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Report

GHG and NOx emissions from gas fuelled engines

Mapping, verification, reduction technologies

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ABSTRACT

The report describe state of the art gas engine technology for marine application.

Gas fuelled ships are measured to obtain new data and to updated emission factor with focus on NOx and CH4 emissions from gas engines. Other emissions as THC, CO and CO2 is also measured. Data is also collected from manufacturer testbed protocols. Additional NOx emission data is collected from the NOx-fund database.

Potential methane reduction technologies are described.

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APPENDICES

1 Summary and conclusions

During the last few years, significant reduction of methane slip from gas fuelled engines for marine application is documented. Previous work by SINTEF Ocean (former MARINTEK) showed significant higher methane emissions than what is observed today. Especially low load operation has improved. However, on-board measurement show that specific methane emissions are relative high on these operation points, and this may be of concern for ships where low load operation is required.

It is a trade-off between methane slip and NOx emission in lean burn engines. Lean operation reduces NOx and if very low NOx-emissions is the target, the level of emitted methane due to incomplete combustion will increase. Simultaneously also CO emission will increase. A countermeasure is to operate the engine with a lower air/fuel ratio (richer combustion). In this way, the combustion process improves with lower methane and CO emissions but the penalty is higher NOx emissions. It is also important to have in mind the relative narrow operating window for a lean burn gas engines at high load where to rich operation increase the risk of knocking and to lean operation increase the risk of slow burning and misfiring.

With a NOx tax regime, there are economic benefits for the ship owner to achieve low NOx factors, and the engine could be adjusted to obtain as low NOx factor as possible. The penalty is higher methane slip and CO emissions.

High attention on GHG emissions has made engine manufacturers to focus on methane slip. They optimize their engine to minimize all exhaust emissions to be in line with regulations (NOx and SOx) and reduce methane and CO emissions to a minimum. Special focus has been to improve low load performance with respect to fuel consumption and emissions.

In this project emission data from gas fuelled ships has been collected by a measurement campaign on six ships and one test bed engine. In addition new measurement data for two ships from SINTEF' database was available. In addition, supplier information from testbed verification of several engines were collected and analysed, and measurement data from the NOx-fund was made available. Main results from the project are summarized as follows:

Engine technology

In December 2016 approximately 120 gas fuelled ships were in operation. Technical specification of the gas fuelled ships currently in operation show approximately a 40-60% split between Lean Burn Spark Ignited engines (LBSI) and Low Pressure Dual Fuel engines (LPDF) for the ships in concern.

The gas fuelled ship marked has so far been limited and dominated by car/passenger ferries and offshore supply vessel operating in Norwegian waters and with three main engine suppliers. New ship types are introduced over the last few years and new engines concepts has been realised as High Pressure Dual Fuel (HPDF) gas engines for the deep-sea ship marked.

The emission profile of a gas fuelled ship is dependent on the engine technology on board. This project evaluate the emission profile in general and the methane slip in particular from sailing ships using LBSI engine and 4-stroke LPDF engine.

Measurement campaign and engine test data

Data from the measurement campaign, supplier testbed data and NOx –fund data was analysed to achieve emission factor for the ships in concern and for the specific engines. Focus has been on NOx and CH4 emissions. Other emissions as THC, CO and CO2 are also measured.

Recommended emission factors based on these sources is shown in **Table 1.1**

Engine type	NOx		CO		THC		CH4		CO2	
	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh
Emission factor, LBSI	5,1	0,9	9,8	1,7	25,4	4,4	23,2	4,1	2687,3	472,4
Emission factor, LPDF	10,4	1,9	11,0	1,9	43,2	7,3	40,9	6,9	2630,3	444,2
Average, all engine type	7,5	1,4	10,3	1,8	33,2	5,7	31,0	5,3	2662,4	460,1

Gas fuel: Hn~49,3 kJ/kg, Density~0,78 kg/Nm^3

Table 1.1: Recommended emission factors, LBSI engines and 4-stroke LPDF engines built after 2010.

In **Table 1.1** the average data for all engines are the mean values for all data available in this project, and this has not been weighted in relation to actual ships in operations. The average data could be used as general factors in cases where technology on board is not known.

It is important to notice that LBSI engines include medium speed and high-speed engines. In general medium speed engines has higher efficiency than high speed engines which reflects that average values for CO2 emissions are higher for LBSI engine than LPDF engines. Data from this study show that engine performance and emission profile varies dependant on engine type and manufacturer.

Compared to previous data presented in 2010 significant reduction of the methane slip are verified by measurement for both LBSI engines and LPDF 4-stroke engines. It is recommended to update previous emissions factor based on project result, as the results likely represent state- of the art emission factors for gas fuelled engines. Data is applicable for new engines built after 2010. From fleet statistic about 20 gas fuelled ships was in operation prior to 2010, and the fleet of gas fuelled ships have increased to more than 120 ship today (December 2016).

The emissions are given as specific values in [g/kWh] and [g/kg gas]. When the emissions are given as [g/kWh], the emission is related to the power production of the engine. Emission factors in [g /kWh] is a good indicator of the emissions from the engine since it incorporates the efficiency of the engine.

When the methane emission is converted into [g/kg fuel gas], it becomes harder to evaluate the level of methane slip (and other emissions) from the engine because this is dependant of the engine efficiency (= specific fuel consumption, g fuel/kWh). We illustrate this issue with the following example:

	CH4	SFC, gas	CH4
	g/kWh	g/kWh	g/kg fuel gas
	A	B	A/B*1000
Engine 1	5	170	29,4
Engine 2	5	190	26,3

In an emission inventory normally the fuel consumption and emission factors in [g/kg Fuel] are input parameters, and in such calculations variation in engine efficiency is counted for.

When comparing one engine to the other the emission factors and the engine efficiency should be evaluated the get the right picture.

Methane slip reduction technologies

Several primary measures on how methane slip can be reduced are presented. This is mostly related to engine component design and engine process control strategies. Today several of the described measures are implemented, which also reflect the results from the measurement campaign as significant improvement of methane slip factor is observed for newer engines compared to engines s built before 2010.

MAN Diesel and Turbo have introduced high-pressure Gas Injection Dual Fuel (HPDF) gas engines to the shipping market for slow speed engines. Several ships are in operation in 2017 and these ships have no methane slip.

Exhaust gas after treatment could be an option to reduce the methane slip but today there are still unsolved technical issues related to methane conversion ratio at low exhaust temperature and catalyst degradation. Further development is required to make this technology durable and efficient.

Recommendation

Gas fuelled ships is a measure to reduce NOx emissions from ships, and such ships operating in Norwegian waters has gained support from the Norwegian NOx fund to cover additional investments cost compared to diesel operation. To validate the actual NOx reducing on these ships, on-board measurement is undertaken on each single ship, which gives good data for emission inventories and national emission accounting.

As technology evolves the emission factors for new ship changes, which is documented in this report regarding methane emissions in particular but also other emissions factors for NOx, CO and CO2.

To obtain good data for emission accounting it is recommended that future onboard measurements should be extended to include all emission relevant for the ship type in concern. In particular, the methane slip on gas fuelled ships should be included.

2 Abbreviations and acronyms

Abbreviations/acronyms	Explanation
CH4	Methane
CO2	Carbone dioxide
DF	Dual Fuel
DF-engine	Dual fuel engine
DNV	Det Norske Veritas
EGR	Exhaust Gas Recirculation
FOC	Fuel oil consumption
FPSO	Floating Production, Storage and Offloading unit
GD-engine (GI-engines)	High pressure gas injection engine (Diesel-cycle)
GHG	Green House Gases
GT	Gas Turbine
GWP	Global warming Potential factor
HFO	Heavy Fuel Oil
HPDF	High Pressure Dual Fuel
Hn	Lower heating value
IGC code	The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code on Safety for Gas-Fuelled Ships (issued by IMO).
IMO	International Maritime Organisation
ISO	International Organization for Standardization
Lambda	Air/fuel ration
kJ	Kilo Joule
kg	kilogram
LBSI	Lean burn spark ignited
LBSI-engine	Lean-Burn spark ignited gas engine (Otto cycle)
LCA	Life Cycle Cost
LCS	Low Carbon Shipping
LNG	Liquefied Natural Gas
LPDF	Low Pressure Dual Fuel
MGO	Marine Gas Oil
NA	Norwegian Accreditation
Nm^3	Normal cubic meter (at t= 0°C, P=101.325 kPa)
NMA	Norwegian Maritime Administration
NOx	Nitrogen oxides
PM	Particulate Matter
ROPAX	Roll on/roll off passenger ship
RORO	Roll on /Roll off
SCR	Selective Catalytic Reduction
SFC	Specific Fuel Consumption, for gas engines: specific gas consumption
SOx	Sulphur oxides
THC	Total Hydrocarbons (=UHC)
UHC	Unburned Hydrocarbons
UNFCCC	United Nations Framework Convention on Climate Change
VVT	Variable Valve Timing

3 Introduction

The NOx Fund has been a deciding instrument for Norway's reduction of NOx emissions from the maritime sector, and an important measure has been the support to gas operation of ships. Gas engine technology has first and foremost been applicable on new construction, but it is also carried out projects where ships have been retrofitted. A consequence of the introduction of NOx-reducing measures can be increased emissions of other substances and increased energy consumption. It is known that the gas operation of ships provides low NOx emissions and has the potential to result in lower energy consumption than by MGO-operation, but this is dependent on technology choice. It is also known that the gas operation has drawbacks in that it provides the emission of environmental harmful methane, which has 25 times stronger climate effect than CO2. A GWP factor for methane of 25 is used by UNFCCC and the Kyoto protocol and thereby in Norwegian emission accounting by Norwegian Authorities /17/.

The amount of methane slip from gas-powered ships is somewhat inadequately documented and the public debate is often based on historical emission factors from when the first gas engines were put into operation. The emission figures in real-world operation with today's technology is not proper documented. To make a good environment comparison, all emission factors should be mapped and weighed against each other according to recognised standards. In this way, potential improvement for the reduction of methane slip can be established and any disadvantages such reductions could lead to for other harmful emissions could be clarified.

It is currently no requirements to methane slip from gas engines and emission measurements of methane is not included in the default verification measurements required by the NOx Fund to get approval of conducted NOx-measures on ships. The net climate effect of natural gas operation of the ship is dependent on technology choice (engine concept) and the operational profile for applicable ships and can not be described unambiguously on general basis. Gas engine development over the past few years has given lower methane emissions, but the actual level in real-world operations is not well documented.

As a response to an announcement from the Norwegian NOx Fund to support development projects and studies to strengthen knowledge about air emissions and measures to reduce emissions, SINTEF Ocean has undertaken this project with focus on emissions from marine gas engines. The main purpose was to do emission measurement on alternative ships and engines types to obtain state of the art data for new gas engines in operation. Through a measurement campaign, emissions from gas fuelled engines has been verified. Specific focus on methane slip from this engines but emission components as NOx, THC (CH4), CO and CO2 has been measured.

In this report more consistent information associated with methane slip from gas engines is provided. The report is split in three parts as follows:

Part 1: State of the art - gas engine and emission reduction technology
Part 2: Update of emission factor for gas fuelled ships
Part 3: Available technologies for emission reduction

The work was carried out by SINTEF Ocean (former MARINTEK) and was funded by the Norwegian NOx-Fund, the Norwegian Environment Agency and SFI Smart Maritime. Ship owners have placed their ships at disposal for on-board measurements to obtain updated emissions factors from ships in operation. Measurements were done on several ship types as ferries, product tankers and bulk ships.

Part 1

State of the art - gas engines and emission reduction technology

4 Gas fuelled ships

4.1 Ships in operation

The first gas fuelled ship was launched in 2000 (MF Glutra) and per December 2016 approximately 120 gas fuelled ships are in operation worldwide. Most of these are operating in Norwegian waters, (>50%).

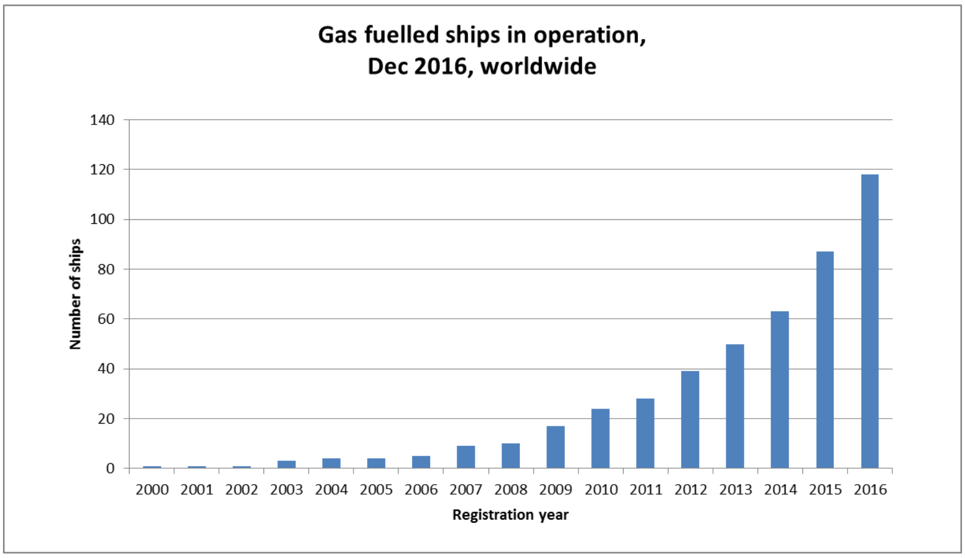

Figure 4.1: Gas ships in operation, worldwide, as per December 2016, (approximate numbers based on public information).

Most of the gas fuelled ships which entered into service in the period 2000-2010 was car/passenger ferries and offshore supply vessels (OSV), but with a few exceptions. From 2011 a larger diversity of ship types going for natural gas as fuel is observed, and today several different ship types are operating on natural gas as main fuel.

Ship type	Ships in operation		Ship type	Ships in operation
Barge	2		LNG FSRU	1
Bulk ship	2		LNG tanker	8
Car carrier	2		Offshore vessel	23
Car/Passenger ferry	32		Ore-bulk-oil carrier	0
Container ship	3		Passenger ship	1
Cruise ship	1		Patrol vessel	4
Dredger	2		Product tanker	8
Gas Carrier*	6		ROPAX	4
General Cargo, (Fish Fodder)	4		RORO ship	3
High speed ROPAX	1		Tug	8
Hopper Barge	1		LNG Bunker ship	1
			SUM, number of ships, 2016	117

*Only ships in typical short sea shipping operation is included

Table 4.1: Gas fuelled ship types in operation, worldwide.

Gas fuelled ships covers a range of ship types and sizes and consequently the installed engine power varies from some hundred kW to several MW. Alternative engine technology is available for the marine market.

4.2 Gas engines concepts

There are four different gas engine concepts as shown below. These have different combustion characteristics that give different effects on efficiency and exhaust emissions. This means that the overall environmental effects of gas operation of ships are dependent on technology choice, something that is not arising in the general environmental considerations around gas operations of ships.

- Lean-Burn Spark Ignited engines (LBSI-engine), medium-high speed, (0,5-8 MW)
- Low pressure Dual-Fuel engines (LPDF-engine), medium speed, 4 stroke (1-18 MW)
- Low pressure Dual-Fuel engines (LPDF-engine), slow speed, 2 stroke (5-63 MW)
- High-pressure Gas Injection (HPDF engine), slow speed, 2-stroke (> 2,5 MW)

As can be seen there are overlap in the power range between the concepts and choice of engine and gas system should be carefully evaluated in each case based on ship type requirements as propulsion power, redundancy, flexibility, endurance, operational profile, gas availability and commercial issues. The LBSI and 4-stroke LPDF engines have been in operation in ships for some years and could be considered as proven technology. The LPDF 2-stroke engine (Winterthur Gas and Diesel, Win-GD) and the HPDF 2-stroke engine (MAN) have also been installed in a few ships today (2017) and is commercially available in a large power range. The HPDF 4-stroke engine from Wärtsilä has been in operation for many years in the power plant of FPSO' s operating in the North Sea and for the onshore power plant market, but has not been used for ship propulsion so far.

Single fuel gas engines (LBSI = Lean Burn Spark Ignited) are used on all gas powered ferries in Norway. Dual Fuel gas engines (LPDF engines) are dominant in the offshore segment, but both the LPDF and LBSI engine concepts are used in this segment. For other types of vessels (e.g. freight ships, tankers, tug boats) both engine concepts are used. Slow speed 2-stroke LPDF engines using low pressure gas has entered the market recently and has been introduced as prime mover in commercial ships.

High pressure dual fuel (HPDF) gas engines have not been used in the current gas fuelled ships operating in Norwegian waters. However, this engine type has been in operation on floating production ships as power plant drives (4-stroke concept). The HPDF 2-strroke slow speed concept is now introduced in larger freight ships for deep sea operation.

The main contributor to CO2 reduction with natural gas operation is the lower carbon content of the gas compared to diesel. The CO2 reduction caused by natural gas operation also depends on the selected engine technology, and will vary for different engine types due to variation in engine efficiency.

The gas engine concepts (LBSI and LPDF) have in common that they have emissions of methane, but they have some different emission profile. Real emissions depend on the operating profile of the ship, and in general, operation on low engine load gives higher specific emissions than on higher load. Methane slip from gas engines is a challenge that has received high focus because of the strong greenhouse effect of methane, and these emissions need to be considered in the overall evaluations of gas fuelled ships.

Today's emission factors for ships are based on test bed measurements and some measurements in reel operation, and engine installed in ships today shall be compliant with NOx tier II requirements. The Norwegian NOx fund has given investment support to several hundred projects for implementing NOx reduction measures on ships operating in Norwegian waters. The effect of these measures has been verified by on-board measurements on the ships in concern to establish new emission factors for the ship. These measurements are confined to the verification of NOx emissions and do not give the full picture of the emissions profile of the affected vessels.

Technical specification of the gas fuelled ships currently in operation show approximately a 40-60% split between LBSI engines and DF engines for the ships in concern.

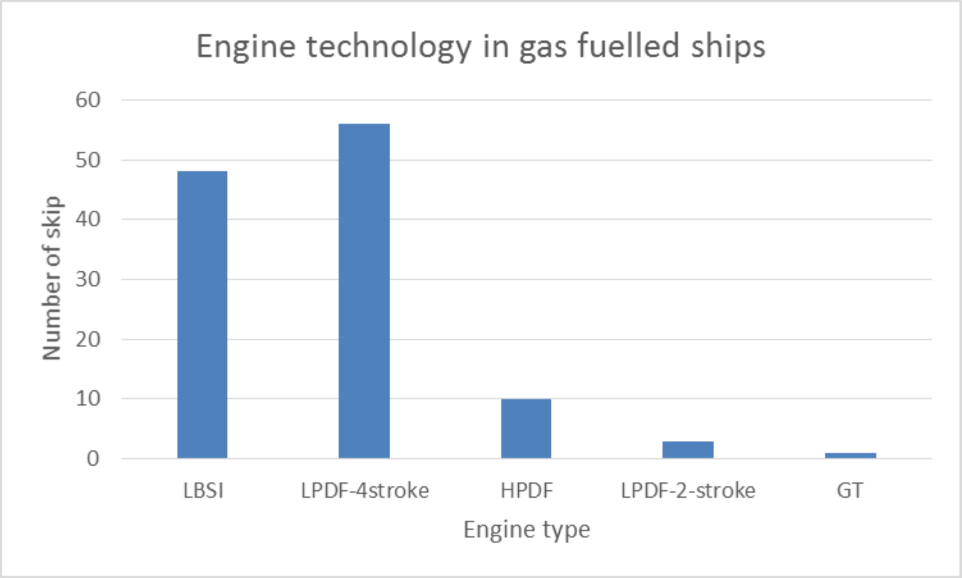

Figure 4.2: Engine technology in gas fuelled ships

The dominating market for LBSI engines has been car/passenger ferries operating on the Norwegian cost. However, other ship types as ROPAX, RORO, Product Tankers, Patrol ships and OSV have also selected this engine type.

LPDF 4-stroke engines have been the first choice for OSV, but are also used in all other ship types. Slow speed LPDF- 2-stroke engines have recently entered the market, and have been installed in a product tanker and this engine type is decided for main propulsion for new container ships under construction.

HPDF engines for the maritime market are available for larger ships. One example is car carriers recently put in service by UECC in the Baltic sea, others are container feeders operated by Tote Maritime in the US coast and LNG carriers operating world wide.

One fast speed vessel has installed two gas turbines, (South America) which can operate on gas or MGO.

Three vendors have been dominant in supplying engine to the Norwegian domestic and short sea market; Rolls Royce, Mitsubishi and Wärtsilä. New suppliers have entered the market the last few years as MAN and MaK (Caterpillar).

4.3 Methane slip – unburned methane from combustion

Methane slip is connected to combustion engines where natural gas and air are compressed in the cylinder before combustion. There is two main reasons for unburned methane emitted form gas engines:

- Dead volume in form of crevices between cylinder unit components such as :
    - ✓ Gasket area between cylinder head and cylinder liner
    - ✓ Between piston top land and cylinder liner
    - ✓ Behind anti-polishing ring

During the compression stroke the gas mixture is compressed into these crevices and hide away from the combustion. The Methane molecule is very stable and need high temperature to ignite/combust (above 600 degree C depending on air fuel ratio). In the expansion stroke the gas flows out from the crevices, but due to lower temperatures during expansion the methane molecules are to a large degree unburned, and comes out in the exhaust flow. This dead volume can be reduced to a minimum by design, but will always give a certain (significant) amount of unburned methane.

- Uncomplete combustion in form of quenching at the coldest part of the combustion chamber is another reason for methane slip. Quenching occur when the mixture is too lean and cooled down along the cylinder liner. This will mainly be the case at low load operation. Quenching can be significantly reduced by improved process control by enriching the mixture closer to stoichiometric condition (lambda =1). Richer mixture will create more NOx so the control need to balance the trade-off between unburned methane and NOx.

Other sources of unburned methane could be blow through in the scavenging process and valve overlap. New engine design run with practically no valve overlap so hence unburned methane is consider neglect able.

4.4 Engine technology

4.4.1 Low pressure gas engines

The various engine concepts will compete in different ship segments. For gas powered ships operating in Norwegian waters, we see a clear split in market shares as LBSI engines has been the preferred solutions for ferries and 4 stroke LPDF engines has been chosen to power offshore vessels. So far only three suppliers have provided engines to this market, RR, Mitsubishi (LBSI-engines) and Wärtsilä (LPDF 4-stroke engines). Winterthur Gas and diesel (Win-GD) has introduced a new LPDF 2-stroke slow speed engine concept recently targeting larger ships.

Low pressure natural gas powered engines have low NOx emissions, but suffer from increased methane slip compared to diesel operation. Ships operating between Norwegian harbours claims for a NOx-tax calculated from fuel consumption and the emission factor for the ship in concern. Hence, it is beneficial to achieve low NOx factors for the engines on board to minimize taxation cost. For a given engine configuration it is a trade-off between HC (mainly methane) and NOx emissions. Lower NOx can be obtained by running the engine leaner, but the methane slip would normally increase consequently. To deal with the methane slip challenges, the engines can be operated at lower A/F ratio (richer operation) at low load. This reduces the methane slip, but NOx emissions increase, but could still be below Tier III requirements.

4.4.1.1 The LBSI engine – technical issues

The Lean Burn Spark Ignition gas engine is Otto cycle concept running with high air excess in the range lambda 2, to reduce the thermal load on components in the combustion chamber and control the level of NOx emission. A spark plug cannot operate with such high level of air excess and is therefore put in a pre-chamber with enrichment by adding fuel gas to make good operation condition for the spark plug.

The combustion chamber is of compact design with controlled level of turbulence to assure fast Rate of Heat Release (RoHR). This make the LBSI engine more energy efficient (higher thermal efficiency) than the diesel engine counterpart. By using spark plug and pre-chamber technology for ignition, gas jets enters the main combustion chamber with high momentum giving good penetration and ignition of the lean mixture in the main combustion chamber. This high intensity of the gas jets from pre-chamber also contribute to turbulence level. Another factor that adds to energy efficiency is low parasitic loss like fuel oil injection system for the diesel engine. Thermal efficiency at high load can reach the level of 48-49%.

The air/fuel ration is controlled by the turbocharging system and at low load (less than 30%) adding a throttle system. By running lean to keep NOx low a tendency to increased methane slip occur due to quenching in coldest parts of combustion chamber.

Enrichment of the mixture in main combustion chamber is another feasibility to this concept giving two advantages:

- Enrichment to give fast load pick up. From low load to approximately 75% load, the load pick up is in the same range as the diesel engine. Form 75% load and up will be slower due to risk of knocking.
- At low load enrichment will reduce or eliminate the emittance of unburned methane caused by quenching. The pre-chamber spark ignition system ensure stable ignition and combustion.

Another feature, applicable for LBSI engines, is variable valve timing (VVT) or variable Miller factor. In combination with an optimised turbocharging system, this gives an opportunity to variation of compression ratio and better control of combustion of poor gas quality with low methane number. By keeping a high expansion ratio high fuel efficiency will be the result at all load conditions.

By employing good air/fuel ratio control system for enrichment at low load operation and reduction of dead space in the combustion chamber by design, methane slip can be reduced to a minimum of 2,5 to 3,0 g/kWh. This means that ships operating LBSI gas engines can give a net reduction of greenhouse gases (GHG) including methane. How large the reduction of GHG can be is depending of operation profile and the fuel in comparison, a reduction range 10-15% is achievable compared to diesel oil operation.

The main disadvantage of the LBSI concept is backup fuel or the possibility to run on diesel oil if LNG is not available, explaining why shipping industry prefer Dual Fuel gas engines.

4.4.1.2 The LPDF 4-stroke engine - technical issues

The Low Pressure Dual Fuel gas engine is similar to LBSI with reference to combustion of a lean mixture of gas and air. The difference is ignition of the mixture. The main reason for choosing the LPDF is the diesel oil as backup fuel and the ability to operate on diesel oil.

LPDF gas engines is a compromise between the Diesel cycle with compression ignition of fuel oil and Otto cycle with a mixture of air and gas prior to the compression stroke. The conflict is between sufficient heat and air excess to secure pilot ignition and low compression ratio to avoid knocking and low air fuel ration (rich combustion) at low load to reduce unburned methane due to quenching.

VVT and throttling have limited impact due to the requirement for good stable ignition and combustion of the pilot fuel, meaning sufficient heat and air excess for ignition and combustion.

The compression ratio is set to meet gas quality defined by the methane number and to get some margin to the knock limit, and at the same time assure good ignition and combustion condition for the pilot fuel. Enrichment cannot be utilised in the same way as the LBSI due to the consideration of the pilot fuel. Load pick up will therefore be slower than the LBSI. Same limitation at high load with slower load pick up to avoid knocking.

Pilot fuel is contribution to NOx emission and need to be as small as possible. A level of 1-2% of full load fuel consumption seems to be a realistic amount. To control such a small quantity fuel oil is a challenge and solved by a separate pilot fuel nozzle either integrated in one housing with the main fuel injector or a separate pilot fuel injector, arranged as common rail with typical range of 1000 bar. Pilot fuel is direct injection in the combustion chamber or by pre-chamber.

LPDF gas engine are a compromise between the Diesel and the Otto cycle. The question is if the LPDF engine should be optimise for diesel oil operation or gas operation. If optimised for gas operation performance can be similar to LBSI gas engines except from methane slip at low load and load pick up. Consequently, the performance in diesel oil operation is suffering, and is therefore important to know the operation profile for the actual ship.

Methane slip is in the same range as the LBSI gas engine at high load but somewhat higher at low load due to quenching at the coldest part of the combustion chamber. Low air/fuel ratio (rich combustion) cannot be fully employed due to the concern of good ignition and combustion of the pilot fuel. LPDF gas engine optimised for low methane slip by improved process control and minimise dead space in combustion chamber by design, can reduce the methane slip to a level of 3,0 – 4,0 g/kWh. This means that ships operating LPDF gas engines can give a net reduction of greenhouse gases (GHG) including methane. How large the reduction of GHG can be is depending of operation profile and the fuel in comparison, a reduction range 5-10% is achievable compare to diesel oil operation.

4.4.1.3 LPDF 2-stroke slow speed engine

The LPDF slow speed engine has been develop by Winterthur Gas & Diesel /5/ (Win-GD) and main feature of this engine concept is the operation on low-pressure gas. This means that the high pressure gas system is avoided. The engine operates according to the Otto cycle and in principle, this engine concept meets the same challenges as the LPDF 4-stroke gas engine concept, e.g. homogenous mixture of air/fuel, good air/fuel ratio control, stable pilot fuel ignition and combustion. Special design and efforts is required for the gas admission systems with gas injectors in the cylinder liner and injection after closing exhaust valve to avoid blow through of gas. Two or more injectors are located symmetrical in the lower part for the liner and gas injection pressure in the range of 10-12 bar.

Pilot fuel injection through minimum two pre-chambers in the periphery of the combustion chamber is required in addition to the main fuel injection system. A common rail system supply pilot oil to an amount in the range of 1% the full load consumption.

Similar to the 4-stroke LPDF concepts the NOx emission can meet the IMO Tier III requirements for this engine concept. Test results also show somewhat lower methane slip compared to the LPDF 4-stroke engines concept.

The main challenge with this concept is uncontrolled combustion (knocking and pre-ignition), especially for poor gas quality with low methane number. The same challenge and limitation is related to load pick up which have to be carefully controlled to avoid knocking. Derating of power is normally the procedure in the case of poor gas quality with low methane number.

4.4.2 High pressure dual fuel engines

High Pressure Dual Fuel (HPDF) gas engines are Diesel cycle concepts. Pure air is compressed and a pilot oil injection secure ignition and a gas jet is injected at top dead centre in similar pattern as diesel sprays. There are two obvious advantages in gas operation for this concept:

- No methane slip as there are no gas in the compression stroke and the gas is burned as is it injected.
- No requirement for gas quality. (Compared to the Otto cycle concept where high Methane number is required).

Another advantage is the suitability for conversion of existing diesel engines. Considering the engine, the conversion is rather simple; it requires a new cylinder head, injection system for gas and control system. The HPDF gas engine has been offered to the market for quite some time. In offshore platforms and floating production ship Wärtsilä 4-stroke medium speed high-pressure gas engines, designated GD (32 GD and 46 GD) have been in operation for more than 20 years. MAN Diesel and Turbo (2-stroke slow speed) is marketing this technology for maritime application. The first ships with this technology are in operation. This engine concept is of special interest for larger ships, which normally would choose slow speed 2-stroke engines. However, all diesel engine, slow, medium and high speed, are applicable for this concept.

According to MAN their entire ME-series engine could be converted to run as dual fuel with high pressure gas injection, and MAN has reported increased interest for their HPGI engine.

4.4.2.1 HPDF engine - Technical issues

HPDF gas engines have the same characteristics as the diesel engine regarding power range, fuel consumption and load pick up. The disadvantage has always been the requirement for high gas pressure supply in the range of 350 bar. As natural gas for ship propulsion is stored as LNG on board, the situation is much easier as pressure is obtained by pumping LNG to required pressure and then heated to ambient temperature.

Pumping LNG as a liquid to 350 bar brings it well above critical condition meaning it become a cold incompressible gas. Is does not require an evaporator, just a simple heater to bring the gas temperature to required level around 20 – 30 degree C. The heat is normally taken from the engine cooling water. Energy consumption to get 350 bar gas pressure is less than for diesel oil injection. This is due to the lower pressure level of the gas of 350 bar compared to about 1500 bar for the diesel oil. The liquid LNG volume pumped to high pressure is about two times the diesel volume due to relative low density, LNG 0,42 kg/l compared to MGO 0,84 kg/l

The high pressure LNG system is complicating the LNG fuel system. Cryogenic high pressure pumps, in this case piston pump, is existing mature technology. However, they are not developed for this kind of application with continuously operation. Experience so far is too short time between overhaul, reporting 2000 to 4000 hours. When market requirement are increasing we assume development of LNG high pressure pumping system will improve lifetime and cost level.

The NOx emission from the HPDF concept falls between the diesel oil and the lean- burn gas engines. Combustion of a gas jet is at a lower and even temperature level compared to a diesel spray. The need for small pilot amount is necessary to keep low NOx emissions. The concept can be optimised for low NOx emission at same fuel consumption as in diesel or Heavy fuel oil (HFO) operation and give a NOx-reduction of 30-40% compared to operation on HFO. To meet IMO tier III after treatment is necessary. It could be Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR).

Another optimisation is to meet IMO tier II for NOx emission and gain a reduction in fuel consumption, especially at part and low load.

Particulate emission is very low on gas operation compared to operation with MDO/HFO. This apply to all gas engine concepts, but with slightly variations between the concepts.

HPDF will give a significant reduction in GHG emission due to the hydrogen/carbon ratio of the fuel and no methane slip.

Part 2:

Update of emission factor for gas fuelled ships

5 Emission profile of marine gas engines

5.1 General

The introduction of natural gas as a fuel on ships has provided significant emissions reduction to the air. Especially natural gas engines have potential to lower exhaust gas emissions as NOx, SOx and PM, which have an impact on local air quality. Compared to marine diesel operation, natural gas operation has potential to reduce the following emissions; CO2, NOx, SOx and PM without any kind of exhaust gas after treatment.

Table 5.1. Potential emission reduction with natural gas operation, for alternative gas engine concepts. Emission reduction in % compared to MGO-operation. E2/E3 test cycle. No after treatment of exhaust.

Reduction factors compared to MGO	**LBSI**	**LPDF*, 4-stroke Medium speed**	**LPDF, 2-stroke Slow speed**	**HPDF, 4-stroke, medium speed**	**HPDF, 2-stroke, slow speed**
CO_2	25-28%	20-25%	20-26%	20-24%	20-24%
NOx	85-90%	75-90%	75-90%	25-30%	25-30%
SOx	>99%	98-99%	95-99%	95-97% **	95-97% **
Particulates	>99%	95-98%	95-98%	30-40%	N/A

*)Highest reduction factors for DF obtained with micro pilot ignition
**)Dependant of S-content in pilot fuel

CO2 emissions is the main greenhouse gas (GHG) from combustion engines. CO2 reduction from natural gas fuelled engines are mainly due to the lower carbon content in the fuel, but also due to higher thermal efficiency at high load of gas fuelled engines compared to diesel engines.

For LBSI and LPDF engines the NOx reduction is in the range 75-90% compared to diesel operation. The LPDF engines has higher NOx emissions than the LBSI, which is mainly explained by the use of pilot fuel in the LPDF engines. Both engine concepts meet IMO Tier III requirements regarding NOx emissions.

HPDF engines operated according to the diesel cycle and has higher NOx emissions, but a reduction of 25-30% compared to diesel combustion can be expected. To reduce NOx emissions from this engine concept to IMO Tier III levels, EGR or exhaust gas after treatment is required.

SOx and PM emissions are reduced with more than 90% for all gas engines concepts. This is due to the low sulphur content of the gas fuel and simple fuel molecule, which burns with low soot and PM formation.

The methane and formaldehyde emissions from gas engines is a challenge and increases compared to diesel combustion. The methane slip is of concern because of their contribution to GHG emissions. Formaldehyde can be toxic, allergenic, and carcinogenic and should be minimized. Currently there are no regulations on methane and PAH emissions for marine gas engines.

For natural gas fuelled engines, the methane slip from incomplete combustion should be included when evaluating the total effects on GHG for gas-fuelled ships. The LBSI and LPDF engines suffers from methane slip due to incomplete combustion while the HPDF engine operates with almost zero methane slip.

5.2 Review of available publications and reports

Correct estimates of emission factors is important from an emission inventory point of view, and emissions factors for regulated emission component as NOx and SOx is published by the IMO an others. Emission factors are technology dependent, meaning that these factors will differ from one engine concept to the other as described above.

Main source for emission factors are manufacturer data. Such data is based on test bed measurement according to standard conditions and give a good basis for the emission levels on the various concepts.

Emission factors for gas fuelled engines has also been published in open reports and publications. For some emission components relative good correlations is observed, but for other components it seems that basic information is missing. Published data is largely based on manufacturer information, but some publications also refer to measurements on engines in real operation. However, only a few studies has performed actual measurements on marine gas engines. The engine settings is defined for the application in concern, and as an example, engines for stationary power production will not have same emission performance as a marine propulsion engines. Some publications are listed in the reference chapter.

5.3 Previous studies

In previous studies carried out by SINTEF (former MARINTEK) /3/ the emission factors of NOx and CH4 for gas fuelled ships was reported as follows:

Table 5.2: NO_x factor for gas engines, (MARINTEK 2010)

Gas operated engine type	NO_x factor for gas engines
	[kg NO_x/ton LNG]
Lean burn gas engine, (LBSI and LPDF, 4 stroke)	5,6

Table 5.3: Methane emission factors, gas fuelled engines, (MARINTEK 2010)

Gas operated engine type	Methane emission factor, ISO/IMO weighted	
	[kg CH_4/ton LNG]	[g CH_4/kWh]
Lean burn spark ignited engine (LBSI)	44	8,5
Dual fuel engines only, (LPDF, 4-stroke)	80	15,6

Previous reported data in 2010 was based on engine technology installed in sailing ships built in the period 2000-2009. At this time the methane slip question was raised and new engines were developed. In 2010 manufacturer claimed that future engine would reduce methane slip significantly and test bed data from 2010 is referred in **Table 5.4**.

Table 5.4: Methane factors for new lean burn gas engine designs, engine manufacturer data 2010.

Load E2 cycle, LBSI engine	ISO/IMO corrected methane factor
Lean burn engine [g CH_4/kWh]	**3.9**
Lean burn engine [kg CH_4/ton LNG]	**25**

Corbet et.al /11/ has reported emissions factor's in a study for the US department of Transportation (2014), with a specific NOx factor of 2 g/kWh and specific CH4 factor of 5 g/kWh for DF or LBSI engines. These data was based on a review of several publications.

5.4 Emission characteristic's of natural gas fuelled engines - manufacturer data

In this project we received state of the art emission data from vendors (Wärtsilä, Rolls- Royce and Mitsubishi), which have been the market leaders for marine gas fuelled engines so far. In addition published data on company web-pages and conferences papers was studied.

The manufacturer data give an indication of the performance and emission levels of the various engine concepts.

5.4.1 Rolls Royce

Emission and performance data from Rolls Royce /18/ is shown in Table 5.5.

RR LBSI Engines, E3 cycle	Unit	Engine type	
		C26:33	B35:40
NOx	[g/kWh]	1,3	1,3
CO	[g/kWh]	1,3	1,4
CH_4*	[g/kWh]	5,1	4,2
CO_2	[g/kWh]	443,2	431,6
GHG_C	[g/kWh]	571,6	536,9
CH_4**	[g/kg Fuel]	31,0	26,2

RR LBSI Engines, E2 cycle	Unit	Engine type	
		C26:33	B35:40
NOx	[g/kWh]	1,3	1,3
CO	[g/kWh]	1,6	1,6
CH_4*	[g/kWh]	5,5	4,6
CO_2	[g/kWh]	468,8	466,9
GHG_C	[g/kWh]	604,9	581,1
CH_4**	[g/kg Fuel]	31,1	26,2

(* - Preliminary values. Methane (CH4) emission values are valid for a (H:C)-ratio (molar) of ~3,9
(** Calculated based on manufacturer FOC data + 5%.

Table 5.5: Emission data, Rolls Royce gas fuelled engines, (Source: Rolls Royce, 2016)

5.4.2 Wärtsilä

5.4.2.1 LPDF engines

As a response to this study SINTEF received emission data on WD portfolio of products. This is shown in Table 5.6. WD has also released the WD 31 engine, which is also available as DF engine. However, emission data was not reported for this engine.

*CH_4 factor is calculated by SINTEF based on the assumption that CO2 and CH4 is the only contributors to the CO2 equivalent factor. GWP factor for methane of 28 was used by Wärtsilä in this calculations which is in line with latest IPPC-report (AR5 2013), /16/.

Engine model	Unit	CO2, weighted average	CO2 equivalent, weighted average	CH4 part of CO2 equivalent*
		E2	E2	E2
W34DF	[g/kWh]	457	564	3,82
W50DF	[g/kWh]	447	546	3,54
W46DF	[g/kWh]	447	547	3,57

*CH_4 factor is calculated by SINTEF based on the assumption that CO2 and CH4 is the only contributors to the CO2 equivalent factor. GWP factor for methane of 28 was used by Wärtsilä in this calculations which is in line with latest IPPC-report (AR5 2013), /16/.

Table 5.6: Wärtsilä engines. Weighted average as per IMO E2 cycle, both for the "CO2 case" and the "CO2 equivalent" case (where also the contribution from unburned hydrocarbons is considered). (Source: Wärtsilä, 2016)

Lean burn operation of WD engines give low NOx emission. In the gas mode operation, the NOx are at least 80% below the current IMO level (Wärtsilä, 2016) and the amount of emitted particles are than 10% compared to a conventional marine diesel engine running on diesel. The Dual Fuel engines the IMO Tier 3 NOx emission level as standard in gas mode operation without the need of a secondary exhaust gas emission control system. Corresponding NOx values to CH_4 data in *CH_4 factor is calculated by SINTEF based on the assumption that CO2 and CH4 is the only contributors to the CO2 equivalent factor. GWP factor for methane of 28 was used by Wärtsilä in this calculations which is in line with latest IPPC-report (AR5 2013), /16/.

Table 5.6 was not available.

NOx emissions based on engine speed according to IMO Tier III requirements will indicate an upper limit for WD DF engines, weighted according to ISO 8178.

Engine type	Engine Speed, rpm	IMO Tier III, NOx upper limit, g/kWh
DF 20	1000-1200	~2,24
DF 34	720-750	~2,40
DF 46	600	~2,5
DF 50	500	~2,6

Table 5.7: Wärtsilä DF engine NOx compliant limits according to IMO Tier III

5.4.2.2 LPDF 2-stroke slow speed engine

A low pressure dual fuel 2-stroke slow speed engine has been developed by Winterthur Gas & Diesel (Win-GD) (former part of Wärtsilä). In gas operation the engine show good performance and low emissions. Specific THC-emissions is in the range 3-4 g/kWh and NOx emissions are significant lower than IMO Tier III requirements. Presented test results indicate weighted NOx emissions below 1 g/kWh.

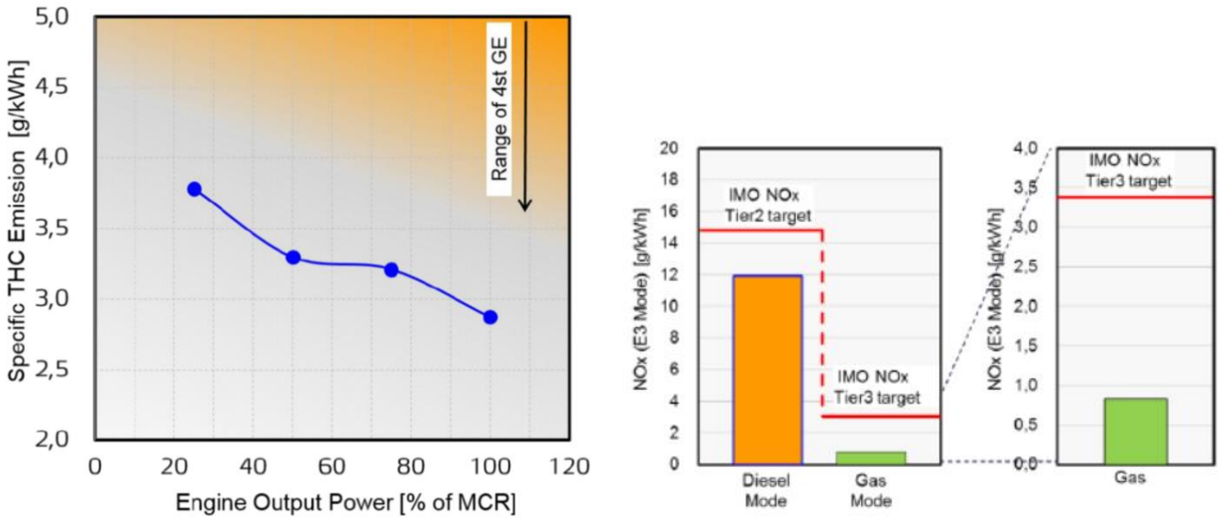

Figure 5.1: Win-GD LPDF 2-stroke slow speed engine emission data, (Source: Win-GD)

5.4.3 **Mitsubishi**

Test data from Norwegian dealer of MHI engines was made available showing typical emissions from their marine engines with alternative lambda adjustment. NOx will decrease at leaner operation but the penalty is higher methane slip.

MHI GS6R2-MPTK, 500 kW	NOx, (g/kWh)	THC (g/kWh)	CH4 (g/kWh)	Lambda (-)
E2cycle, g/kWh	0,97	3,80	3,57	1,8
E2cycle, g/kWh	1,57	3,17	2,98	1,7

Table 5.8: Emission from MHI GS6R2-MPTK engine. LBSI engine concept. Source: Mitsubishi Turbocharger and Engine Europe B.V.

Weighted NOx tier III emission limit is 2,08 g/kWh for engines operating at 1500 rpm and these limits can easily be achieved.

5.5 NOx Fund data

To verify NOx reducing measures on ships operating in Norwegian waters, on-board measurements is carried out. Measurement reports was made available to SINTEF in this project, and data from these reports has been analysed. Only NOx emissions are verified in these reports.

This means that NOx data for several gas fuelled ships in operation is available to estimate NOx emission factors for various engine and ship types.

A summary of available data based on on-board measurements on gas fuelled ships are shown in Table 5.9.

NOx Fund data	Units	Average		
		All engines	LBSI engines	LPDF engines (4-stroke)
NOx	g/kg fuel	6,9	4,2	10,1
NOx	g/kWh	1,3	0,8	1,8

Table 5.9: NOx emission factors for gas fuelled ships based on on-board measurement on ships reported to the NOx fund. Average data based on measurements on 39 engines.

Data presented in Table 5.9 is based on new ships built in 2010-2015 except four ships built in 2007-2009.

Unfortunately, there are no requirements to verify THC emissions and methane slip from gas fuelled ships, and no international requirements for such emissions. This means that third-party data from real operation of gas fuelled ships is limited.

6 Measurement campaign

6.1 Introduction

The main purpose of this project has been to collect data from ships in real operation and update emission factors for gas fuelled ships using state of the art technology. Focus has been on exhaust gas emission to air from the gas fuelled engines on board. The following emission components has been measured:

- CO2
- CO
- NOx
- THC
- CH4
- O2

IMO MARPOL regulations has implemented requirements to NOx and SOx emissions from ships. For THC and methane slip such requirements does not exist.

6.2 Measurement procedures

To obtain emission data from ships in real operation a measurement campaign was carried out on six sailing ships and on one testbed engine at manufacturer premises. SINTEF Ocean is an accredited institute for exhaust gas measurement. The campaign followed the established procedures for accredited exhaust gas measurements.

6.2.1 Measurement instruments and data acquisition system

The instruments are maintained and calibrated in accordance with SINTEF Ocean`s procedures for accredited measuring equipment, which implies continues maintenance and repair in accordance with instrument manuals. An equipment set-up and functional test in the Sintef Ocean laboratory is done in advance of every field work.

Table 6.1 - Measurement instrument description

Gas component	Measured unit	Equipment / measuring principle	Measuring range
NOx	ppm	Horiba PG-350/ CLD (Chemiluminescence method)	250 / 500 ppm
CO	ppm	Horiba PG-350/ NDIR (Non-Dispersive infrared method)	500 ppm
CO_2	%	Horiba PG-350/ NDIR (Non-Dispersive infrared method)	10 %
O_2	%	Horiba PG-350/ Paramagnetic	25 %
THC	ppm	JUM 3-200 / HFID (Heated Flame Ionization Detection method)	1000 ppm
Methane*	ppm	JUM 3-200 / HFID (Heated Flame Ionization Detection method)	1000 ppm
Ambient conditions		KIMO AMI 300 for measuring of Barometric pressure (bar), Humidity (%RH), Air inlet temperature (°C)	

*Methane measurement procedure are not accredited by NA.

A PC-based data logging system for data storage and presentation is used. Measurement signals are transferred from the measurement instruments to a PC. DasyLab software is used for storage of data and presentation of results.

Data acquisition:
- DASY Lab version 6.0 Data Acquisition System
- ADAM 4017/ ADAM 4520- A/D converter
- Portable PC.

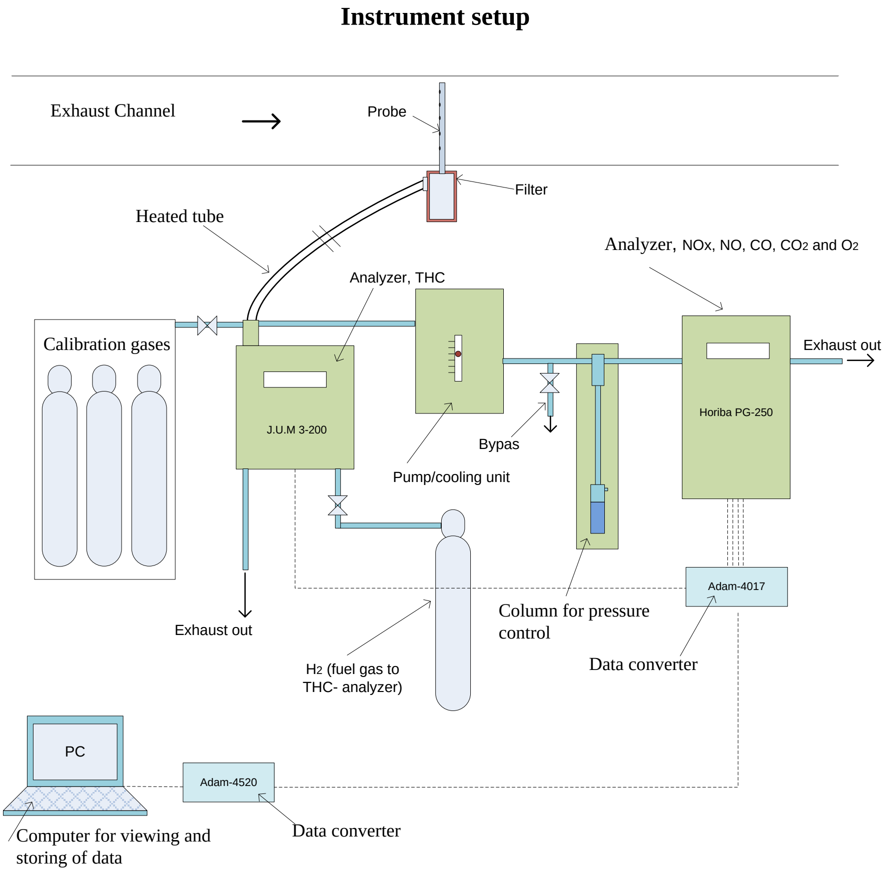

Figure 6.1 - Measurement instrument setup

Accredited calibration gases was used during the measurement campaign. Example of calibration gases is shown in Table 6.2.

Table 6.2 – Example of Calibration gases

Type Gas	Gas concentration	Accuracy
NO	202,7 mol ppm	± 2,0 mol ppm
CO	409,0 mol ppm	± 4,2 mol ppm
CO_2	8,147 mol %	± 0,041 mol %
$C_3 H_8$	810 mol ppm	± 6 mol ppm
O_2	20,95 %	N/A

6.2.2 Fuel gas consumption and composition

As input to the accredited specific emission factor calculations, fuel composition and consumption is required.

The fuel consumption is estimated by using readings from the ship instrumentation. If such data is not available, acceptance test data from the engine manufacturer can be used. The fuel gas composition is analysed by the bunker provider, and a gas analyse is received by the ship after each bunkering. Based on this analyses, C/H-ratio of the fuel is calculated using computer program "AVL Methane".

For DF engines the amount of pilot fuel is accounted for in the total fuel consumption for each operating point.

Example of fuel gas composition is shown in Appendix B.

6.2.3 Calculations of specific emission factors

The specific emission factors are calculated based on measurements and calculations of fuel and emission data in accordance with formulas presented in ISO 8178.

6.2.4 Uncertainty

Calculation of the measurement uncertainty of the emission components follows a standard procedure taking into account the instrument specification regarding linearity, span drift and zero-drift and calibration gas properties. Typical uncertainty for a measurement series is shown in **Table 6.3**

Table 6.3 – Example of expanded measurement uncertainty calculated with a coverage factor (k) 2 which corresponds to a confidence level of approximately 95%.

Measurement uncertainty [%], 95% confidence interval		
Type of measurement	Based on measured values	Based on specific values
NOx	3.5	5.0
CO	2.8	4.5
UHC	1.9	4.0
CO2	4.8	N/A
O2	5.0	N/A

6.2.5 Test cycle and weighting factors

The measurements are carried out in accordance with ISO 8178, E2 (Generator operation) or E3 (Propulsion engine) test cycle with tolerances for engines operation on board in accordance with IMO NOx Technical code.

Table 6.4: ISO 8178 E2 and E3 test cycle

Marine application				
Type E2, Mode #	1	2	3	4
Power, %	100	75	50	25
Speed, %	100	100	100	100
Weighting factor	0,2	0,5	0,15	0,15

Tolerances: Actual load point ± 5% for rated power for the modal load points and +0 to (–10)% for 100 % load point.

Marine application				
Type E3, Mode #	1	2	3	4
Power, %	100	75	50	25
Speed, %	100	91	80	63
Weighting factor	0,2	0,5	0,15	0,15

Tolerances: Actual load point ± 5% for rated power for the modal load points and +0 to (–10)% for 100 % load point.

6.2.6 **On board measurements**

Measurements were carried out on the main engines in accordance with the E2 or E3 cycle depending of machinery configuration. The E2 cycle is used for diesel electric systems where main engine(s) are connected to generator(s) and operate at fixed engine speeds. The E3 cycle is used for propulsion engines operating in accordance with the propeller curve. Actual measuring points are within specified tolerances.

In some cases the engine speed and corresponding load will not meet the specified combinations in the E3 cycle as the load can be varied by changing propeller pitch without changing the engine speed. In such cases, the load was decided by readings from the load calculator on board, and deviation in engine speed compared to standard was neglected in the calculation of specific emission factors.

For each load point stable condition was established after a few minutes of operation (steady state operation). Logging of emission data was then carried out for a period of 15-20 minutes on each load point with a sampling frequency of 1 Hz. The last 7-10 minutes of the sampling period, the UHC instrument where switched to methane mode. Readings of relevant engine data (Load, Engine Speed, Air Receiver Pressure and Temperature) were taken from the ship control system. Average values from both emission logging and readings from ship control system were used in emission calculations.

During each test ambient data (air temperature, air humidity and barometric pressure) in engine air inlet area were measured with SINTEF Ocean's KIMO AMI 300 instrument.

The emission instruments were calibrated before the test started. As a minimum, instruments are required to be calibrated every two hour. Before a new calibration the drifting since last calibration was calculated and written in Calibration log to be sure that the drifting during the test was within acceptable values. No measurements were rejected due to drifting error of the instruments.

The engine stability during the measurement is dependent on cycle-to cycle stability of the engine itself and on load variations from propeller or other equipment. Evaluation of the standard deviation of the measurement series for THC and CH4 shows an average standard deviation of 3-4% of the measured values for all load points on 32 measurement series.

6.2.7 **Data collection**

Engine emission performance and emission data was also collected from technical files from the ships, which normally is based on acceptance tests from manufacturer test-bed.

7 Results from measurement campaign and data collection

7.1 Definition of ship and engine types

Most important activity in the project has been to do third-party verification of emission factors on sailing ships. This was a challenging approach to the project as ship owners have not been a contractual partner in the project, but was accessed by SINTEF and asked to place their ships at disposal for the measurement campaign.

Dedicated measurements within the scope of the project included measurement on six ships and one test bed engine. In one of the ships, two engines was measured. For the test-bed engine four separate measurement series was done, two by SINTEF (E2 and E3 cycle) and two in parallel by engine manufacturer. In addition, data was available from measurements on two other ships in other verification projects. Data has also been available from manufacturer test-bed measurements documented in technical files of the ships in concern. In sum, 18 separate measurement series have been provided in this project. Two older engines was not representative regarding latest technology updates, so 16 separate measurement series was used as basis for state of the art emissions from gas fuelled engines. Only LBSI engines and LPDF 4-stroke engines has been measured. Based on the measurement emission factor have been calculated.

7.1.1 LBSI engines

Data from nine single measurements-series was used to calculate emission factors for LBSI engines. This includes measurements on board ships generated in this project, earlier data not published before and measurements on manufacturer testbed.

Two older LBSI engines was included in the measurement campaign, as one of these was modified with the purpose to reduce the methane slip. However, only slight reduction of methane was observed so the older engines is not representative for state of the art LBSI technology. Hence, measurements from these older engines was rejected and are not used for average emission factor calculations.

Average emission factors based on measurements are shown in Table 7.1.

Source	NOx		CO		THC		CH4		CO2		No. of engines
	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	
Sintef measurement	7,1	1,3	10,3	1,9	27,3	4,8	25,0	4,4	2677,4	480,5	7
Manufacturer testbed data	8,3	1,3	8,0	1,3	18,8	3,1	17,0	2,8	2721,9	444,0	2
All sources, LBSI	7,3	1,3	9,8	1,7	25,4	4,4	23,2	4,1	2687,3	472,4	9

Table 7.1: Average emission factors for LBSI engine built after 2010 based on on-board measurements on ships and test-bed carried out by Sintef Ocean and manufacturer. E2 and E3 test cycles.

The emission factors is based on measurements and standard calculation procedures according to ISO 8178, and is corrected to standard conditions.

Medium speed and high speed engines are represented among the LBSI engines. As seen in Table 7.1 the CO2 emissions for manufacturer data is lower than average data as these represent data for medium speed engines and are in line with SINTEF measurements for this engine type.

7.1.2 LPDF 4-stroke engines

Measurements were done on two ships with LPDF 4 stroke engines. These represent state of the art engines from two suppliers. In addition supplier testbed data was available. Emission factors based on measurements from LPDF 4-stroke engines are shown in Table 7.2.

Source	NOx		CO		THC		CH4		CO2		No. of engines
	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	
Sintef measurement	13,7	2,3	9,8	1,6	33,8	5,7	31,2	5,3	2682,8	452,1	2
Manufacturer testbed data	10,3	1,7	11,5	2,0	47,0	7,9	44,8	7,6	2609,3	441,1	5
All sources, DF	11,3	1,9	11,0	1,9	43,2	7,3	40,9	6,9	2630,3	444,2	7

Table 7.2: Average emission factors for LPDF 4-stroke engines built after 2013 based on on-board measurements on ships and testbed. E2 and E3 test cycles.

Individual adjustment of lean burn engines influence on the emission levels and it is a trade-off between low NOx emissions and methane slip. From available data in the project as presented in Table 7.1and Table 7.2, NOx-CH4 relations has been plotted, (Figure 7.1). The general observation is that LBSI engines has lower NOx-CH4 values than LPDF engines, but it is also individual differences between engine models and from one manufacturer to the other.

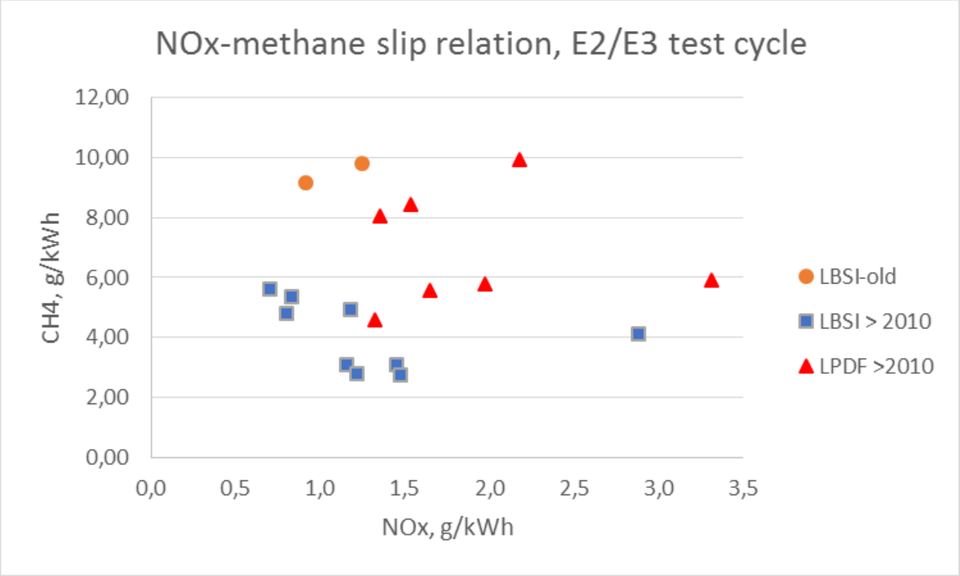

Figure 7.1: Specific methane slip versus NOx emissions for gas fuelled engines, E2/E3 test cycle, based on-board measurement on ships and manufacturer test bed data, total of 18 engines test protocols.

7.2 Recommended methane and NOx emission factors

Emission data from various sources has been collected by literature reviews, supplier information and on-board measurements on ships.

Comparison of emission factors from on-board measurements and manufacturer data show good correlation, but individual variation from one engine to the other can be expected. A general observation is that the ship engines are operating leaner than test data presented by manufacturer. This result in lower NOx emissions. This is especially the case for low load operation.

One explanation for this variation is the practical adaption in the lambda control to obtain good transient performance and still have safety margins to the knocking limit. It is also observed that emission levels are different between manufacturers. LPDF engines from Wärtsilä has lower NOx and CH4 levels than the LPDF engine from Caterpillar (MAK-engine). LBSI engines has in general lower emission levels than LPDF engines, but we find approximately equal levels from both manufacturer in concern, Rolls Royce and Mitsubishi. The CO2 emissions is derived from fuel composition and fuel consumption, and medium speed engines have in general lower fuel consumption than high speed engines. Hence, emission factors for CO2 should be linked to the technology in use. Average values should only be used when technology on board is unknown.

For LBSI engines on board measurements show lower NOx emissions than indicated by public data from manufacturer and the resulting trade-off is higher methane slip.

For 4-stroke DF engines, public data from Wärtsilä indicate lower methane slip than was documented in the on-board measurement. In the on-board measurement, the NOx emissions are low with a good margin to Tier III requirements.

For NOx emission factor additional data from the NOx-Fund has been analysed. Data sources for calculation of NOx emission factors are as follows:

- Average calculations from current measurement campaign and NOx-fund verification measurement for gas fuelled ships and supplier test bed data.
    - 18 measurement-series provided in this project
    - 39 measurement-series based provided by verification data reported to the NOx fund

Dats sources for THC, CH4, CO and CO2:

- Average measurement from current measurement campaign and from supplier test bed data.
    - 16 measurement series provided in this project, two series rejected due to old engine technology.

Engine type	NOx		CO		THC		CH4		CO2	
	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh	g/kg fuel	g/kWh
Emission factor, LBSI	5,1	0,9	9,8	1,7	25,4	4,4	23,2	4,1	2687,3	472,4
Emission factor, LPDF	10,4	1,9	11,0	1,9	43,2	7,3	40,9	6,9	2630,3	444,2
Average, all engine type	7,5	1,4	10,3	1,8	33,2	5,7	31,0	5,3	2662,4	460,1

Table 7.3: Recommended emission factors, LBSI engines and LPDF 4-stroke engines

In Table 7.3 the average data for all engines are the mean values for all data available in this project, and this has not been weighted in relation to actual ships in operations. The average data could be used as general factors in cases where technology on board is not known.

It is important to notice that LBSI engines include medium speed and high-speed engines. In general medium speed engines has higher efficiency than high speed engines which reflects that average values for CO2 emissions are higher for LBSI engine than LPDF engines. Data from this study show that engine performance and emission profile varies dependant on engine type and manufacturer.

Part 3:

Available technologies for methane slip reduction

8 Measures for methane slip reduction from gas engines

It is importance to handle the excessive hydrocarbon slip from the gas engine. For a marine engine, operating on natural gas based on LNG the hydrocarbon slip is close to pure methane. Especially in marine use when running on medium to low load, the state-of- art lean-burn gas engines still have quite much higher hydrocarbon emission than a diesel engine. In future regulations stricter THC limits are foreseen and reduced methane slip could also have an effect on efficiency/fuel consumption. The total greenhouse gas emission for gas fuelled ships is dependent of the thermal efficiency of the combustion process and the amount of methane slip. In this respect, the methane slip should be minimized.

Methane slip from gas engines can be reduced by primary measures related to engine design and operation or secondary measures, which means exhaust gas after treatment.

Primary measures related to engine optimisation by improving the combustion in the cylinder could be:

- avoiding crevices where gas can "hide" during combustion
- more compact combustion chamber with squish area for faster Rohr
- improve process control
- variable valve timing (VVT)
- various control technics as skip firing
- improved gas metering
- direct cylinder control
- minimize valve overlap to avoid blow-through.

Several of the measures listed above are in use by the engine industry today, which is reflected in the observed emission factors for methane slip for new engines put in service after 2010.

Secondary measures i.e. exhaust gas cleaning in a catalytic process has not been used for methane slip reductions on ships so far. Oxidation catalyst have been tested for stationary engines and for automotive application. As methane is a stable molecule these catalyst needs precious metals to obtain high conversion ratios, and one main challenge is to maintain high conversion ratio over time.

8.1 Engine development issues for reduced methane slip

Methane slip is connected to combustion engines where natural gas and air are compressed in the cylinder before combustion, meaning the LBSI and LPDF concepts.

There is two main reasons for unburned methane emitted form gas engines:

- Dead volume in form of crevices between cylinder unit components such as :
    - ✓ Gasket area between cylinder head and cylinder liner
    - ✓ Between piston top land and cylinder liner
    - ✓ Behind anti-polishing ring

  During the compression stroke the gas mixture is compressed into these crevices and hide away from the combustion. The Methane molecule is very stable and need high temperature to ignite/combust (above 600 degree C depending on air fuel ratio). In the expansion stroke the gas flows out from the crevices, but due to lower temperatures during expansion the methane molecules are to a large degree unburned, and comes out in the exhaust flow.

  This dead volume can be reduced to a minimum by design, but will always give a certain (significant) amount of unburned methane.

- Incomplete combustion in form of quenching at the coldest part of the combustion chamber is another reason for methane slip. Quenching occur when the mixture is too lean and cooled down along the cylinder liner. This will mainly be the case at low load operation. Quenching can be significantly reduced by improved process control by enriching the mixture closer to stoichiometric condition (lambda =1). Richer mixture will create more NOx so the control need to balance the trade-off between unburned methane and NOx.

Other sources of unburned methane could be blow through in the scavenging process and valve overlap. New engine design run with practically no valve overlap so hence unburned methane is consider neglect able.

The increased methane slip with reduced load implies that the methane slip factor is affected by the operation profile of the engine. For 4-stroke DF engines the methane slip is higher than for LBSI engines.

Previous research on reducing methane in catalyst has not been successful, and further development is required if this strategy should be followed. Methane is a stable molecule and oxidation of methane in an oxidation catalyst requires high exhaust gas temperatures and an efficient catalyst design with precious metal. Soot deposits on the active surfaces of the catalyst will also reduce the catalyst efficiency. Hence, primary measures to reduce the methane slip should be the preferred strategy. The various measures will be effective in different operation modes and engines loads. Alternative methods to reduce methane slip from gas fuelled engines are:

- Improved engine operation and control
    - Improved air/fuel ratio control over the load range by turbocharger design (variable turbine geometry), compressor bypass or waste gate
    - Direct cylinder control by gas metering and throttle system
    - Variable valve timing
    - Optimal ignition timing adjustment
    - Skip firing (low load)
    -)
- Engine construction and design
    - Optimum design to minimize dead space
    - Optimisation of combustion chamber
- Exhaust aftertreatment
    - Oxidation catalyst

8.1.1 Combustion chamber design

During initial design, the basic parameters for the combustion chamber and cylinder head are established to optimize the combustion performance. This includes air inlet port geometry with optimized swirl and piston bowl shape with optimized squish area to enhance the combustion process. For some engines concept further development is required to improve performance and efficiency and reduce emissions, and optimization of the combustion chamber may contribute in this aspect.

To achieve high gas engine efficiency the compression ratio and air/fuel ratio has to be carefully analysed and balanced to obtain acceptable knocking margin. Optimum combustion chamber design is a compromise between low emission and high efficiency and the most important piston/cylinder head/liner design criteria are:

- Compact bowl design
- Optimum compression ratio

- Optimum top clearance and squish area
- Minimize dead volumes/crevice and quenching zones by optimum design of piston ring positions, anti-polishing ring and cylinder head gasket
- Optimum swirl level

The piston shape/cylinder head design related to piston rings placement and top clearance between the piston top and cylinder head has influence on the efficiency and emissions, especially unburned hydro carbons. Reducing dead volumes/quenching areas are one important aspect in the design requirements. The distance between the cylinder head and the piston top (top clearance) should also be optimized.

Piston bowl

Example of alternative piston bowl design is shown in Figure 8.1, and test carried out by Mitsubishi shows increased efficiency and lower THC emissions for the bowl shape design. With such piston design dead volumes are reduce due to reduced top clearance and the squish flow is retained due to shallow dish outer shape, /13/.

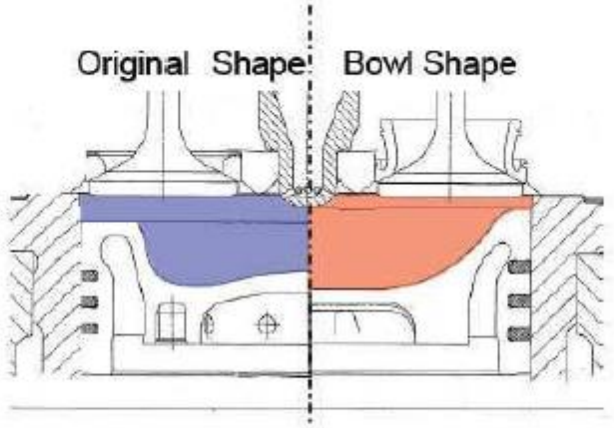

Figure 8.1 – Alternative combustion chamber design, /13/

Reduced dead volumes by design

One operational challenge of gas fuelled engines is high methane slip. This is due to crevices in the combustion chamber, which act as dead volumes where combustion not takes place. Typical crevices in the combustion chamber are:

- clearance between piston top and liner
- height of anti-polishing ring
- piston ring pack crevices
- head gasket crevice
- crevices around valve seats

In a premixed combustion process as the Otto Cycle the crevices are filled with fuel/air mixture during compression stroke. During the combustion these volumes are not ignited, and during the exhaust stroke the unburned mixture which was "hidden" in the crevices are emitted into the exhaust pipe causing increased THC emissions. Main dead volumes in a medium speed gas engine are shown in Figure 8.2.

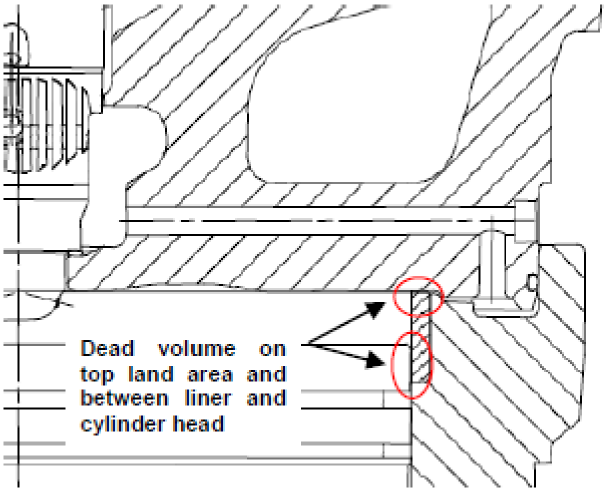

Figure 8.2 - Dead volumes in combustion chamber, /4/

Effects on methane emissions by reducing the dead volume has been demonstrated by engine manufacturer as shown in Figure 8.3. These effects are common knowledge by all manufacturers, and it is assumed that most suppliers have implemented optimum design as a part of their CH4 reduction improvement the last few years.

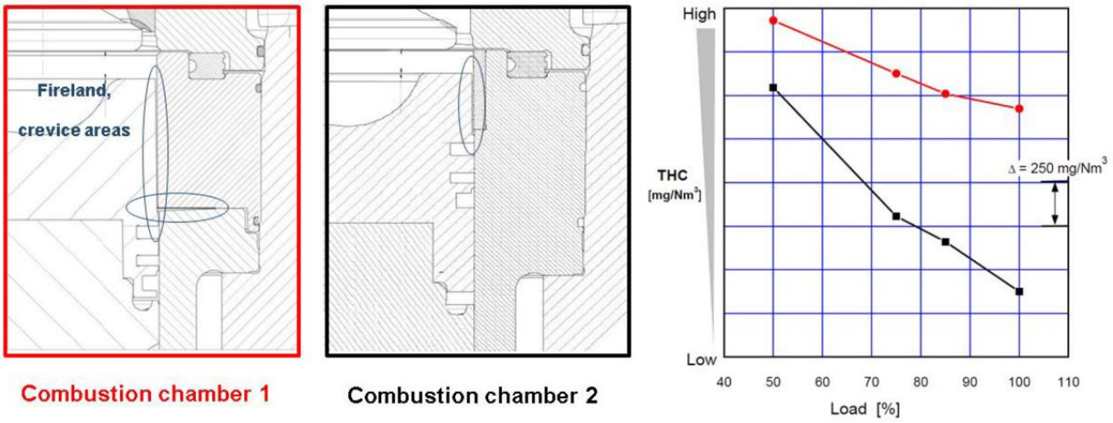

Figure 8.3: Impact of crevice areas on the emission level of Methane, /8/, /14/.

Compression ratio

Optimum compression ratio should be decided as a compromise of knock margin, firing pressure and efficiency, and the optimum compression ratio is a trade-off between NOx-formation and THC formation and engine efficiency. So optimal compression ratio need to be decided on basis of operational parameters as boost pressure, air temperature and ignition timing.

8.1.2 Optimization of the combustion process including ignition control

A fuel efficient high power gas engines is ideally run in the operating area shown in Figure 8.4. This means a rather small margin to both misfire and knocking.

Optimum operating point

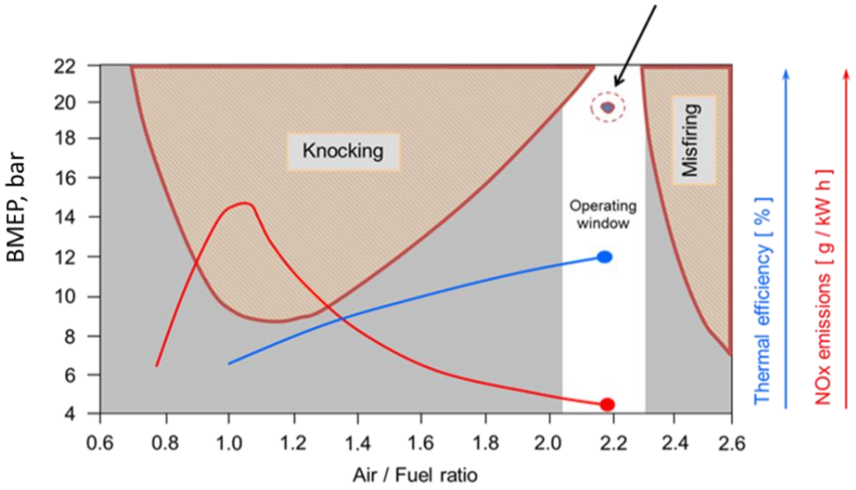

Figure 8.4 – Ideal operating area of lean burn gas engines.

The margin to knock is not only dependent on lambda but also the gas quality. This margin decreases quite significant when the gas contains heavier hydrocarbons, i.e. the methane number (MN) decreases. Gas from LNG normally has a rather high MN, but it is also experienced knock problems with LNG as fuel, especially during quick load increases. Looking worldwide the LNG quality varies quite significant from MN about 85 down to 60. This imply a need for advanced engine control which can handle gas quality variations and knock control while still keeping high overall efficiency and low emissions.

Technics to improve performance is EGR (Exhaust Gas Recirculation), Miller timing, Variable valve timimg (variable Miller factor), improved turbocharging and combustion chamber design, and first demonstrations of engines which have reach 50% efficiency has been reported.

According to MHI, EGR could be one of the possible solutions to achieve thermal efficiency greater than 50 %. By using EGR to extend the knocking margin due to the effect of inert gas it is possible to increase the compression ratio on a gas engine and achieve a higher efficiency.

GE Jenbacher has described their latest development work to further increase engine efficiency above 50% for their gas engines, which includes a combination of performance improvements technics as described above. High pressure charging, higher compression ratio in combination with high-pressure turbo charging and advanced Miller process is implemented, which requires a more complex engine control system to handle all parameter variations and secure high reliability of ignition and lambda control.

Wärtsilä reports that cylinder pressures measurements has been included in their engine control system for cylinder balancing and knock control.

To improve the engine efficiency in the coming years it is believed that a significant improvement in fuel utilization is achievable in a few years. This implies that major changes are required on combinations of hardware development and implementation and process control. Especially interesting is development of two-stage turbocharging with variable valve timing in combination with extreme Miller process which may allow for higher compression ratio. These technology combinations has been investigated as described above but are yet not commercialized due to complexity and high cost.

8.2 Methane slip reduction by aftertreatment

To reduce the methane slip from lean gas engines oxidation catalysts can be installed. This will also reduce CO and formaldehyde emissions. However, only Wärtsilä reports that such products are available for their gas fuelled engines. So far, such systems have not been used in marine applications for methane slip reduction. An oxidation catalyst for methane removal meet at least two major challenges:

- Oxidation of methane requires high temperature
- Catalyst sensitivity to pollution resulting in fast degradation of catalyst efficiency

Methane is a stable molecule and oxidation of methane requires high temperature. By using a palladium based catalyst oxidation of methane can be achieved at reduced temperatures. High methane conversion efficiency is required and even with palladium catalyst 100% conversion is achieved at a temperature level of app. 500 °C. For a lean burn gas engine normal operating exhaust temperature are in the range 420-500 °C depending of engine load, meaning that oxidation with high efficiency is a challenge.

Catalyst poisoning due to impurities in the exhaust, especially sulphur is also a big challenge, and for Pd-catalyst this will deactivate the chemical reaction in the catalyst and will reduce the methane conversion ratio significantly. Tests have shown that such deactivation can occur after only 100 hours of operation, and regeneration of the catalyst would be required.

The EmX R&D project is executed by NTNU and SINTEF. One of the objectives is "Improving catalysts for reducing CH4 slip and NOx emissions from NGV engines". Initial laboratory test /15/ has shown promising results on methane conversion and has demonstrated activity and stability of novel catalyst at relevant conditions with typical exhaust gas composition from lean burn engines has been used in a laboratory test set-up.

Wärtsilä has presented information on their Xcat-system /4/, which is a combined heat exchanger and oxidation catalyst suitable for applications in marine engines. The system could be installed after the turbine and preliminary tests in 2010 indicated high methane conversion ratios (>90%) with new device. Long-term stability or deactivation has not been reported.

8.3 Concluding remark

Today no requirements apply to methane emissions from ships, but methane slip from gas engines are of concern, as it is a strong GHG gas with a GWP Factor 25 higher than CO2. (Norwegian Authorities use GWP factor of 25 in their emission accounting, IPPC recommend to use GWP factor of 28).

It is a trade-off for NOx emissions and methane- and CO emissions. By running lean, NOx emissions will be reduced, and as leaner an engine run as lower will NOx emissions become. However, at a point the THC and CO emission starts to rise and at very lean mixtures the combustion process becomes poorer resulting exponential increase in THC and CO and significant reduction in engine efficiency.

So far, the main strategy from engine suppliers seems to have been to apply primary measures as optimising engine components by design and engine control strategy. This has shown significant improvement on methane slip compared to first generation marine gas engines.

If stricter regulations should apply, which not could be handles by primary measures, a methane reduction catalyst would be required. To the knowledge of the author such catalyst need further development to achieve high methane conversion ratio and long term efficiency, and are not considered to be commercially available for ship application with low methane slip concentration. This will add investment and operation cost for the LPDF and LBSI gas engine concepts.

Data for HPDF concept is only briefly presented in this report. This concept has almost no methane slip, but will suffer from higher NOx emissions than the LBSI and LPDF engine concepts.

9 References

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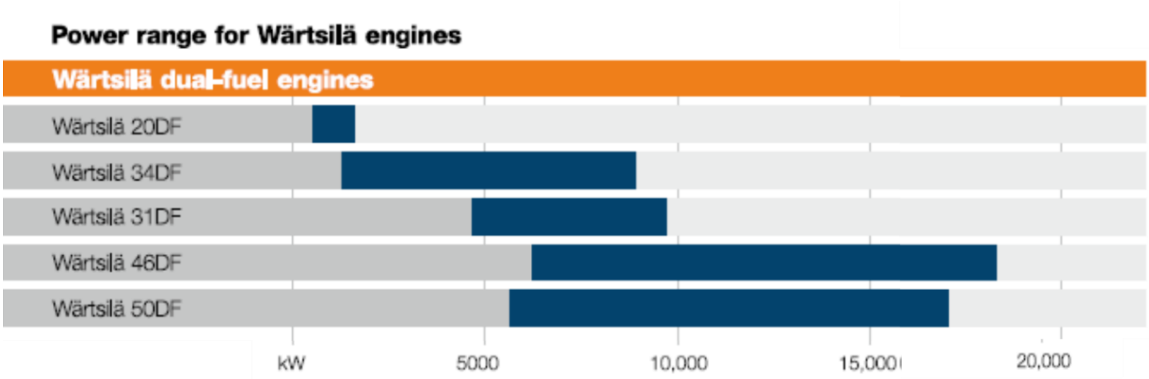
A Appendix A - Gas engine suppliers

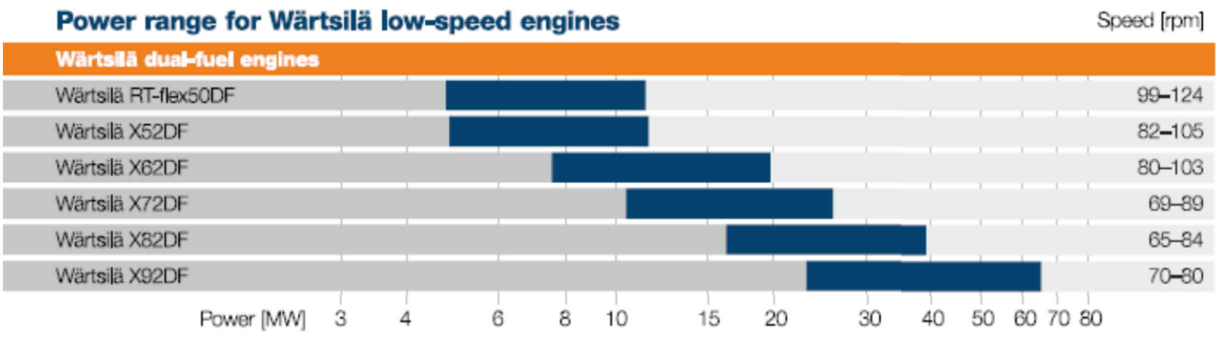
A.1 Wärtsilä

For marine application Wärtsilä manufacturer DF engines in the power range 1000 kW to 18 MW.



Power range of Wärtsilä DF engines for maritime application, http://www.wartsila.com

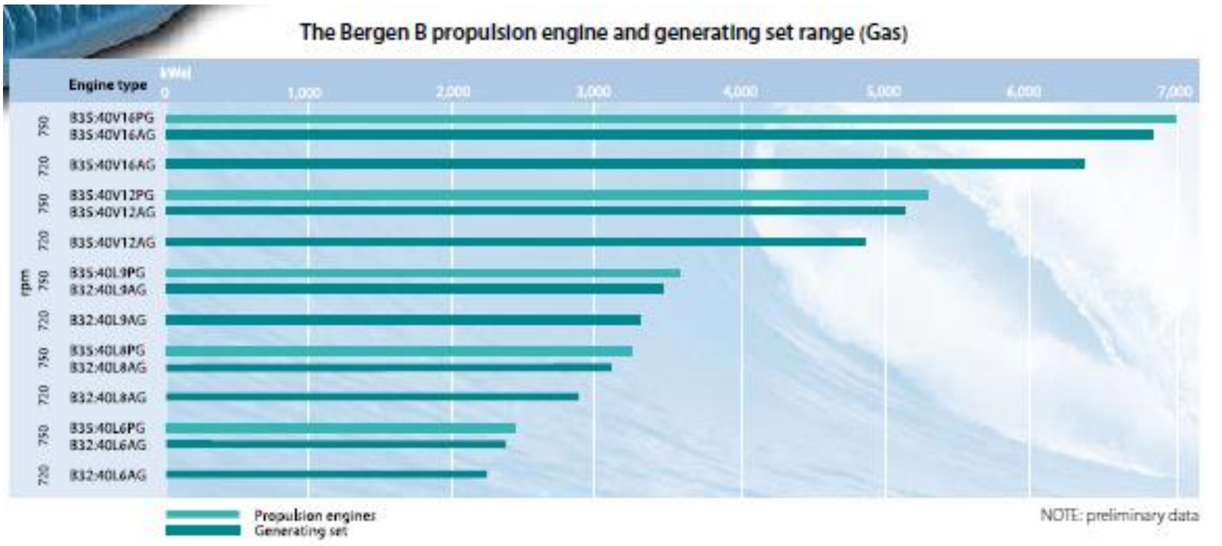
A.2 Win-GD/Wärtsilä

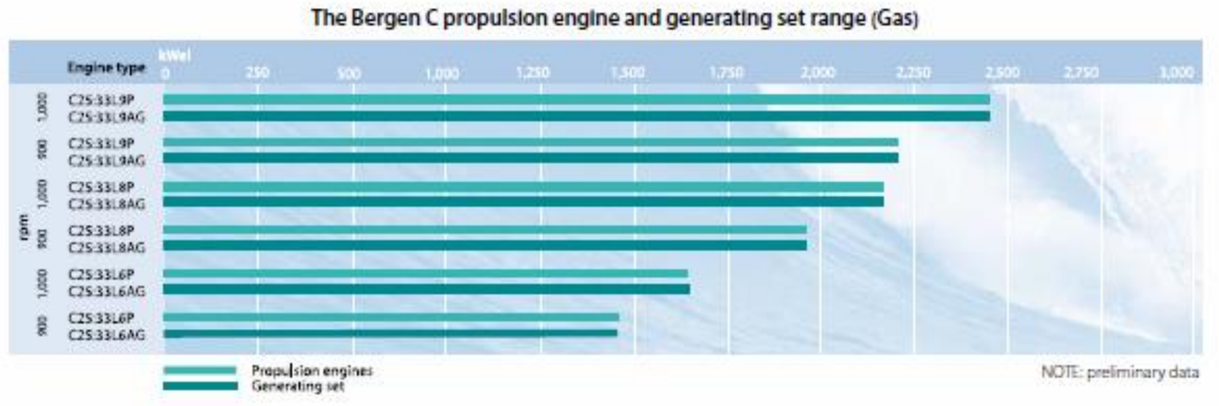


DF-ready option

All Generation X engines can be converted to use LNG as fuel. For simplifying the future conversion WinGD has introduced the DF-ready version as an option. The DF-ready engines can be easily converted to dual-fuel, as no major structural components need to be modified. All parts, which are to be replaced at a later conversion, are either typical wear parts or specific X-DF components and systems. The DF-ready version is the recommended solution for LNG-ready ships.

A.3 Rolls Royce



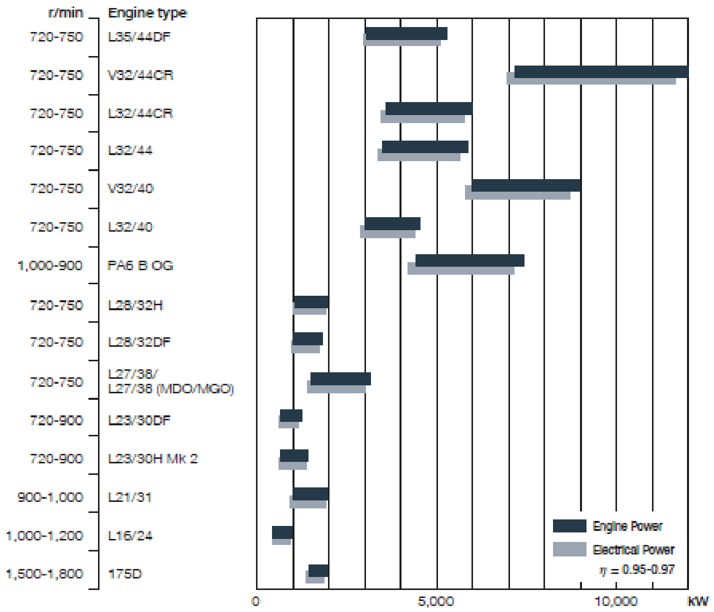


Ref.: Rolls-Royce. Diesel and gas engines, brochure. https://www.rolls-royce.com/

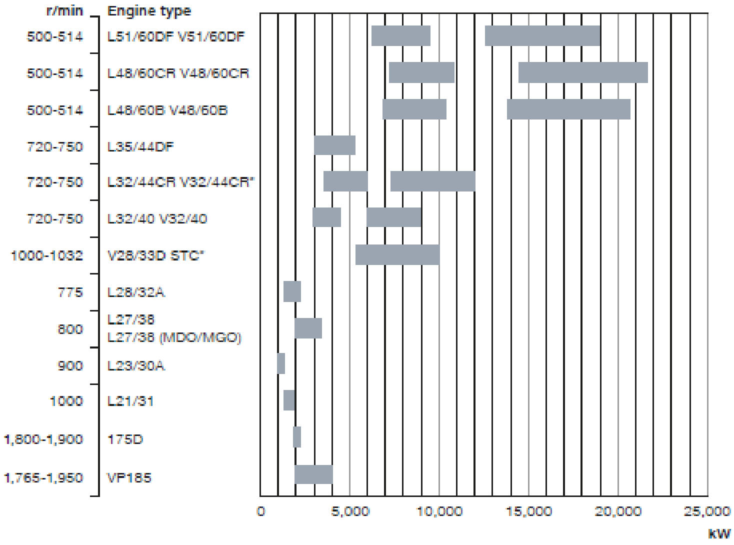
Power range of Rolls Royce gas engines, (LBSI engines), 2017

A.4 MAN

MAN Four-Stroke Marine GenSets



MAN Four-Stroke Propulsion Engines



* *The engine complies with EPA Tier 2*

A.5 Caterpillar

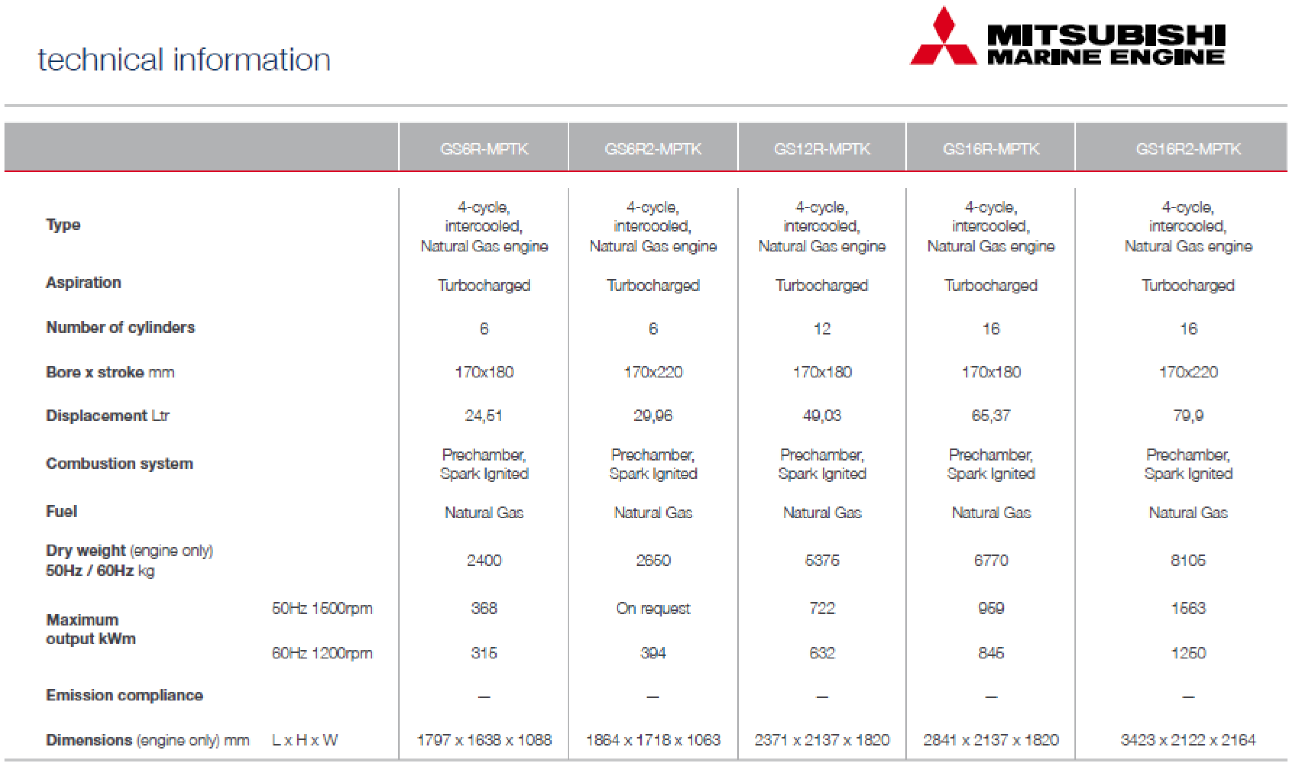
Engine type	Power range
M34DF	3060-4770 kW
M46DF	5400-8685 kW
VM46DF	10800-15440 kW

Caterpillar also supply several genset- modells covering the power range from 160-4300 kW. It is not stated whether these are applicable for marine use or not, but Caterpillar has delivered engines for an LNG barge in Germany based on their 3516C engine.

On the Hummel hybrid barge Caterpillar Marine, through its dealer Zeppelin Power Systems, supplied five category G3516C marine gas engines. The G3516 is a spark-ignited, gas engine certified by Bureau Veritas and is compliant with safety of life at sea (SOLAS) regulations. Each gas-powered generator set will generate 1,550ekW at 1,500 rotations per minute (rpm). The power plant produces 7.5MW electricity at 50 / 60Hz when operating on LNG alone.

Caterpillar has also undertaken a conversion of their 3618 engine for DF operation for application in a catamaran high speed car/passenger ferry.

A.6 Mitsubishi



technical information

		GS6R-MPTK	GS6R2-MPTK	GS12R-MPTK	GS16R-MPTK	GS16R2-MPTK
Type		4-cycle, intercooled, Natural Gas engine	4-cycle, intercooled, Natural Gas engine	4-cycle, intercooled, Natural Gas engine	4-cycle, intercooled, Natural Gas engine	4-cycle, intercooled, Natural Gas engine
Aspiration		Turbocharged	Turbocharged	Turbocharged	Turbocharged	Turbocharged
Number of cylinders		6	6	12	16	16
Bore x stroke mm		170x180	170x220	170x180	170x180	170x220
Displacement Ltr		24,51	29,96	49,03	65,37	79,9
Combustion system		Prechamber, Spark Ignited	Prechamber, Spark Ignited	Prechamber, Spark Ignited	Prechamber, Spark Ignited	Prechamber, Spark Ignited
Fuel		Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas
Dry weight (engine only) **50Hz / 60Hz** kg		2400	2650	5376	6770	8105
Maximum output kWm	50Hz 1500rpm	368	On request	722	959	1563
	60Hz 1200rpm	315	394	632	845	1250
Emission compliance		–	–	–	–	–
Dimensions (engine only) mm	L x H x W	1797 x 1638 x 1088	1864 x 1718 x 1063	2371 x 2137 x 1820	2841 x 2137 x 1820	3423 x 2122 x 2164

A.7 Niigata

NIIGATA

Dual Fuel Engine

World's First Marine Gas Fuel Engine Directly Coupled with Fixed Pitch Propeller
(Realized by Original Technology)

Natural gas burns far cleaner than petroleum fuel,to there is growing interest in the ship field.
We successfully delivered the world's first 4 stroke Dual Fuel engine for Fixed Pitch Propeller directly couple driven LNG fueled harbor tug boat. It offers high dynamic performance of load following capacity in gas mode, equivalent in diesel mode for tug operation, and safe redundancy as instantly switch between gas & diesel mode.

6MG28AHX-DF

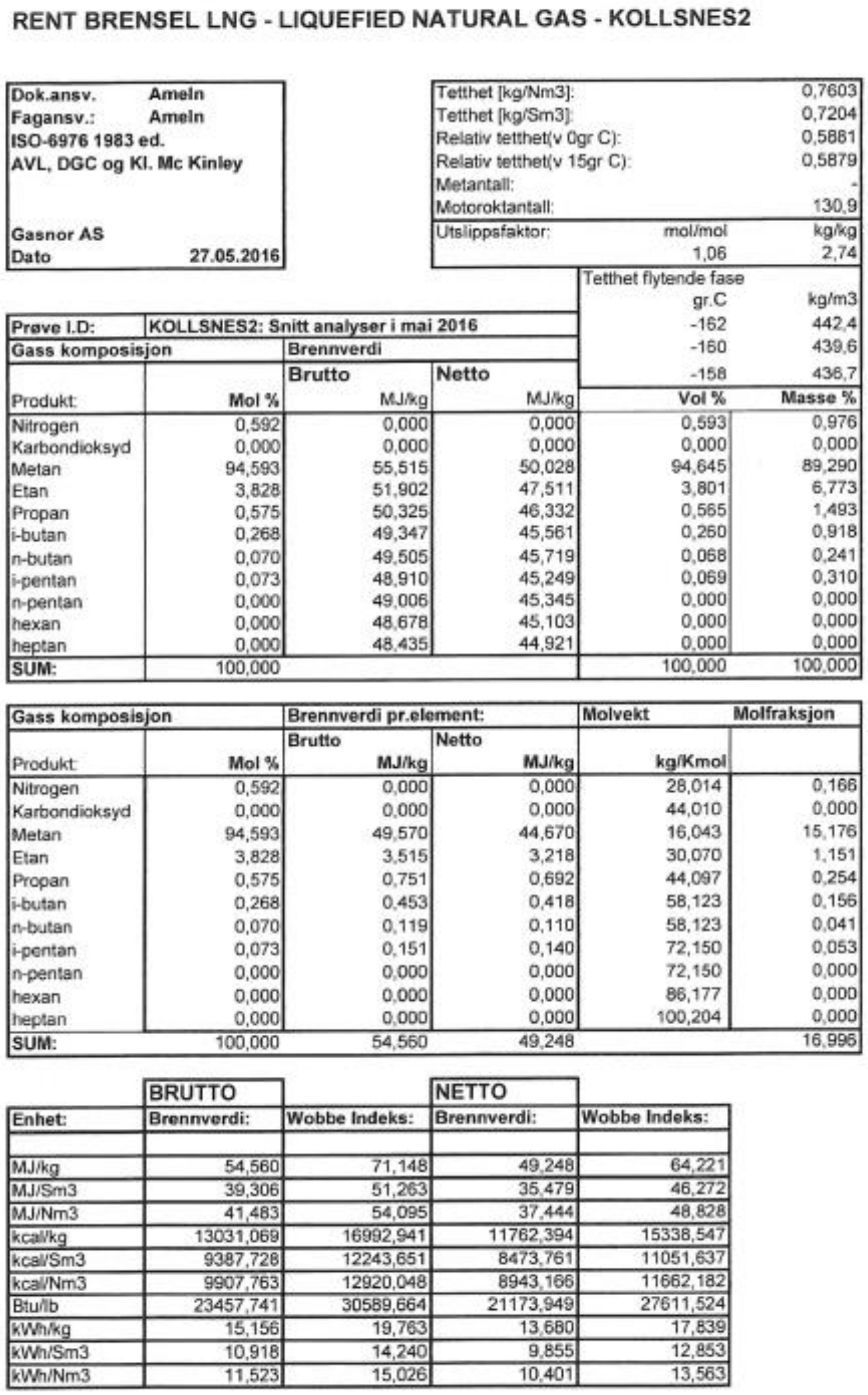
General Specifications

Model	Max.Continuous Rating		Engine Speed	Cyl. Bore	Piston Stroke	Approx. Dry Mass
	kWm	PS	min^{-1}	mm	mm	t
6L28AHX-DF	1920	2610	800	280	390	22
8L28AHX-DF	2560	3480	800	280	390	28
9L28AHX-DF	2880	3915	800	280	390	31

※All information will be subject to change without notice.

B Appendix B. Example of fuel gas composition

Fuel gas analyses has been received from several ships and as can be seen there are deviation of the composition dependant on supplier. Examples of fuel gas composition is shown below.



RENT BRENSEL LNG - LIQUEFIED NATURAL GAS - KOLLSNES2

Dok.ansv. **Ameln**
Fagansv.: **Ameln**
ISO-6976 1983 ed.
AVL, DGC og Kl. Mc Kinley

Gasnor AS
Dato **27.05.2016**

Tetthet [kg/Nm3]:		0,7603
Tetthet [kg/Sm3]:		0,7204
Relativ tetthet(v 0gr C):		0,5881
Relativ tetthet(v 15gr C):		0,5879
Metantall:		-
Motoroktantall:		130,9
Utslippsfaktor:	mol/mol	kg/kg
	1,06	2,74

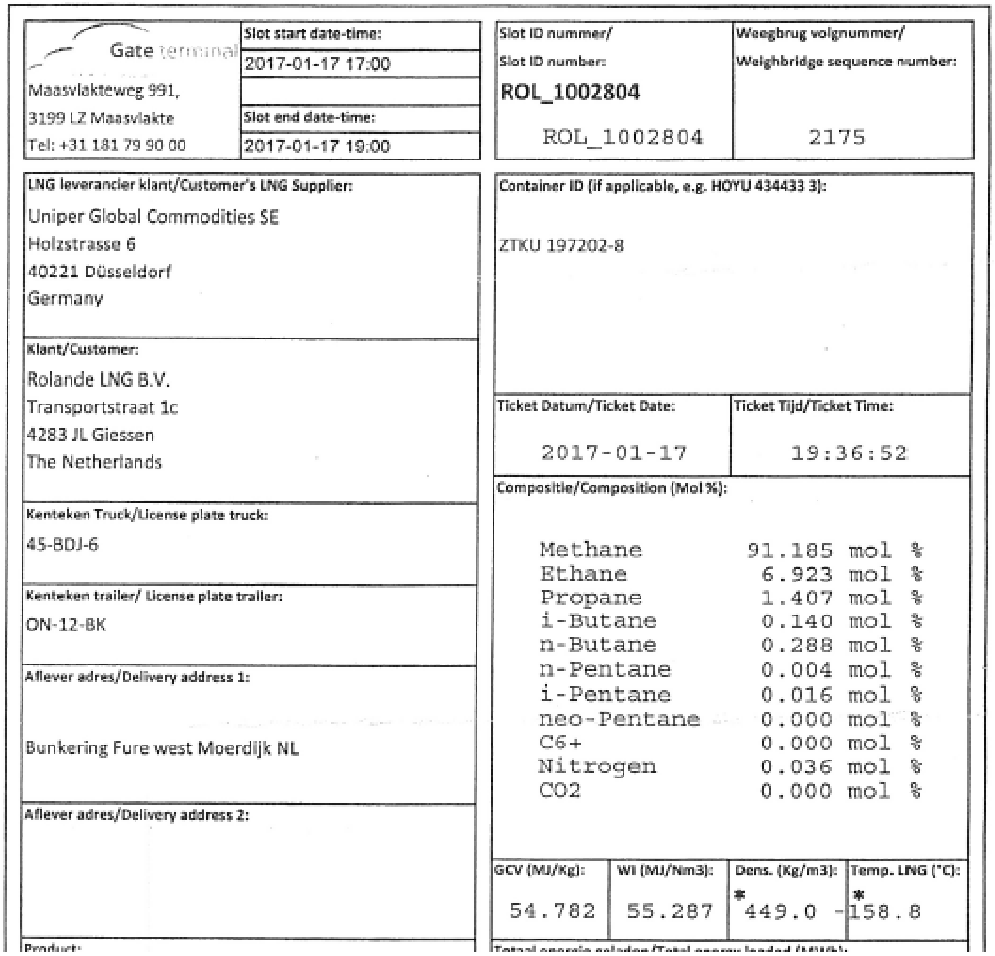
Tetthet flytende fase	
gr.C	kg/m3
-162	442,4
-160	439,6
-158	436,7

Prøve I.D: **KOLLSNES2: Snitt analyser i mai 2016**

Gass komposisjon		**Brennverdi**			
		Brutto	**Netto**		
Produkt	**Mol %**	MJ/kg	MJ/kg	**Vol %**	**Masse %**
Nitrogen	0,592	0,000	0,000	0,593	0,976
Karbondioksyd	0,000	0,000	0,000	0,000	0,000
Metan	94,593	55,515	50,028	94,645	89,290
Etan	3,828	51,902	47,511	3,801	6,773
Propan	0,575	50,325	46,332	0,565	1,493
i-butan	0,268	49,347	45,561	0,260	0,918
n-butan	0,070	49,505	45,719	0,068	0,241
i-pentan	0,073	48,910	45,249	0,069	0,310
n-pentan	0,000	49,006	45,345	0,000	0,000
hexan	0,000	48,678	45,103	0,000	0,000
heptan	0,000	48,435	44,921	0,000	0,000
SUM:	100,000			100,000	100,000

Gass komposisjon		**Brennverdi pr.element:**		**Molvekt**	**Molfraksjon**
		Brutto	**Netto**		
Produkt	**Mol %**	**MJ/kg**	**MJ/kg**	**kg/Kmol**	
Nitrogen	0,592	0,000	0,000	28,014	0,166
Karbondioksyd	0,000	0,000	0,000	44,010	0,000
Metan	94,593	49,570	44,670	16,043	15,176
Etan	3,828	3,515	3,218	30,070	1,151
Propan	0,575	0,751	0,692	44,097	0,254
i-butan	0,268	0,453	0,418	58,123	0,156
n-butan	0,070	0,119	0,110	58,123	0,041
i-pentan	0,073	0,151	0,140	72,150	0,053
n-pentan	0,000	0,000	0,000	72,150	0,000
hexan	0,000	0,000	0,000	86,177	0,000
heptan	0,000	0,000	0,000	100,204	0,000
SUM:	100,000	54,560	49,248		16,996

	BRUTTO		**NETTO**	
Enhet:	**Brennverdi:**	**Wobbe Indeks:**	**Brennverdi:**	**Wobbe Indeks:**
MJ/kg	54,560	71,148	49,248	64,221
MJ/Sm3	39,306	51,263	35,479	46,272
MJ/Nm3	41,483	54,095	37,444	48,828
kcal/kg	13031,069	16992,941	11762,394	15338,547
kcal/Sm3	9387,728	12243,651	8473,761	11051,637
kcal/Nm3	9907,763	12920,048	8943,166	11662,182
Btu/lb	23457,741	30589,664	21173,949	27611,524
kWh/kg	15,156	19,763	13,680	17,839
kWh/Sm3	10,918	14,240	9,855	12,853
kWh/Nm3	11,523	15,026	10,401	13,563



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3199 LZ Maasvlakte
Tel: +31 181 79 90 00

Slot start date-time: 2017-01-17 17:00

Slot end date-time: 2017-01-17 19:00

Slot ID nummer/ Slot ID number:
ROL_1002804
ROL_1002804

Weegbrug volgnummer/ Weighbridge sequence number: 2175

LNG leverancier klant/Customer's LNG Supplier:
Uniper Global Commodities SE
Holzstrasse 6
40221 Düsseldorf
Germany

Container ID (if applicable, e.g. HOYU 434433 3): ZTKU 197202-8

Klant/Customer:
Rolande LNG B.V.
Transportstraat 1c
4283 JL Giessen
The Netherlands

Ticket Datum/Ticket Date: 2017-01-17

Ticket Tijd/Ticket Time: 19:36:52

Kenteken Truck/License plate truck: 45-BDJ-6

Kenteken trailer/ License plate trailer: ON-12-BK

Composítie/Composition (Mol %):

Methane	91.185 mol %
Ethane	6.923 mol %
Propane	1.407 mol %
i-Butane	0.140 mol %
n-Butane	0.288 mol %
n-Pentane	0.004 mol %
i-Pentane	0.016 mol %
neo-Pentane	0.000 mol %
C6+	0.000 mol %
Nitrogen	0.036 mol %
CO2	0.000 mol %

Aflever adres/Delivery address 1: Bunkering Fure west Moerdijk NL

Aflever adres/Delivery address 2:

GCV (MJ/Kg):	WI (MJ/Nm3):	Dens. (Kg/m3):	Temp. LNG (°C):
54.782	55.287	* 449.0	* -158.8

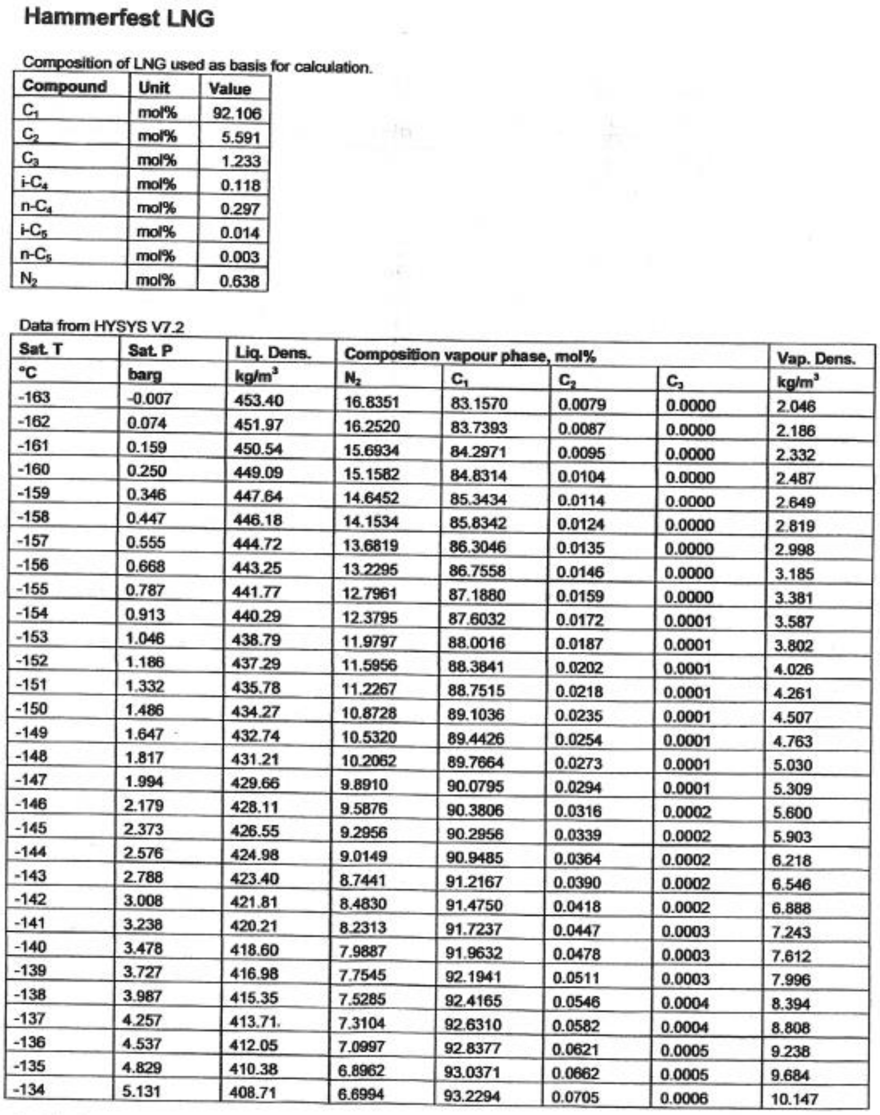
Product:

Calculations with AVL Methane:
Methane number = 76.4

Density (at 0°C, 101.325 kPa) : 0.78874 kg/m³
Gas constant : 470.30 J/K*kg
Lower calorific value : 49578.1 kJ/kg
Molecular weight of the gas : 17.5949 kg/kMol
Stoichiometric air/fuel ratio : 16.8695 kg Air/kg Gas

Masspart of C : 0.75763 kg C/kg Gas
Masspart of H : 0.24181 kg H/kg Gas
Masspart of N : 0.00056 kg N/kg Gas

Y for Exhaust-O2 calculations : 3.7343
Molecular weight for THC corr. to C1 : 15.8411 kg/kMol
Non methane masspart in THC : 0.1710 g NMHC/g THC



Hammerfest LNG

Composition of LNG used as basis for calculation.

Compound	Unit	Value
C_1	mol%	92.106
C_2	mol%	5.591
C_3	mol%	1.233
i-C_4	mol%	0.118
n-C_4	mol%	0.297
i-C_5	mol%	0.014
n-C_5	mol%	0.003
N_2	mol%	0.638

Data from HYSYS V7.2

Sat. T	Sat. P	Liq. Dens.	Composition vapour phase, mol%				Vap. Dens.
°C	barg	kg/m^3	N_2	C_1	C_2	C_3	kg/m^3
-163	-0.007	453.40	16.8351	83.1570	0.0079	0.0000	2.046
-162	0.074	451.97	16.2520	83.7393	0.0087	0.0000	2.186
-161	0.159	450.54	15.6934	84.2971	0.0095	0.0000	2.332
-160	0.250	449.09	15.1582	84.8314	0.0104	0.0000	2.487
-159	0.346	447.64	14.6452	85.3434	0.0114	0.0000	2.649
-158	0.447	446.18	14.1534	85.8342	0.0124	0.0000	2.819
-157	0.555	444.72	13.6819	86.3046	0.0135	0.0000	2.998
-156	0.668	443.25	13.2295	86.7558	0.0146	0.0000	3.185
-155	0.787	441.77	12.7961	87.1880	0.0159	0.0000	3.381
-154	0.913	440.29	12.3795	87.6032	0.0172	0.0001	3.587
-153	1.046	438.79	11.9797	88.0016	0.0187	0.0001	3.802
-152	1.186	437.29	11.5956	88.3841	0.0202	0.0001	4.026
-151	1.332	435.78	11.2267	88.7515	0.0218	0.0001	4.261
-150	1.486	434.27	10.8728	89.1036	0.0235	0.0001	4.507
-149	1.647	432.74	10.5320	89.4426	0.0254	0.0001	4.763
-148	1.817	431.21	10.2062	89.7664	0.0273	0.0001	5.030
-147	1.994	429.66	9.8910	90.0795	0.0294	0.0001	5.309
-146	2.179	428.11	9.5876	90.3806	0.0316	0.0002	5.600
-145	2.373	426.55	9.2956	90.2956	0.0339	0.0002	5.903
-144	2.576	424.98	9.0149	90.9485	0.0364	0.0002	6.218
-143	2.788	423.40	8.7441	91.2167	0.0390	0.0002	6.546
-142	3.008	421.81	8.4830	91.4750	0.0418	0.0002	6.888
-141	3.238	420.21	8.2313	91.7237	0.0447	0.0003	7.243
-140	3.478	418.60	7.9887	91.9632	0.0478	0.0003	7.612
-139	3.727	416.98	7.7545	92.1941	0.0511	0.0003	7.996
-138	3.987	415.35	7.5285	92.4165	0.0546	0.0004	8.394
-137	4.257	413.71	7.3104	92.6310	0.0582	0.0004	8.808
-136	4.537	412.05	7.0997	92.8377	0.0621	0.0005	9.238
-135	4.829	410.38	6.8962	93.0371	0.0662	0.0005	9.684
-134	5.131	408.71	6.6994	93.2294	0.0705	0.0006	10.147

Calculations with AVL Methane:
Methane number = 78.6

Density (at 0°C, 101.325 kPa) : 0.78067 kg/m^3
Gas constant : 475.17 J/K*kg
Lower calorific value : 49169.5 kJ/kg
Molecular weight of the gas : 17.4207 kg/kMol
Stoichiometric air/fuel ratio : 16.7359 kg Air/kg Gas

Masspart of C : 0.74894 kg C/kg Gas
Masspart of H : 0.24080 kg H/kg Gas
Masspart of N : 0.01025 kg N/kg Gas

Y for Exhaust-O2 calculations : 3.7621
Molecular weight for THC corr. to C1 : 15.8693 kg/kMol
Non methane masspart in THC : 0.1456 g NMHC/g THC