produced on board.

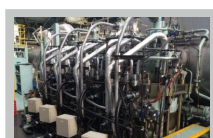
By installing the blending system, selective catalytic reduction (SCR) systems and exhaust gas recirculation (EGR) systems can be avoided, at significant cost savings. The latest ME-LGIM engine order included the methanol-and-water blending system.

Currently, the list of orders for LGIM engines is for methanol carriers, but the market shows an increasing interest in installing the engine in non-methanol carriers for especially the merchant tanker trade. Many operators consider methanol as one of the future carbon-neutral fuels. Methanol is easy to handle, and it is stored and injected into the engine as a liquid, just as easily as conventional

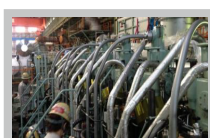
bunker fuels. The use of methanol as a fuel calls for a simple and cost-efficient fuel gas supply system (FGSS).

As for other types of MAN B&W dual-fuel engines, that is as liquid natural gas (LNG) or ethane for the GI-engine and liquefied petroleum gas (LPG) for the LGI-engine, methanol has the potential as a retrofit solution for ME-C engines already in service. All ME-C engines are delivered as so-called 'dual-fuel ready' engines. Therefore, in new projects, the engines are prepared for later conversion to dual-fuel independent of vessel application (tanker, bulk, container, etc.).

Shipowners operating the ME-LGIM engines are important marine players, such as Mitsui, O.S.K. Lines, Marininvest and Westfal-Larsen. More recently, the ME-LGIM technology has been opted by the Proman Group and Stena Bulk.



LGI demonstration event at RCC  
4T50ME-X



Test at MES  
7S50ME-B9.3-LGIM



Test at HHI  
7G50ME-B9.3-LGIM

2015

2016

Fig. 1: ME-LGIM development milestones

## Fuelling the ME-LGI engine

Contrary to the ME-GI engine, operating on fuel in a gaseous state, the MAN B&W ME-LGI engine is the dual-fuel solution for low-flashpoint-liquid fuels. The ME-LGI engine is available in various versions depending on the choice of low-flashpoint fuel (LFF) type. Due to the differences in fuel properties, the ME-LGI injection system components and auxiliary systems will be different from those of the ME-GI engine. Despite these differences, the operating principle and safety concept of the ME-LGI engine are similar to those of the ME-GI concept.

Fuels for the ME-LGI engine are categorised by their vapour pressure at 60°C. The vapour pressure (and the related boiling point) is a fundamental physical property describing the transition between liquid and gaseous states. The boiling point has been included in Table 1 in the first column (energy storage type), i.e. for LPG, for example, to remain in liquid form it has to be cooled to below -42.4°C. If the temperature increases above the boiling point, additional pressure needs to be applied to maintain the LPG in liquid form. The pressure required to maintain the state of equilibrium between liquid and vapour states is the

vapour pressure at a given temperature.

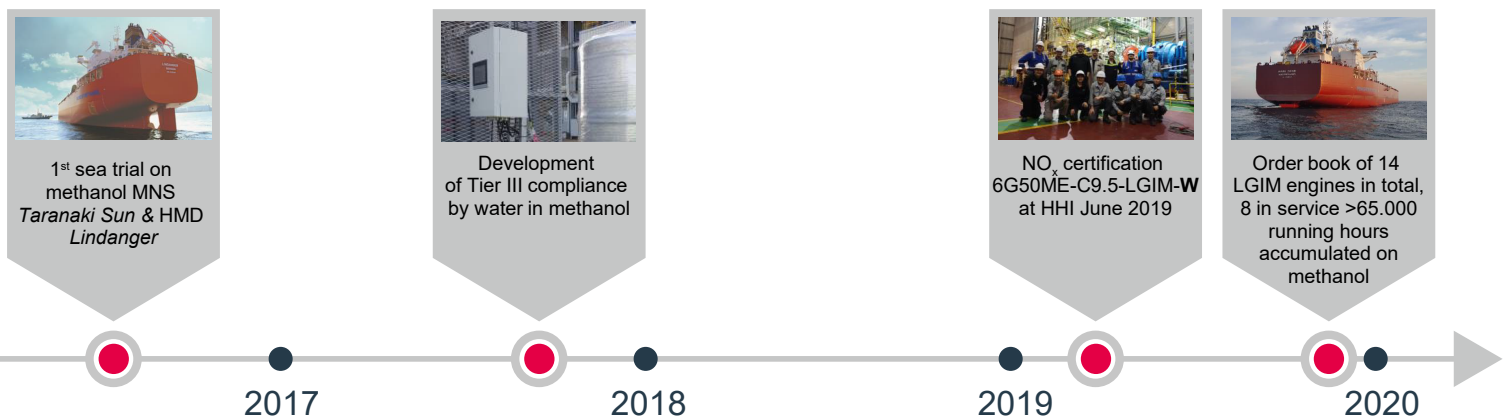
For comparison, Table 1 shows the characteristics of methanol, LPG, ammonia and hydrogen. Methanol is characterised by a low cetane number, lowering the self-ignition quality and requiring a small amount of pilot fuel (95% methanol and just 5% diesel pilot fuel).

As of November 2020, methanol has been approved and will be incorporated in the International Code of Safety for Ships using gas or other low-flashpoint fuels (IGF code) [2].

Energy storage type/chemical structure	Energy content, LHV [MJ/kg]	Energy density, [MJ/L]	Fuel tank size relative to MGO	Supply pressure [bar]	Flash-point [°C]	Vapour pressure at 20°C [bar]	Auto-ignition temperature [°C]	Emission reduction compared to HFO Tier II [%]			
								SO <sub>x</sub>	NO <sub>x</sub>	CO <sub>2</sub>	PM
Ammonia (NH <sub>3</sub> ) (liquid, -33°C)	18.6	12.7(-33°C) / 10.6 (45°C)	2.8 (-33°C) / 3.4 (45°C)	80	132	0.13 / 0.13	630 / 470	100	Compliant with regulation	~90	~90
Methanol (CH <sub>3</sub> OH) (65°C)	19.9	14.9	2.4	10	9	2.2-8.5		90-97	30-50	5-7	90
LPG (liquid, -42°C)	46.0	26.7	1.3 <sup>1</sup>	50	-104		410-580 (depending on the composition)	90-100	10-15	13-18	90
LNG (liquid, -162°C)	50.0	21.2	1.7 <sup>1</sup>	300				90-99	20-30	24	90
LEG (liquid, -89°C)	47.5	25.8	1.4 <sup>1</sup>	380				90-97	30-50	15	90
MGO	42.7	35.7	1.0	7-8							
Hydrogen (H <sub>2</sub> ) (liquid, -253°C)	120.0	8.5	4.2		Not defined		500				

<sup>1</sup> assuming fully refrigerated media

Table 1: Alternative fuel properties. Note that the values in the table show the emission reduction potential for fossil-based methanol, a much higher potential is available with the right feedstock, see chapter 3.



## Methanol as a fuel has beneficial aspects

Methanol is interesting for ship operators because it contains no sulphur and is liquid in ambient air conditions. This makes it easy to store on board ships, similar to distillate fuels.

For ships operating in IMO emission control areas (ECA), methanol is a feasible solution to meet the lower-sulphur requirements and, by using the MAN ES water injection system, the very low Tier III NO<sub>x</sub> requirements. When operating the two-stroke ME-LGIM engine on methanol, the SO<sub>x</sub>, NO<sub>x</sub> and particle emission reductions are similar to the reduction obtained by operating on LNG thanks to the lower working pressure, and the fact that methanol remains in liquid phase. However, installation costs are only a fraction of the costs for LNG.

Furthermore, methanol can be produced from biomass, municipal solid waste (MSW), or other biogenic matter, as well as via electrolysis and carbon capture, utilisation and storage (CCUS) technology, thus allowing for other “harder to decarbonise” industries such as cement, steel or even power generation to utilise their waste CO<sub>2</sub>.

### Producing and distributing bio-methanol and fossil-based methanol

There are several ways to produce methanol, and the final products are often termed either black, grey, green or blue methanol. Methanol, irrespective of the production pathway, is a clear liquid and an organic water-soluble chemical that is readily biodegradable.

- Black (or brown) methanol production is based on coal and is largely concentrated in China.
- Grey methanol is produced predominantly from natural gas by reforming the gas with steam,

converting and distilling the resulting synthesised gas mixture to get pure methanol.

Brown and grey methanol is considered high carbon intensity, when produced from coal or natural gas without carbon capture (CC) or use of renewable power input.

- Blue methanol is produced from waste streams or by-products of other manufacturing processes, with the methanol produced considered renewable.
- Green methanol can be produced in different ways, all of which are CO<sub>2</sub> neutral:
  - Methanol produced from biomass or from the biodegradable part of production waste, for example wood.
  - Methanol produced from renewable energy sources like solar panels or wind power, the electricity is stored in the chemical bonds of methanol and later converted into energy. This method is termed green methanol synthesis.

Blue and green methanol are considered to have a lower carbon

intensity when produced from fossil fuels combined with the use of renewable energy, carbon capture, or a combination of these.

Since methanol can be classified as either renewable or non-renewable, it has been defined what qualifies as renewable methanol: all feedstocks used to produce the methanol need to be of renewable origin (biomass, solar, wind, hydro, geothermal, etc.) [3].

Many vessels can function as bunker vessels if the interest in using methanol increases, with conventional methanol already available at over 115 of the world's top ports. Exact locations can be found via DNV GL's AFI Portal [4].

An indexed market price for methanol as a marine fuel is not yet fully established. However, Methanex (the largest global producer and distributor of methanol) suggests that the price has closely collated to that of MGO over the past 5 years on an energy equivalent basis. This being subject to the amount, the place where the methanol is sold, and the proximity to any of the major methanol storage hubs globally in Fig. 2.

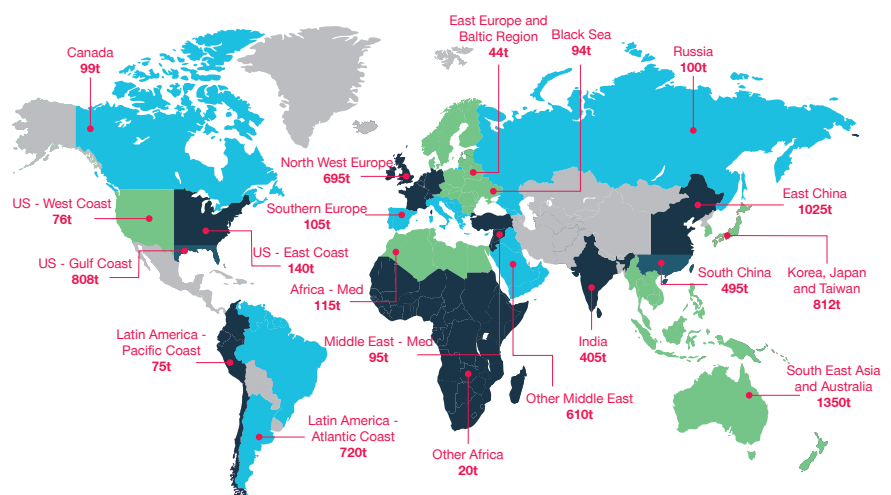


Fig. 2: Methanol storage hubs worldwide (courtesy of the Methanol Institute)



The discussion and interest in methanol is increasing with its suitability as a sustainable marine fuel candidate, with many ship owners and class societies now of the belief it will capture a reasonable share of the future fuels market. Initially, conventional methanol will be adopted with increasing amounts of blue or green methanol being blended in, and further reducing its CO<sub>2</sub>e footprint. It is expected that, eventually, more blue and green methanol than grey will be produced, likely post-2040.

Representing the world's leading methanol producers, distributors, and technology companies, the Methanol Institute serves as the trade association for the global methanol industry to promote the use of methanol for numerous applications. The explanatory illustration from the

Methanol Institute in Fig. 3 shows some of the production pathways of methanol and the advantages of marine application of methanol.

**Methanol as a drop-in fuel can co-evolve with green methanol production**

Methanol, as a sulphur-free fuel, is fully compliant with the 2020 IMO low-sulphur regulation. Low-sulphur compliance is not the only beneficial reason for adopting methanol though, as the lower CO<sub>2</sub> formation (up to 7% lower than HFO) during the combustion process is also advantageous. Furthermore, since the methanol molecule contains no carbon-to-carbon bonds, it does not produce particulate matter or soot when burned.

With IMO's CO<sub>2</sub> and greenhouse gas (GHG) targets for 2030 and 2050, the number of drop-in fuels is expected to increase during the transient period (initially to 2030 and subsequently to 2050), towards a lower carbon footprint. For the LGIM-engine, methanol as a drop-in fuel is readily achieved by blending increasing amounts of green or blue methanol with grey methanol (conventional methanol using natural gas as a feedstock and steam methane reforming technology) until, eventually, the lower carbon methanol becomes the main fuel. This is a net carbon-neutral solution that may co-evolve with an increasing production of green or blue methanol and gradually assist the industry in meeting the IMO's target for CO<sub>2</sub> and GHG emissions.

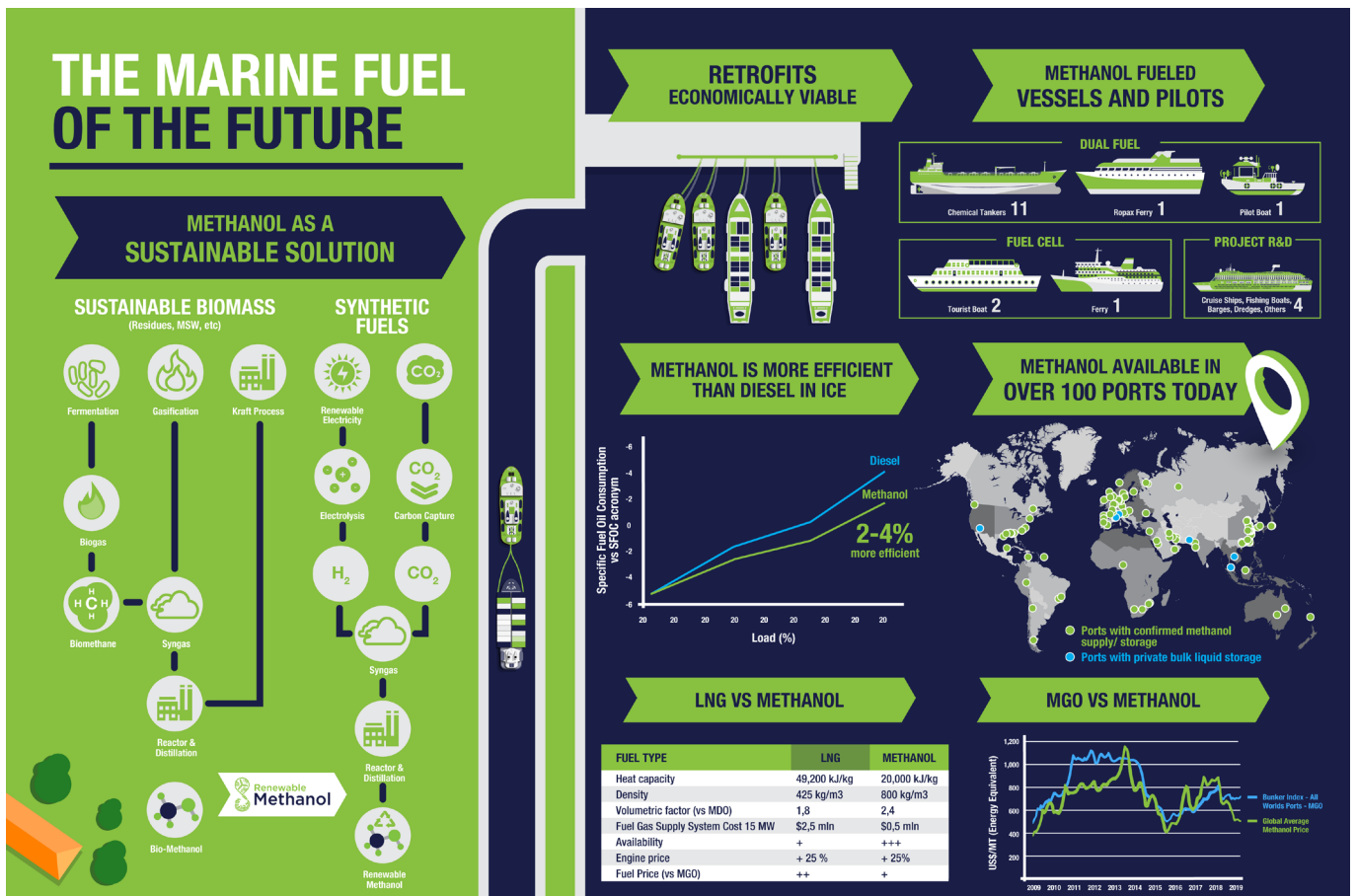


Fig. 3: Methanol as the marine fuel of the future (courtesy of the Methanol Institute)

This provides fuel flexibility for the ME-LGIM engine, and combined with the ability to burn green methanol, when available, the engine becomes advantageous for other vessel types than methanol carriers having the methanol on board already. As methanol is easily bunkered, this is in a very similar method as diesel.

**Low-carbon fuels lower the energy efficiency design index**

Other circumstances increase the interest in methanol and other new fuel types. As early as 2013, IMO decided to adopt the energy efficiency design index (EEDI) as the mandatory

instrument to limit CO<sub>2</sub> emissions for ships built later than January 2013. This influences the engine market and the technical solutions faster than anticipated.

To lower the EEDI, alternative low-carbon fuels such as natural gas (LNG), LPG, and methanol are serious candidates to becoming the future fuel. By nature, LNG, LPG, and methanol generate less CO<sub>2</sub> during combustion than fuel oils. Furthermore, methanol is interesting because bio-methanol and e-methanol can be made from a vast variety of biomasses and renewable energy feedstocks, and be mixed with methanol made from fossil fuels.

In October 2020, IMO’s intersessional GHG working group introduced short-term measures to address [5-8]:

- Technical (i.e. design): Energy Efficiency for Existing Ships (EEXI)
  - EEDI applied to existing ships
- Operational: Enhanced Ship Energy Efficiency Management Plan (SEEMP) with mandatory Carbon Intensity Indicator (CII) rating scheme (A-E) as in Fig. 4
- Measures consolidated into a single package; the outcome is a finely balanced political compromise
- As approved at MEPC 75 in November 2020: Entry into force is expected on 1 January 2023.

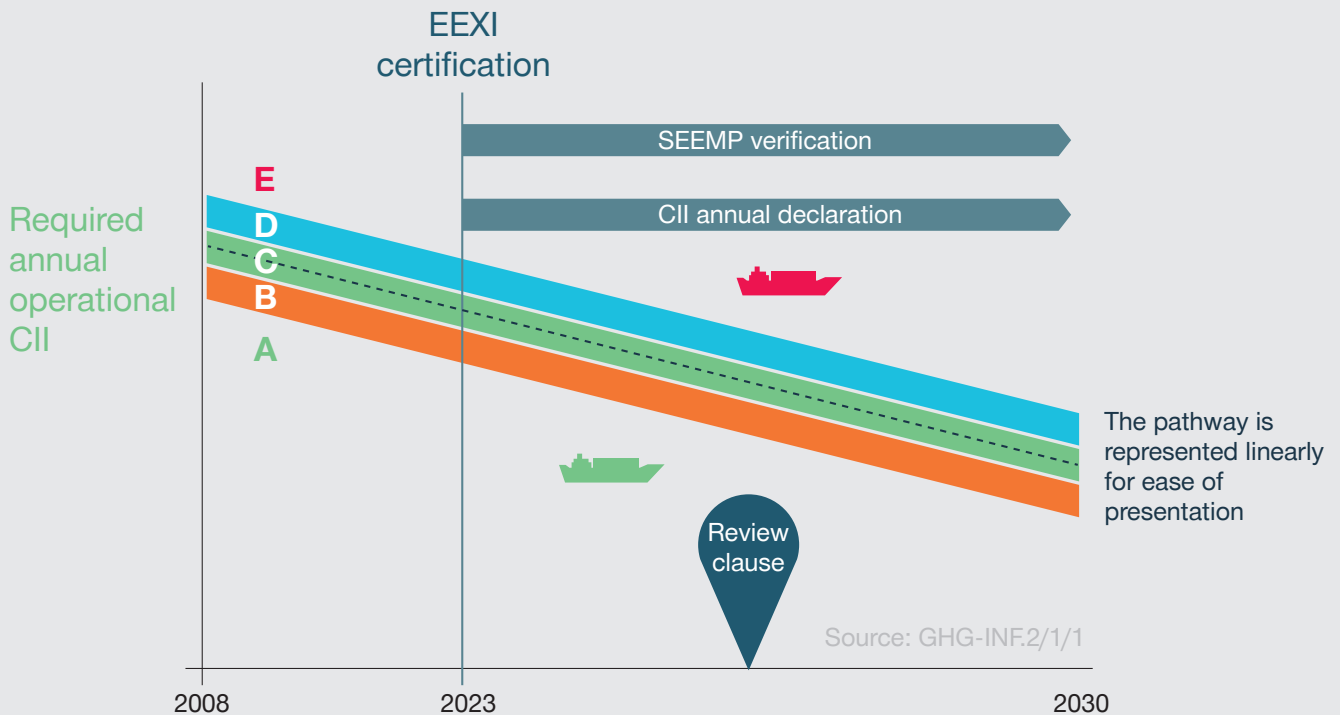


Fig. 4: Enhanced SEEMP with mandatory CII rating scheme (A-E) [5]

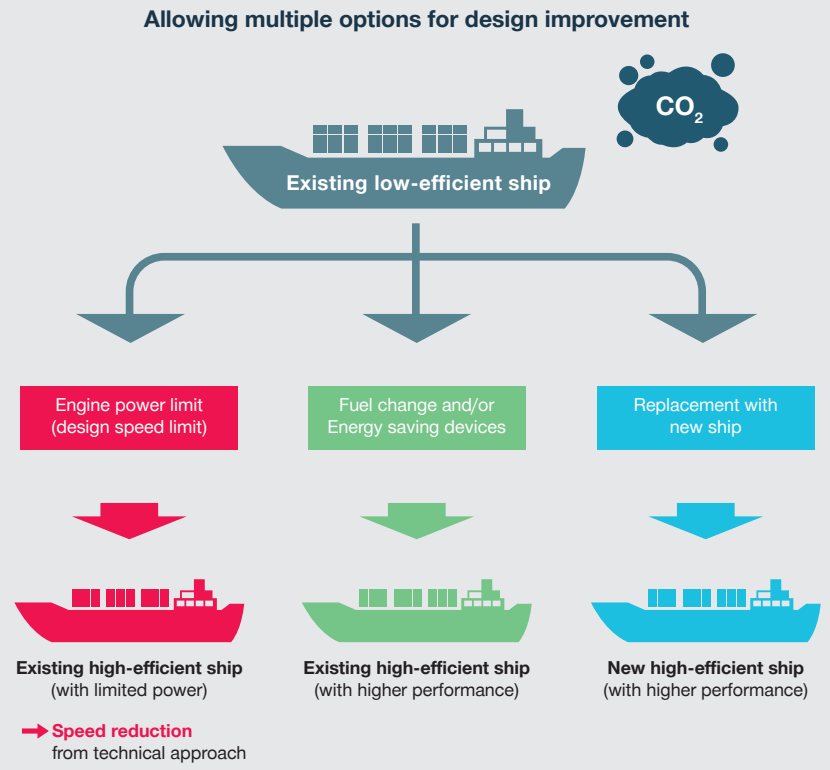
Furthermore, IMO will implement the EEXI technical measure, in a goal-based fashion, to ensure that the sector does not miss its targets. In this respect, both requirements and specific guidelines for the calculation of the EEXI will be adopted, see also Fig. 5 [5-8]:

**Requirements**

- All cargo and cruise ships above size thresholds on first annual survey after 1 January 2023 (same ship types and sizes as for EEDI): attained EEXI to be below required EEXI
- Required EEXI is equivalent to EEDI requirements early 2022 (Phase 2/ Phase 3) – with some adjustments

**Calculating EEXI**

- Existing ships determine their EEXI using the same method as for EEDI, with further options available for determining speed
- Goal-based: Operators decide how to achieve target (engine power limit, fuel change, energy saving devices, retrofitting and/or any other options)
- Engine power limit can be overridden: allows for extra power in an emergency



Ship type	Required EEXI*
Bulk carrier	Δ15-20% by size
Tanker	Δ15-20% by size
Container	Δ20-50% by size
General cargo	Δ30%
Gas carrier	Δ20-30% by size
LNG carrier	Δ30%
Reefer	Δ15%
Combo	Δ20%
Ro-ro/ro-pax	Δ5%
Ro-ro (vehicle)	Δ15%
Cruise ship	Δ30%

\* Reduction from EEDI reference line

Fig. 5: EEXI obtained through different design improvement options: engine power limit, fuel change and energy saving devices [5]



## Latest ME-LGIM engine design considerations

Since the first engine tests made in Copenhagen and at our licensee Mitsui, vessels have been in operation and further developments of the LGIM-engine design have been completed. Furthermore, in line with the frequently used development process, a number of concept verification tests have been carried out at the Research Centre Copenhagen (RCC). In this paper, we will explain the LGIM concept and discuss the verification test results of the ME-LGIM engine.

The ME-LGIM engine has inherited well-known aspects and features of the standard MAN B&W two-stroke diesel engine, like the ME-GI dual-fuel engine. The LGI and GI concept engines are based on the conventional, electronically controlled ME-C engine with dual-fuel injection integrated as add-on parts. Beneficial features of the standard MAN B&W two-stroke diesel engine have been passed on, including options for: optimising the engine layout for high-load or part-load operation, derating the engine and combining the engine with waste heat recovery systems (WHRS).

Fig. 6 highlights components added on the cylinder top for methanol combustion.

The functionalities of the ME-LGIM concept include:

- Unit injectors, the so-called LGI fuel booster injection valves for injection of methanol (FBIV-M) into the combustion chamber around the top dead centre (TDC)
- Hydraulic control systems to control the LGI fuel booster valve operation
- Sealing oil supply unit mounted on the engine to ensure that no methanol leakage occurs in the moving parts of the methanol injection system
- Double-walled piping to distribute methanol to the individual cylinders
- Draining and purging system for quick and reliable removal of methanol from the engine
- In addition to the engine control

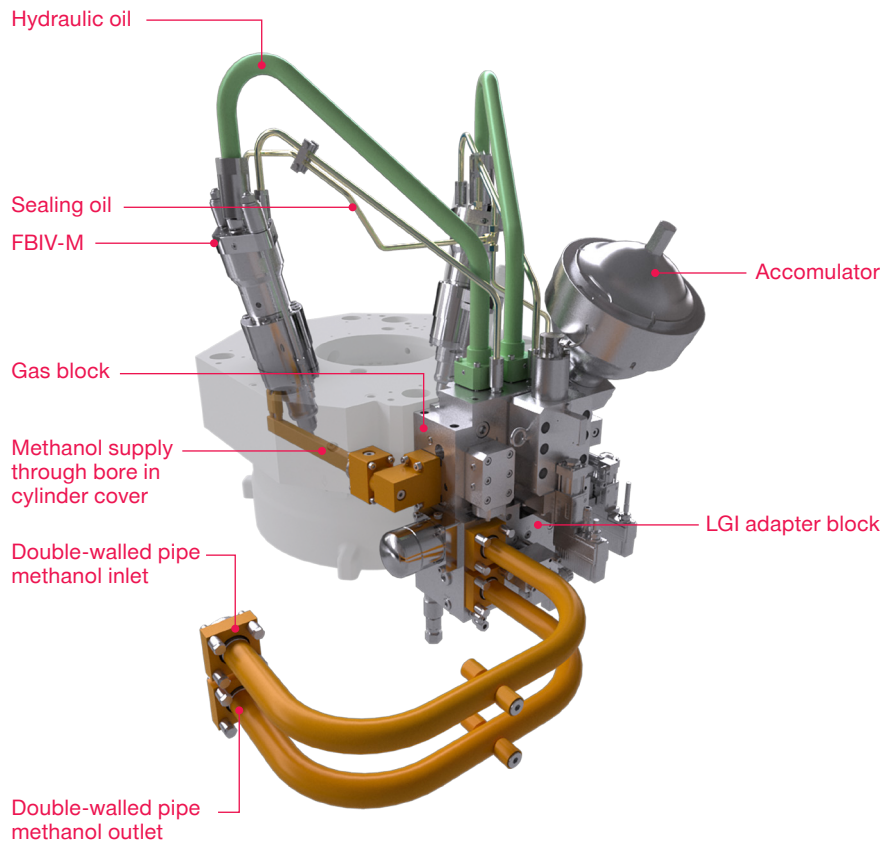


Fig. 6: Methanol components and pipes on each cylinder

system (ECS), a safety system monitors the methanol injection and combustion, and ensures that the engine reverts to diesel oil operation in case of alarms

- Fuel valve train (FVT) provides a block-and-bleed function between the fuel supply system and the engine
- Fully automated methanol supply system with an embedded purge system.

The design of the methanol fuel supply pipes in Fig. 6 is based on a double-barrier concept. It means that a second layer encapsulates all methanol piping inside the engine room. This outer-piping is ventilated to the outside atmosphere to eliminate the risk of a

methanol leakage to, for example, the engine room and to allow detection of a leakage from the inner pipe with hydrocarbon (HC) sensors.

The diesel fuel system has not been altered significantly on an LGI engine compared to a standard ME engine. As is the case for the ME-GI, the ME-LGI fuel system can change to fuel mode, burning diesel oil or VLSFO from one stroke to the other without any limitation in speed or load.

As the LGI functionality is an add-on to the electronically controlled ME engine, converting an existing diesel engine to a dual-fuel engine capable of using both diesel, VLSFO and, for example, methanol is possible.

**Injection system**

Fig. 6 shows the ME-LGIM cylinder cover with components for methanol injection (FBIV-M, fuel and hydraulic control blocks) and the supply for FBIV-M passing through the cylinder cover. Fig. 7 shows the methanol booster injection valve for the ME-LGIM engine.

The FBIV has been designed as a batch-injector, combining a hydraulically actuated plunger pump with a spring-held injection needle valve that opens at a given fuel pressure. The pump functionality of the

FBIV uses hydraulic pressure to increase the methanol pressure to the required injection pressure of approximately 600 bar. A suction valve (check valve) ensures filling of the pump chamber after each stroke. The methanol supply pressure lies within 8 to 10 bar. A small pilot injection from the diesel fuel system ignites the methanol. In the tests presented in this paper, the fuel injection valves are positioned clockwise from the LGI FBIVs in order to optimise the ignition of the methanol fuel jets.

The ME-LGIM system contains several internal safety features. The fixed

pump-chamber-volume design of the FBIV limits the amount of fuel that can enter the cylinder during each stroke, which eliminates the risk of injecting too much fuel.

The parts of the FBIV, where hydraulic oil and methanol could potentially mix, are specifically designed to minimise this risk with sealing oil added at critical points. The drained used sealing oil is recirculated to a separate tank in the sealing oil unit mounted on the engine, which handles a potential methanol contamination in a safe way.

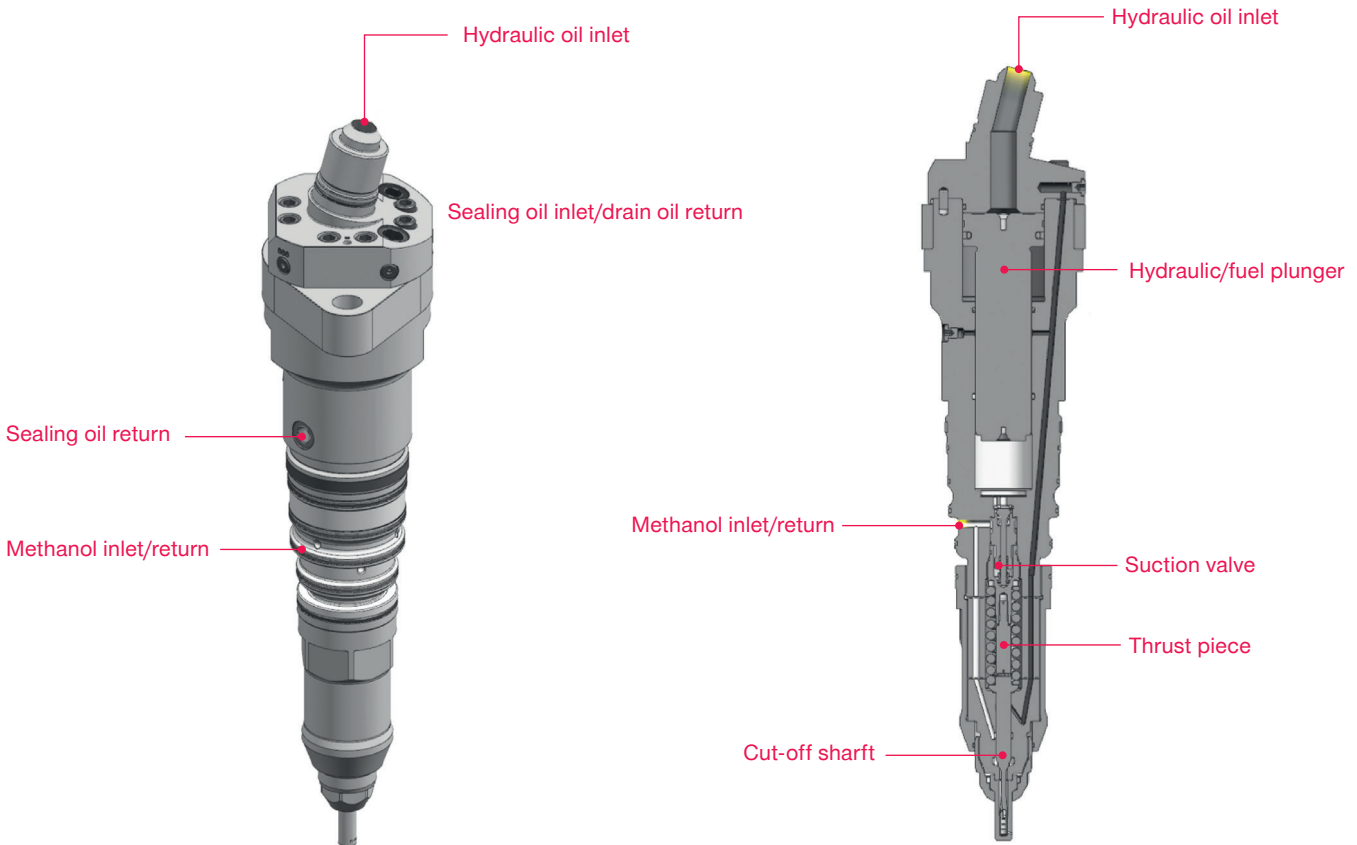


Fig. 7a: Graphic and 7b: Cross-section (right) showing the latest FBIV-M design and points of interest

### Fuel supply system for ME-LGI engines

This section describes auxiliary systems specifically designed for the ME-LGI engine. In addition to the systems described here, the normal ME auxiliary systems are also required – and since the ME-LGI is a dual-fuel engine, a standard supply system for operation on fuel oil is needed. Fig. 8 gives an overview of the LGI system, including a water injection unit for the LGIM-W engine introduced later.

#### Methanol supply system

The engine is using temperature-conditioned methanol at a fixed supply pressure and varying flow depending on the engine load. The methanol low-flashpoint-fuel supply system

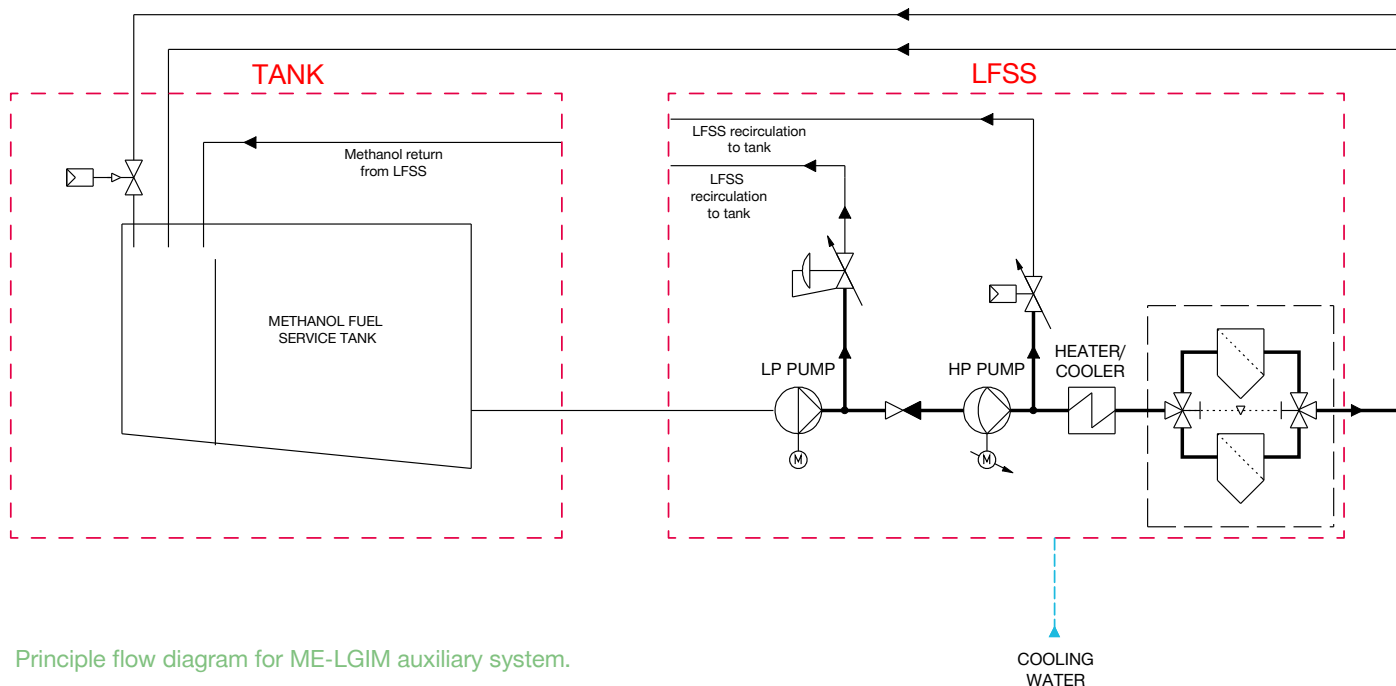
(LFSS) has to supply this fuel to the engine while complying with the requirements described regarding temperature, flow, pressure and capabilities.

The methanol LFSS is designed according to the same concept as an ordinary fuel oil supply system. The fuel is drawn from the service tank containing liquid fuel, and boosted to the supply pressure by a low-pressure (LP) and a high-pressure (HP) pump, to finally deliver approximately 10 bar pressure from the HP pump. The delivery pressure must ensure that the fuel will stay liquid, and that cavitation is not generated at the temperatures to which the fuel is exposed before injection in the FBIV. To ensure the correct fuel delivery temperature, a

heater/cooler is placed in the circulation circuit. It is recommended to connect this to a secondary cooling circuit and the low-temperature (LT) cooling system.

#### Water injection unit

The water injection unit has the purpose of delivering pressurised water at the necessary flow to be mixed with methanol in order to reduce NO<sub>x</sub> and thereby meet Tier III levels. It consists primarily of a pump, filters and pressure transmitters. It delivers water to mix with methanol through the FVT, and therefore water mixing is controlled by the ECS. The water injection unit is designed to be placed in a gas safe area, for example in the engine room.



Principle flow diagram for ME-LGIM auxiliary system.



**Methanol fuel service tank**

The methanol is stored in a pressure-less tank, for methanol carriers typically on deck. The methanol fuel service tank is split in two compartments, a drain/purge compartment and a supply compartment, connected by a spill over bulkhead.

**Fuel valve train**

The fuel valve train connects the LFSS with the engine through a master fuel valve (MFV) arranged in a double-block and bleed configuration. For purging purposes, the valve train is also connected to a nitrogen source, separated by a double-block and bleed configuration.

Furthermore, a water connection is also

connected to the valve train in order to meet Tier III NO<sub>x</sub> reduction levels, separated by a double-block and bleed configuration.

The valve train will be placed in the hazardous zone to avoid the need for double safety barriers, for example in a ventilated room together with the LFSS. From the valve train, the fuel is fed to the engine in a double-walled and ventilated pipe through the engine room.

**Purge return system**

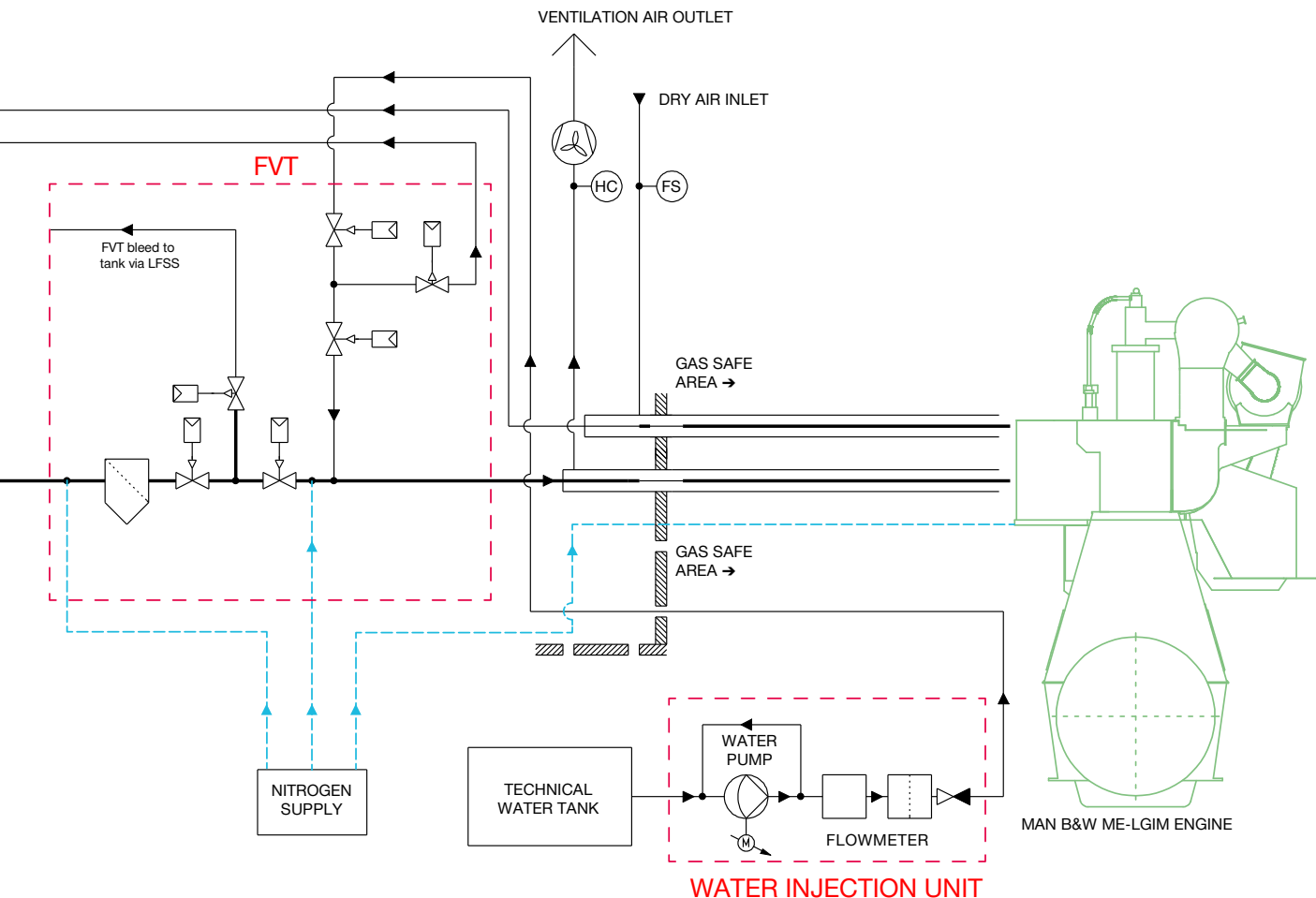
As mentioned, the LGI concept involves methanol fuels on the engine. Because of the low flashpoint, there are a number of operating scenarios where the fuel piping must be emptied and inerted. For the ME-LGI, the fuel piping

on the engine and in the engine room is arranged so that the liquid fuel can purge it, and thereby return it to the fuel service tank. After the methanol fuel has been returned to the service tank, full purging and inerting are conducted for the double-walled piping system.

**Shutdown of liquid gas system**

In a complete shutdown of the liquid gas system, all piping is emptied of methanol fuel and the LFSS and ventilation is turned off.

Additionally, the entire ME-LGI methanol fuel system, including the FVT, is pressure-tested with nitrogen as part of the start-up procedure. When dual-fuel operation ends, the fuel pipes are purged clean of methanol using a pressurised flow of nitrogen.



## Performance results

In the spring of 2015, the first functionality tests of LGI sub-systems and the initial performance tests were conducted on the 4S50ME-T9 test engine at Mitsui's Tamano shipyard in Japan. These tests confirmed the LGIM design applied on the 26 ME-LGIM engines sold as of October 2020.

Fig. 9 shows an ME-LGIM engine installation on board a vessel.

### Injection system layout

Initially, the chosen spray directions of the nozzle holes of the LGI methanol injector were similar to that of the standard diesel injector, and the dimensions of the LGI injector were laid out so that the injection duration of methanol at MCR would be roughly similar to that of the standard diesel layout.

As Table 1 shows, the lower calorific value (LCV) of methanol is as low as 19.9 MJ/kg, which is roughly half that of the ISO standard value 42.7MJ/kg for diesel oil. Furthermore, the methanol injection pump has been designed for a nominal injection pressure of about 600 bar, being somewhat lower than that of the standard fuel oil (MGO/HFO) injection system. Thus, if the initial goal is equal injection durations of methanol and diesel oil, the LGI injector must have more than twice the total nozzle-hole area of the standard diesel injector. However, results from small scale combustion chamber testing indicated that such simple scaling would lead to too large injectors, and in the initial tests, the effective nozzle flow area of the methanol injector was chosen to be roughly twice that of the diesel injector.

### Cylinder pressure measurements

The performance diagrams in this section were obtained from the latest ME-LGIM engine that went into service.

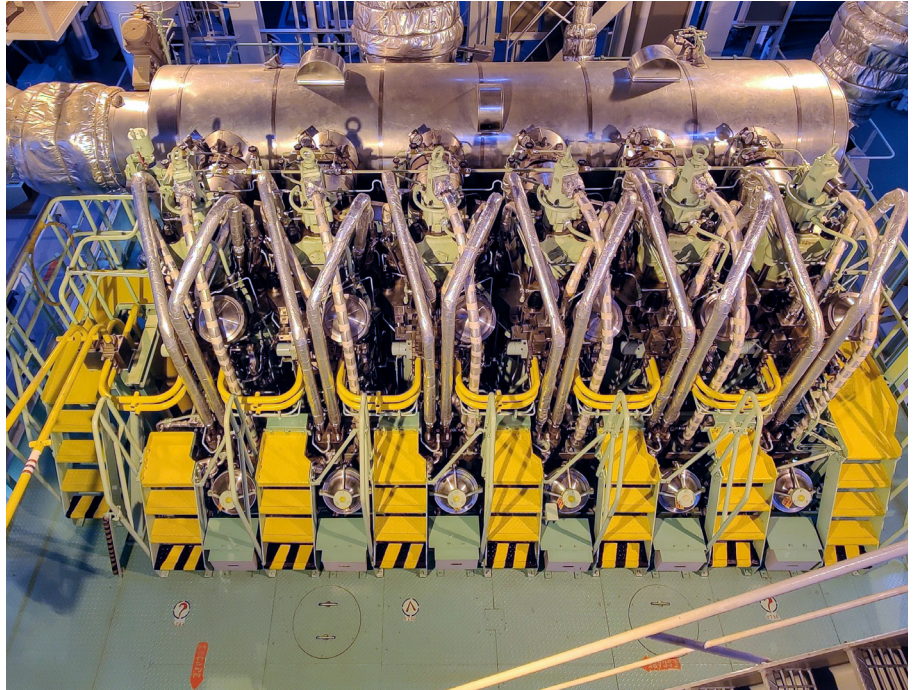


Fig. 9: ME-LGIM engine top

Fig. 10 shows the cylinder pressure and the corresponding calculated heat release for 100% load.

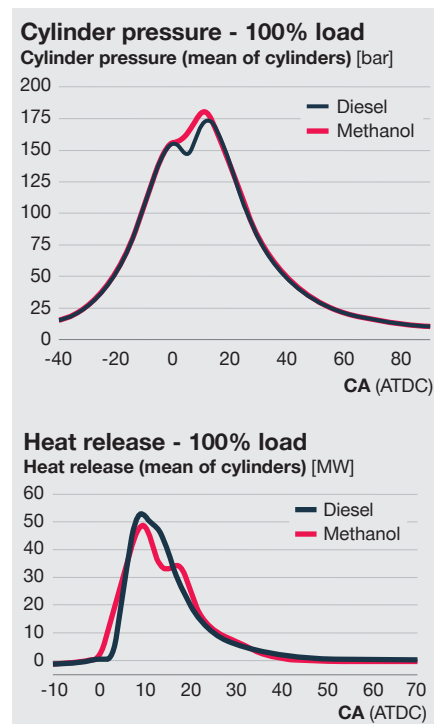


Fig. 10a: Cylinder pressure and 10b: Heat release rate, both for reference diesel operation (black) and methanol operation (red) at 100% load

Two cases are compared in Fig 10: the diesel fuel combustion in black and methanol (LGIM) combustion in red. Note that the methanol combustion includes a small diesel pilot oil amount as well. The cylinder pressure traces of the two modes are similar, but with some intentional differences. The methanol injection starts earlier and reaches a slightly higher maximum pressure, while the heat release is also slightly longer due to a longer injection duration. This combination leads to a lower methanol consumption, which has been achieved by actively optimising the methanol mode for this very purpose.

Furthermore, the late cycle heat release rate for methanol decreases faster, indicating that the methanol combustion ends earlier. In theory, this also gives a better thermodynamic efficiency for methanol relative to the diesel reference. The first reason that the methanol combustion ends earlier is the larger injected mass of methanol, giving a higher mixing rate. The second reason is the intrinsically high oxygen content in methanol that significantly increases the soot oxidation chemistry

in the flame, leading to a faster burn rate in the late flame.

### NO<sub>x</sub> emission measurements

Fig. 11 shows the raw NO<sub>x</sub> concentrations in the engine emissions and the relative specific fuel oil consumption (SFOC) for diesel and methanol as a function of engine load.

In general, NO<sub>x</sub> emissions decrease about 30% when changing from diesel to methanol combustion, given that the same operating parameters are used. This is an effect of the intrinsically colder methanol flame. Therefore, there is a large headroom for SFOC optimisation of the methanol process, while still maintaining NO<sub>x</sub> emission compliance with IMO Tier II legislation. Fig. 11 illustrates this.

NO<sub>x</sub> emissions for methanol (a) have been increased as much as possible, which is still below the diesel reference, in order to reduce the methanol consumption. On an energy basis, the SFOC for methanol (b) is now lower

than that for the diesel reference.

### Pilot oil consumption

The amount of pilot oil is up to 5% of the MCR fuel consumption in diesel oil mode. The amount of pilot oil needed for securing ignition of the injected methanol is very small. It is, however, a technical challenge to design a robust injection system that is large and powerful enough to enable fuel-efficient, high-load operation on fuel oil, while being small and fast enough to be able to inject minute amounts of pilot oil in LGI operation. In fact, the only particulate matter emissions generated from methanol dual fuel vessels is from the pilot fuel.

It is not the requirement for secure ignition of the methanol that sets the lower limit for the pilot oil amount, but the minimum amount of fuel that can be injected reliably by the fuel injection system. In this context, it should be noted that the pilot oil injection is not wasted energy since the oil combustion takes place close to top-dead centre

(TDC) and therefore contributes with maximum thermodynamic efficiency to the engine power output.

In general, the engines showed very good performance with no major component failures during the tests. The engines were operated with the same rating and performance layout regardless of fuel, diesel or methanol, thus demonstrating the robustness of the LGI-engine design.

The tests showed that methanol is a good combustion engine fuel, giving roughly 30% lower NO<sub>x</sub> emissions and a slightly better SFOC compared to diesel oil operation when operating with identical thermodynamic operating points. In conclusion, both NO<sub>x</sub> and SFOC targets are easily reached with methanol as fuel.

Technically, the pilot oil can be any renewable hydrocarbon fuel, for example bio-fuel or Power2X diesel, thereby making the engine operation CO<sub>2</sub>-neutral.

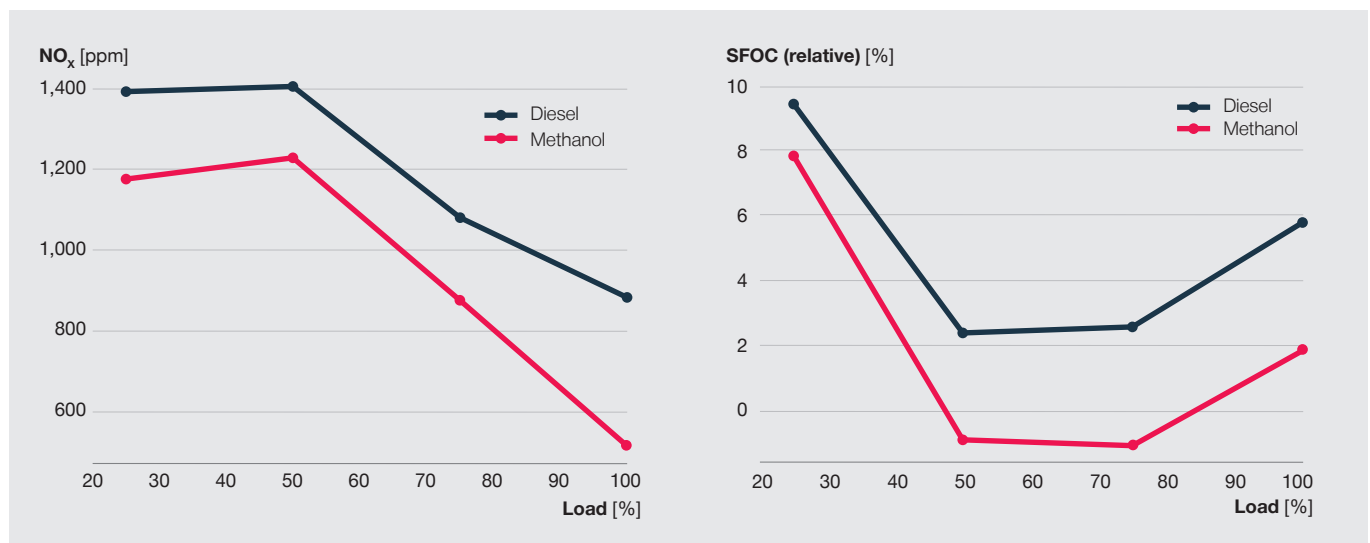


Fig. 11a: Measured NO<sub>x</sub> emissions and 11b: Relative SFOC (%) comparing methanol and diesel operation



## Service experience

The service experience described is based on close to 90,000 running hours. The first generation of ME-LGIM engines, designated Mk. 1.1, have been installed on seven vessels, accumulating more than 80,000 running hours in total. ME-LGIM Mk. 1.2 engines have been installed on four vessels, and they have accumulated more than 8,000 running hours in total.

### Mk. 1.1 engines

For vessels with Mk. 1.1 engines, the main issue observed was the tendency of the FBIV-M cut-off shaft to stick inside the valve if the engine was running 3 to 4 days on HFO. This was caused by corrosion in the nozzle followed by ingress of exhaust gas. However, with the introduction of a

stainless steel nozzle, which is less susceptible to the sticking phenomenon, some vessels have been running a few weeks on HFO without problems. The stainless steel nozzles are now standard for all methanol-powered engines.

After several thousand running hours on methanol, signs of cavitation were observed at the sealing position of the suction valve inside the FBIV-M, see Fig. 12a. To avoid future problems, a soft-iron sealing ring was introduced between the suction valve and the FBIV-M housing (previously lapped surfaces), see Fig. 12b.

### Mk. 1.2 engines

On Mk. 1.2 engines, the external methanol supply pipes on the engine as well as the internal complexity of the FBIV-M were reconsidered. By simplifying the design of the FBIV-M, it was possible to reduce the amount of external piping and to simplify the sealing oil system, which again led to a reduction in sealing oil consumption.

On these engines, the methanol supply pipes are placed inside the cylinder cover to ease maintenance, see Fig. 6. The flexible connection visualised in Fig. 13 between the LGI control block and the cylinder cover has shown to be susceptible to the relative

movement that caused a seal on the connection to wear out. Our solution will be to tighten the clearances and change from a u-cup type seal to an O-ring seal.

### Cylinder lubricating oil and combustion chamber conditions

The BN value and the feed rate of the cylinder lubricating oil depend on the sulphur level in the fuel. When running on methanol, the cylinder oil feed rate must be minimum 0.6 g/kWh during normal operation. In the latest cylinder oil guideline, we recommend a low-BN cylinder oil, but as for all engines, it is essential to make a scrape-down analysis to obtain an optimal performance of the compression chamber.

The detergency is often challenged for the BN40 cylinder oils available on the market today. To ensure free movement of the piston rings, the cylinder oil must be able to keep the ring pack clean and prevent deposits from building up, see also Fig. 14.

We therefore distinguish between category I and II cylinder oils, where category II is for the latest high-performing engines. Reference is also made to the Service Letter SL2020-694/JUSV, which is available for download on our homepage [9].

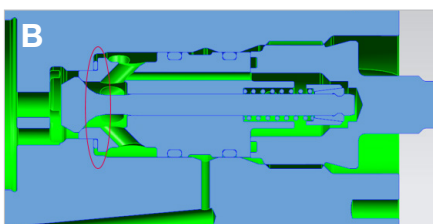
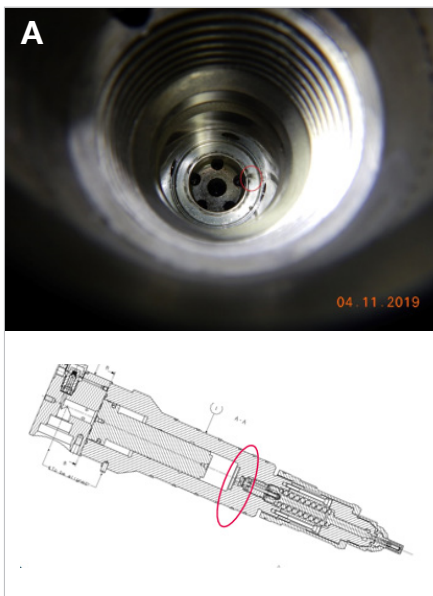


Fig. 12: Cavitation of the suction seat (12a) and New design with sealing ring (12b)

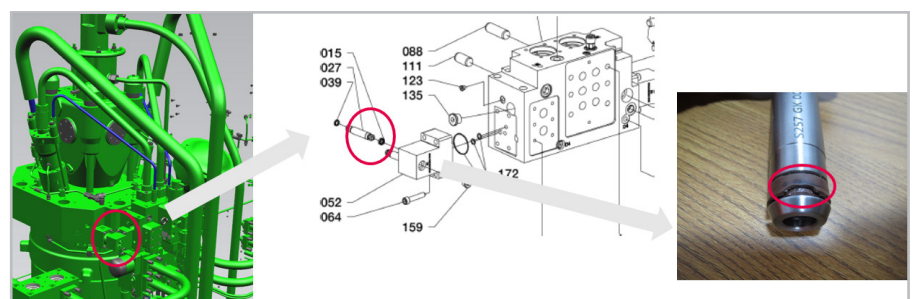


Fig. 13: The flexible connection and a worn-out seal on the connection

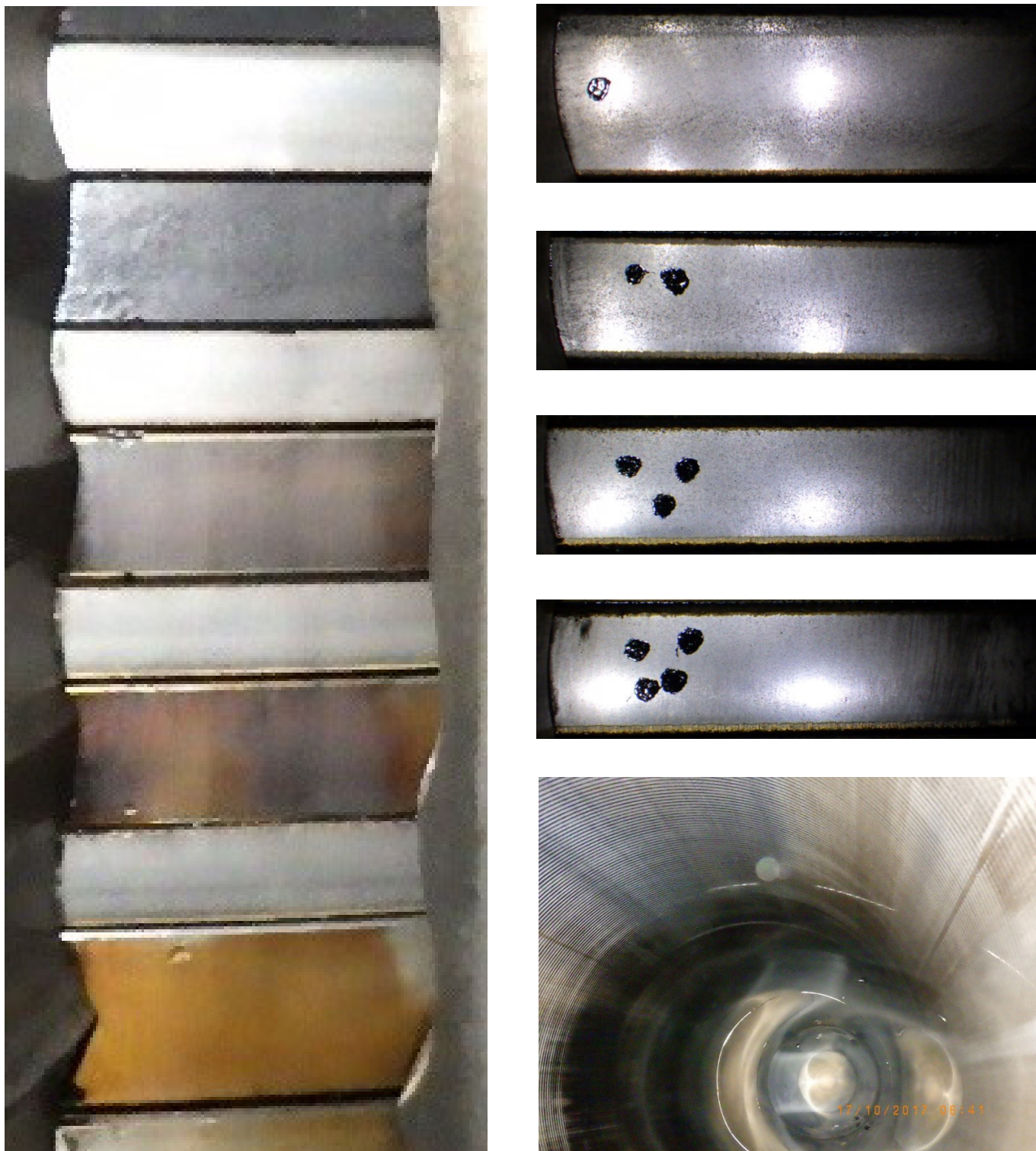


Fig. 14: Ring pack and combustion chamber with visible wave-cut after 7,058 running hours on methanol

## Mixing water into methanol gives Tier III compliance

The diesel pilot injection of LGIM engines ensures a stable ignition and combustion of even very poorly igniting fuels. Through research, MAN Energy Solutions has now demonstrated that the pilot injection principle has further advantages as it enables combustion of water and methanol mixtures. Fig. 8 shows the fuel supply system and the water injection system.

The operating concept of the LGIM-W engine is that the addition of water to methanol lowers the combustion temperature and thereby the NO<sub>x</sub> formation. The economic benefit of complying with Tier III NO<sub>x</sub> emission levels by adding water to the fuel is that

EGR or SCR systems are no longer required, as illustrated in Fig. 15.

Tests have confirmed that by running on methanol mixed with approximately 25-40% water and 5% pilot oil (diesel) it is possible to reduce NO<sub>x</sub> emissions sufficiently to reach Tier III emission levels, see Fig. 16.

An LGIM-W engine operating according to the developed and further optimised concept has passed Tier III compliance tests, and MAN Energy Solutions has obtained NO<sub>x</sub> certification for the LGIM-W engine.

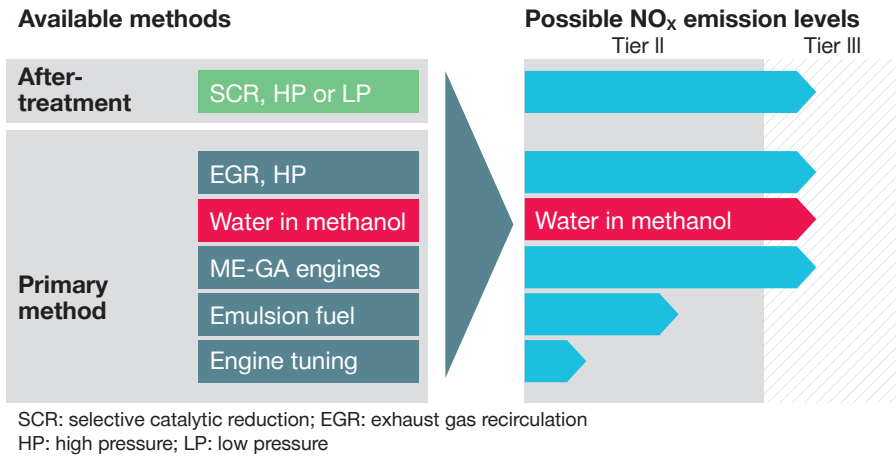


Fig. 15: NO<sub>x</sub> reduction methods

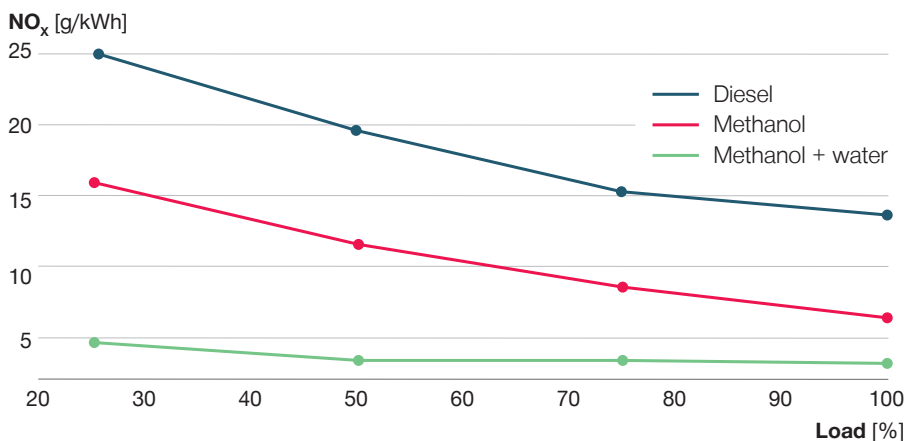


Fig. 16: NO<sub>x</sub> reduction as a function of load

## Summary

The MAN B&W ME-LGI engine is our dual-fuel solution for low-flashpoint liquid fuels injected in liquid form into the engine. Currently, 26 ME-LGIM engines for operation on methanol have been installed on new methanol carriers.

The discussion of and interest in methanol as one of the future fuels has intensified, and many vessel owners believe that, ten years from now, it will be one of the future fuels of the decarbonisation. Methanol, as a sulphur-free fuel, is completely compliant with the 2020 IMO low-sulphur regulation. Low-sulphur compliance is not the only beneficial reason for adopting methanol though, as the lower CO<sub>2</sub> formation (up to 7% lower than for HFO) during the combustion process is advantageous. Since the methanol molecule contains no carbon-carbon bonds, it does not produce particulate matter or soot when burned.

To lower the carbon footprint during the transition period (initially to 2030 and subsequently to 2050), it is expected that IMO's CO<sub>2</sub> and GHG targets for 2030 and 2050 will lead to an increased number of drop-in fuels.

For the LGIM-engine, methanol as a drop-in fuel is readily achieved by blending increasing amounts of green or blue methanol with grey methanol, until, eventually, the lower-carbon methanol becomes the main fuel. This is a net carbon-neutral solution that may co-evolve with an increasing production of green or blue methanol. As a result, it may gradually assist the industry in meeting the IMO targets for CO<sub>2</sub> and GHG emissions. This provides fuel flexibility for the ME-LGIM engine, and combined with the ability to burn green methanol, when available, the engine becomes advantageous for other vessel types as well and not only methanol carriers having the methanol on board already.

The first generation ME-LGIM engines

designated Mk. 1.1 were installed on seven vessels in 2016, which have accumulated more than 80,000 running hours in total. Second-generation ME-LGIM Mk. 1.2 engines were installed on four vessels and they have accumulated approximately 8,000 running hours in total.

For Mk. 1.1 engines, the main difficulties observed were related to the FBIV-M. By simplifying the design of the FBIV-M, it was possible to reduce the amount of external piping and to simplify the sealing oil system. These design changes have been implemented on the Mk. 1.2 engines.

In the further development of the LGIM engine, a simple methanol-and-water blending system has been introduced to lower the NO<sub>x</sub> level for Tier III compliance. The LGIM-W engine operating according to the developed and further optimised concept has passed Tier III compliance tests, and MAN Energy Solutions has obtained NO<sub>x</sub> certification of the engine.



## Acknowledgements

We would like to thank the Methanol Institute for valuable contributions.

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## Acronyms and abbreviations

BN	Base number
CC	Carbon capture
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CII	Carbon Intensity Indicator
ECA	Emission control area
ECS	Engine control system
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency for Existing Ships
EGR	Exhaust gas recirculation
FBIV-M	Fuel booster injection valve-methanol
FVT	Fuel valve train
GHG	Greenhouse gas
GI	Gas injection
HC	Hydrocarbon
HP	High pressure
IGF	International Code of Safety for Ships using gas or other low-flashpoint fuels
IMO	International Maritime Organization
IMPCA	International Methanol Producers & Consumers Association
LCV	Lower calorific value
LFF	Low-flashpoint fuel
LFSS	Low-flashpoint-fuel supply system
LGI	Liquid gas injection
LGIM	Liquid gas injection methanol
LGIM-W	Liquid gas injection methanol with water emulsion
LGIP	Liquid gas injection propane
LNG	Liquefied natural gas
LP	Low pressure
LPG	Liquefied petroleum gas
LT	Low-temperature
MCR	Maximum continuous rating
MFV	Master fuel valve
MSW	Municipal solid waste
NG	Natural gas
PIFIW	Pilot-oil-ignited fuel in water
RCC	Research Centre Copenhagen
SCR	Selective catalytic reduction
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific fuel oil consumption
TDC	Top-dead centre
WHRS	Waste heat recovery system

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