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Methane slip from gas fuelled ships: a comprehensive summary based on measurement data

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Abstract Strict NO_x emission regulations set for marine vessels by Tier III standard make ship owners/operators finding new efficient methods fulfilling these requirements. Utilization of LNG as main fuel at the moment is one of the most promising solutions with lean burn spark ignited (LBSI) engines and low pressure dual fuel (LPDF) ones being of primary choice. Technology provides not only low NO_x levels, but also allows to reduce operational costs due to LNG currently being a cheaper fuel. The main drawback of low-pressure gas engines is rather high levels of methane slip, especially at low loads, as a result of poor fuel utilization due to low operational fuel-air ratios. Nevertheless, there are no standards that directly regulate methane slip for marine gas engines, but the topic starts to receive more and more attention due to the concerns associated with environmental effect of methane as well as due to ship operators analyzing ship data more thoroughly revealing substantial increase in gas fuel consumption at low loads. Presented study summarizes all gas engine technologies that are available for the maritime sector considering their current status and maturity and present a comprehensive measurement data summary for the main groups, namely LBSI and LPDF engines. The measurement data pool consists of both on-board and test-bed emission data revealing an interesting moments such as possible "overtuning" of engines for low NO_x resulting in excessive levels of methane slip, importance of on-board measurements due to their more realistic nature, utilization of non-perfections, like

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fixed emission weight factors for loads, in Tier III regulations, etc. The article also quantitatively indicates the progress in gas technology development and provides updated specific emission factors for the considered gas engine types.

Keywords Methane slip · Gas engine · LBSI · LPDF · Ship emissions · Tier III · Measurements

1 Introduction

The importance of sea trade cannot be underestimated as more than 80 % of the world trade by volume and more than 70 % of its value is carried on board of seagoing vessels and handled by seaports worldwide [1]. In fact only around 2.2 % of anthropogenic greenhouse gas (GHG) emissions are produced by the sea transport, making shipping one of the most energy- and emission-effective ways of commercial transport. At the same time, it might be challenging to achieve the goals of the Paris Agreement [2] in lowering global emitted GHG levels as the number of marine vessels is expected to increase in future to provide the necessary supplies to constantly growing world population. Moreover, the local emissions of NO_x, particulate matter (PM) and SO_x from ships [3, 4, 5] that has a strong negative impact both on local climate and on human health [6, 7] should be also considered.

Current emission regulation for international maritime transport is set by International Maritime Organization (IMO) [8] and consists of direct NO_x emission regulations [9] and limits for maximum sulfur content in fuel used that has proportional effect on produced SO_x emissions (and corresponding sulfate fraction of PM) [67]. To meet future stricter NO_x regulations a number of technological methods can be used as for example Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR) together with various water-induction methods and/or Miller cycle [10] or alternative fuels, like Liquefied Natural Gas (LNG), can be applied. Desired SO_x levels can be achieved by complete switch from HFO to distillate fuels such as marine gas oil (MGO) or other alternative fuels such as biofuels, methanol or LNG [11, 12, 13]. The application of "at least as effective in terms of emission reduction" exhaust gas aftertreatment systems (i.e. seawater scrubbers) together with HFO is also allowed [8].

Based on all this information it is quite obvious why application of LNG as marine fuel is gaining popularity as it allows to achieve both current and future emission standards set for international shipping without use of aftertreatment systems [14, 15, 16]. Not surprising that number of LNG fuelled vessels is constantly increasing with technology being adopted for much broader type of vessels as can be seen in Figure 1 below.

As interest in LNG as marine fuel increases, increases the size and capacity of the available gas infrastructure both in Europe [18] and worldwide [19]. At the same time, another problem, that was almost ignored the early years after the first LNG-powered ferry was introduced in the Norwegian waters in 2000, receives more and more attention. The emissions of unburned methane or so-called methane slip is the main environmental issue related to the operation of gas-fuelled MDEs and has to be considered due to its great impact on the global warming. Methane

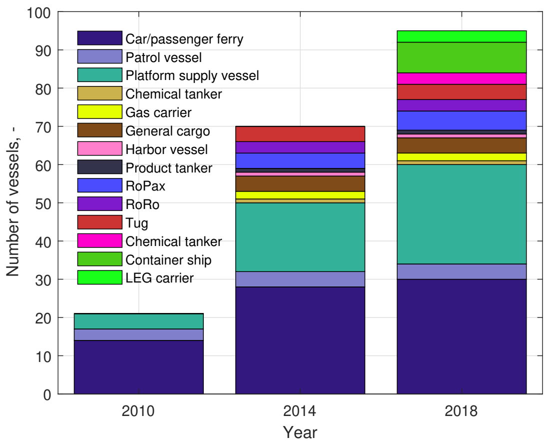

Fig. 1 LNG fuelled fleet by vessel type (adopted from [17])

has a 86 times higher 20-year global warming potential (GWP) than carbon dioxide [20], while on 100-year time perspective it is still considered rather high, but reduced to 25 [21]. If methane slip is not controlled in proper manner, environmental benefits of LNG usage are considerably reduced or even completely eliminated (comparing to diesel or HFO fuels) due to the high greenhouse effect of methane [11]. In addition to all that the amount of measurement data related to methane slip is very limited and mainly comes from test-bed measurements provided by the engine manufacturers, so there is apparent lack of real field data from on-board measurements. Only this type of data can be a good indicator of the gas technology developing in the right direction, i.e. towards lower methane slip and higher efficiency of fuel utilization. The main purpose of this article is to provide the research society with the comprehensive set of emission data coming from both test-bed and on-board measurements from LNG-fueled marine diesel engines (MDEs). The study reports mainly methane emission data as function of load for different types of gas engines and addresses the main issues related to further reduction of still unregulated methane slip and regulated NO_x emissions.

2 LNG fuel, engine concepts and emissions

2.1 Natural gas as a fuel

Natural gas (NG) is a mixture of various light-weigth hydrocarbon gases like methane, ethane and others, but may contain some carbon dioxide, nitrogen and water vapour. The actual composition slightly varies depending on the origin of the gas and details of the production process with methane normally accounting for 87-96 % of natural gas [22]. Even despite such minor change in composition, the change in methane number, that determines the knocking resistance of the fuel [23], can be significant as can be seen from Table 1 that provides the summary of LNG composition from different gas suppliers across Europe that are relevant to the study.

Table 1 Fuel gas (LNG) composition from different suppliers across Europe

Component	Gasnor, Kollsnes (NO)		Titan LNG, Moerdijk (NL)	Statoil, Hammerfest (NO)	BBG[a], Bilbao (ES)	Skangas, Risavika (NO)
Methane, mol %	95.901	94.593	91.185	92.106	91.908	92.270
Ethane, mol %	3.037	3.828	6.923	5.591	7.039	6.873
Propane, mol %	0.370	0.575	1.407	1.233	0.674	0.417
Isobutane, mol %	0.142	0.286	0.140	0.118	0.083	0.030
n-Butane, mol %	0.001	0.070	0.288	0.297	0.098	0.040
Isopentane, mol %	0.019	0.073	0.016	0.014	0.005	0.003
n-Pentane, mol %	0	0	0.004	0.003	0.001	0
Nitrogen, mol %	0.530	0.592	0.036	0.638	0.929	0.370
GCV[b], MJ/kg	54.737	54.560	54.993	N/A	N/A	54.740
NCV[b], MJ/kg	49.383	49.338	49.578	49.169	49.554	49.380
Density, kg/m^3	0.747	0.756	0.789	0.781	0.775	0.772
Methane number[c], -	85.5	81.0	76.4	78.6	79.8	81.6

[a] Bahia de Bizkaia Gas (BBG)
[b] Gross Caloric Value (GCV) and Net Caloric Value (NCV)
[c] Calculated with AVL Methane v. 3.10b

Application of NG as fuel for internal combustion engines (ICEs) allows to reduce NO_x emissions by 50-85 %, CO_2 by 20-30 %, CO by 70-95 %, emissions of non-methane hydrocarbons (HC) by around 50 % and at the same time produce almost no smoke and particulate matter (PM) [24]. To be used as the fuel for spark-ignition engines methane does not require any big engine modifications and its excellent antiknocking quality (octane number >120) [25] allows to employ high compression ratios resulting in higher thermal efficiency and corresponding lower fuel consumption [26, 27]. When it comes to compression-ignition engines, a certain difficulty arises associated with rather high auto-ignition temperature of methane, so a high-energy ignition source is required.

On an energy equivalent basis, natural gas should be a cheaper fuel comparing to both gasoline and diesel [28], which results in lower running costs. Moreover, the lack of distillate marine fuel starting from 2020 might be expected due to stricter global sulfur cap with majority of existing engines most likely converted from HFO to MGO operation.

While NG is typically used in gaseous form in industry and domestic applications, the liquefied natural gas (LNG) is a preferred solution by maritime sector [30]. LNG is a proven technology as has been used as a main fuel on board of LNG carriers for the last 45 years [31], originally in traditional boiler/steam turbine systems, but nowadays its application in ICEs becomes more and more common [20].

Nowadays LNG is used as a main fuel for different vessel types as indicated in Figure 1 with several gas engine concepts successfully utilized by maritime industry.

2.2 Gas engine concepts

Five different gas engine concepts can be identified to be used for marine application. Each concept has its own combustion characteristics which results in different efficiency and exhaust gas emission profile [32]. With all that it appears quite clear that the choice of the gas technology will determine the overall economic and environmental impact of gas operation for a particular vessel [33]. These five main gas engine concepts can be allocated to three engine groups (including corresponding covered power range):

- Lean Burn Spark Ignited engines
  - Medium and high speed, 4-stroke cycle (LBSI): ***0.5 - 8 MW***
- Low Pressure Dual Fuel engines
  - Medium speed, 4-stroke cycle (LPDF): ***1 - 18 MW***
  - Low speed, 2-stroke cycle (LPLSDF): ***5 - 63 MW***
- High Pressure Dual Fuel engines
  - Medium speed, 4-stroke cycle (HPMSDF): ***2 - 18 MW***
  - Low speed, 2-stroke cycle (HPLSDF): ***> 2.5 MW***

As there is an overlap in the covered power range between the specified gas technologies, the right choice between the available concepts has to be done by the shipowner depending on the carefully evaluated requirements in terms of propulsion power, redundancy, operational profile of the designed vessel, gas availability across the planned transport route and other potential commercial issues.

Based on the operational experience only LBSI and LPDF engines can be considered a proven gas technology as number of marine vessels with corresponding engines have been in operation for quite some years now. The main suppliers of such engines are Rolls-Royce Bergen Engines, Norway (LBSI, medium speed), Mitsubishi, Japan (LBSI, high speed) and Wärtsilä, Finland (LPDF). The LPLSDF engines (Winterthur Gas and Diesel (Win-GD), Switzerland) and the HPLSDF (MAN Diesel and Turbo, Germany) have also been installed in a several ships so far and are commercially available in a large power range. The HPMSDF concept (Wärtsilä) has been in operation for many years now, but only in FPSO's power plants operating in North Sea and in onshore power generation units, but has not been used for ship propulsion so far.

A schematic representation of all three existing gas engine concepts is given in Figure 2, while each of the technologies with corresponding advantages and disadvantages is discussed further on. The main emphasis here is placed on the applicability of certain gas technology to the maritime transport sector and potential limitation which each of them has.

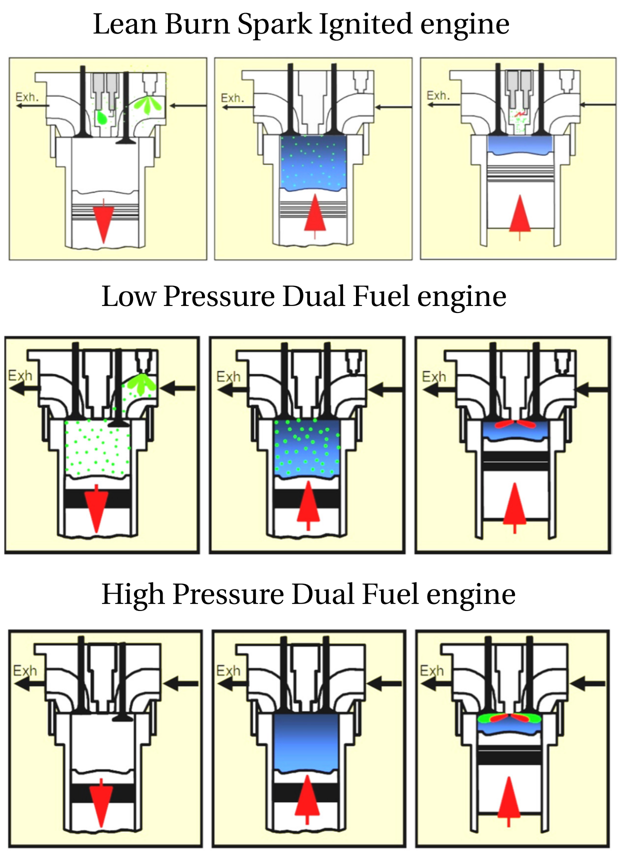

Fig. 2 Three main gas-fuelled engine concepts for marine application [33]

2.2.1 Lean Burn Spark Ignited engines

The Lean Burn Spark Ignited gas engines operation is based on Otto cycle running typically at high air excess ratio ($\lambda \approx 2$) which results in lower peak combustion temperature and corresponding lower NO_x emissions. Conventional spark plug is not capable to operate at such lean conditions, so has to be placed in a pre-chamber with locally lower λ (obtained by adding fuel gas) to provide stable operational conditions for the spark plug [33]. The combustion chamber's compact design and controllable level of turbulence result in higher thermal efficiency comparing to the conventional diesel engine counterparts. Combination of a spark plug and pre-chamber technology provides gas jets entering the main chamber with high momentum, thus resulting in good jet penetration and stable ignition of lean fuel-air mixture [34]. Absence of conventional fuel oil injection systems provides lower parasitic losses resulting in higher thermal efficiency that reaches 48-49 % (at high engine loads).

The air-fuel ratio in LBSI engines is controlled by the turbocharging system and a throttling system at low loads (< 30 % load). Operation at high air excess ratio leads to increase methane slip (especially at low loads) due to the bulk quenching in the coldest areas of the combustion chamber [27]. To overcome that it is possible to enrich the mixture in the main chamber, which most likely eliminate the emissions of the unburned methane, at the same time providing overall stable ignition and combustion process even at very low loads [34, 35] . Another advantage of the enrichment is that it allows fast load pick up, almost in the same range (up to 75 % load) as in conventional diesel engines [15, 36].

The application of advanced fuel-air ratio control system for enrichment at low loads together with proper design of the combustion chamber oriented towards the reduction of the volume of crevices [37, 38], the methane emissions can be substantially reduced down to 2.5-3.0 g/kWh. Eventually LBSI engines can provide overall reduction of GHG emission including methane. This reduction is very much dependent on the ship's operational profile and gas fuel composition, but the average 15-20 % reduction (comparing to diesel oil operation) is a fair number [33]. It should be also mentioned that the application of variable valve timing (VVT) or variable Miller factor together with optimized turbocharging system can provide a better control of combustion process for gas fuels even with lower methane number. It results in possibility of varying compression ratio, thus allowing a high expansion ratio and providing high fuel conversion efficiency at challenging low load operational range [39, 40].

Despite being a proven technology and despite all the aforementioned advantages, LBSI engines suffer from high methane slip at low loads and are very sensitive to gas quality. In addition, the main operational disadvantage is a lack of backup fuel (i.e. diesel fuel) if LNG is not available. This basically explains why the shipping industry (especially deep sea ships) prefers Dual Fuel engine concept (refer to Figure 3).

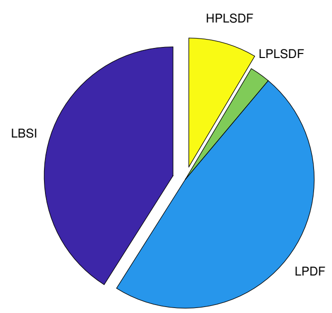

Fig. 3 Preferred gas engine technology in shipping (as per December 2016)

2.2.2 Low Pressure Dual Fuel engines

In general the operational principle of LPDF engines is similar to that described for LBSI ones with reference to combustion of lean fuel-air mixture. The main difference is related to the ignition process where LPDF engines rely on diesel fuel as an ignition source, which can also be used as backup fuel [41]. This is one of the main reasons why Dual Fuel engines are a preferred solution for international shipping. LPDF is a sort of compromise between Diesel cycle compression ignition of fuel oil and Otto cycle with induction of fuel-air mixture prior to compression. The conflict lies between the sufficient heat and air excess to secure pilot ignition and low compression ratio to avoid knocking [33] and rather low fuel-air ratio at low loads for reduction of unburned methane emissions due to bulk quenching.

VVT and throttling have a limited applicability in this case due to requirements for stable ignition and combustion of the pilot fuel. The compression ration has to be also adjusted to satisfy the conditions set by the fuel's methane number (MN) at the same time providing certain margin to the knock limit [38] (assume slower load pick up comparing to LBSI concept). Enrichment suitable for LBSI engines cannot be utilized in the same manner here due to considerations of pilot fuel. The contribution of pilot fuel to NO_x emissions has to be minimized which can be achieved by reducing the amount of injected diesel pilot fuel. Pilot injections with 1-2 % of full load fuel consumption is achievable, but is rather challenging for stable control. One of the most promising solution is installation of a separate pilot fuel nozzle (either integrated in one housing or installed as a separate fuel injector) [42, 43, 44]. Pilot fuel can be either injected directly into the (main) combustion chamber or in a pre-chamber.

As Dual Fuel concept allows operation on two different fuels, the operational profile of the considered marine vessel should determine whether the LPDF engine should be optimized for diesel oil operation or for gas operation. When optimized for gas operation - better performance level of LBSI engines should be expected at the same time keeping the same problems as methane slip at low loads and slow load pick up. In this case one should also expect non-optimal performance operating on diesel oil [33].

The considerations regarding methane slip are similar as for LBSI engines (meaning low emissions at high loads and high at low loads) with local and bulk quenching being the main formation principles. Higher air-fuel ratio utilization is challenging due to concerns regarding stable ignition and combustion of the pilot fuel. The main methods for minimization of methane slip include improved process control and reduction of the "dead space" (i.e. crevice volume) inside the combustion chamber [45, 46] and can result in methane emission reduction down to 3.0-4.0 g/kWh. With all these net GHG reduction from LPDF engines is possible and will be in the range of 12-18 % when compared to operation on conventional diesel fuel.

LPLSDF concept's main feature is operation on low-pressure gas, thus avoiding need for dedicated high-pressure gas system. It has been recently developed by Winterthur Gas and Diesel (Win-GD) and meets almost the same challenges as LPDF engine concept, including homogeneous air-fuel mixture, proper air-fuel mixture control and stable pilot fuel ignition and combustion. Special considerations have to be made regarding the gas admission system with gas injectors in the cylinder liner and injection after the closing of the exhaust valve to avoid the gas being blown through [33]. Two or more injectors are located symmetrically in the lower part of the cylinder liner providing gas injected at around 10-12 bar [38].

Pre-chamber is required for the considered LPLSDF concept with minimum two equal volume pre-chambers located in the periphery of the main combustion chamber. Pilot fuel injection will occur through these pre-chambers and will be a supplement to the main fuel injection system [38]. Typically a common rail system will supply the amount of pilot fuel in the range of 1 % of full load fuel consumption. This allows the concept to meet IMO Tier III requirements without any additional aftertreatment system at the same time providing somewhat lower methane emissions than LPDF engines [33].

The concept has certain challenges with regard to uncontrolled combustion (pre-ignition and knocking) especially in the case of poor gas quality with low MN [47]. The load pick up is rather slow due to required careful control to avoid knocking. Power derating is the most practical approach dealing with low MN fuels and is normally a preferred solution in shipping.

2.2.3 High Pressure Dual Fuel engines

High Pressure Dual Fuel engines are based on Diesel cycle concept, where only air is compressed and pilot fuel oil injection is used to secure ignition of main gas injection near the top dead centre (similar to diesel sprays) [48, 27]. This approach has a number of advantages over other considered concepts, namely absence of methane slip as there no fuel gas in the cylinder during compression process and gas burns as being injected; flexible in regard to the main fuel quality, i.e. to methane number. Another important feature of the concept is possibility of converting existing diesel engines to gas operation at minimal cost. For successful conversion it is required to change only cylinder head, install new gas fuel supply and injection systems as well as adopt the control system for new gaseous fuel.

HPMSDF engines have been on the market for more than 20 years (consider Wärtsilä 32 GD and 46 GD engines), but mostly for offshore platforms and on-land applications [49]. The technology is still to be introduced to marine engine market. On the other hand, HPLSDF engines have already been installed in several ships and the technology is being successfully marketed by MAN Diesel & Turbo in recent years [50]. This concept is of special interest for deep sea shipping companies operating larger ships, where low-speed 2-stroke engines are of primary interest. At the same time, high pressure dual fuel technology can be successfully implemented in all types of engines: slow, medium and high speed ones.

High pressure dual fuel engines basically have similar operational characteristics as diesel engines considering the power range, fuel consumption and load pick-up. The main disadvantage that is typically pinpointed [48] is the need for high pressure gas supply system (around 300-350 bar). In case of marine application the importance of this issue is somewhat lower as fuel gas is stored on board as LNG which can be first pumped to the required pressure and only then heated to the ambient temperature. LNG is pumped to 350 bar as cold incompressible gas, which requires less work actually less than is required for conventional diesel injection systems. To bring LNG up to the ambient temperature it is required to install a simple heater, where engine cooling water can be used as a working medium, not an evaporator. At the same time, the high pressure engine gas supply system will make the entire LNG fuel system more complicated, where one special concern can be related to high pressure cryogenic pumps [33]. Piston-type high pressure cryogenic pumps is a mature technology, but are not developed for continuous operation resulting in rather short time between overhauls (2000-4000 hours). It is expected that current issue will be addressed together with expansion of the market share of high pressure dual fuel technology.

To keep NO_x emissions low it is required to reduce the amount of pilot injection as much as possible at the same providing stable ignition source. Keeping in mind that combustion temperature of gas fuel is lower than that of diesel and low NO_x tuning, it is possible to achieve fuel consumption at the same level as for diesel (distillate or residual) fuel with 30-40 % lower NO_x emissions. This means that IMO Tier III requirements can be fulfilled only with the help of additional aftertreatment technology like exhaust gas recirculation (EGR) or selective catalytic reduction (SCR) [51].

2.3 Gas engine emissions and methane slip

As it was highlighted above, the application of LNG as fuel in MDEs can result in substantial reduction of not only regulated emissions, like NO_x and SO_x, but also other still unregulated emissions, for example PM [32, 20]. Moreover, comparing to conventional distillate and residual fuels, the CO_2 emissions also can be reduced by 20-25 % depending on the engine concept [33] without any additional aftertreatment system needed. It is believed that both lower fuel C/H ratio and higher thermal efficiency at high loads contribute to this advantage.

Both LBSI and LPDF engine concepts are based on Otto cycle, hence allowing combustion of leaner homogeneous fuel-air mixtures [27]. This can result in 75-90 % reduction of produced NO_x. The LPDF engines has somewhat higher NO_x emissions than LBSI ones due to use of pilot (diesel) fuel; at the same time both the concepts meet IMO Tier III emission requirements (as well as LPLSDF engines) [33, 36]. HPLSDF engines are operated according Diesel cycle and have higher NO_x emissions than LBSI, LPDF and LPLSDF concepts, but still allow 25-30 % NO_x reduction comparing to standard diesel.

The methane and formaldehyde emissions is a serious challenge for gas engines and become of great concern as more and more gas-operated vessels been built and commissioned. Formaldehyde emissions are known to be toxic, allergenic and cancerogenic [52, 53] and should be minimized. The unburned methane or '*methane slip*' is still of the main concern because of its contribution to greenhouse gas (GHG) emissions [11, 54] and due to the fact that methane emissions at low engine loads can be very high, up to 15 % [32]. As can be seen, the economic losses for the shipowner in such cases can be also substantial, so the right choice of the gas engine concept is essential.

In fact, current emission regulations for ships state that NO_x emissions should be within Tier III limit within ECAs and within Tier II - outside ECAs respectively [8]. Simultaneously, maximum allowed sulfur content in fuel should not exceed 0.1 % in ECAs and 3.5 % - globally. These limits can be achieved with conventional distillate or even residual fuel combined with an appropriate combination of various abatement technologies like EGR and scrubbing, selective catalytic reduction, etc. [10] or using alternative fuels. Among all alternative fuels available, LNG seems to be the most feasible solution at the moment [55], not only because of the economical benefits [54], but also due to fact that gas technology is being on the market for marine application for decades as well as suggests additional operational [56, 57] and environmental benefits [10, 58, 59]. Moreover,on the way towards carbon-free fuel LNG is probably the most logical 'intermediate stop' that also allows to stay within a stricter global fuel sulfur cap (0.5 %) coming into power in 2020 [9].

Finally, it should be mentioned that justification of use of certain solution towards higher efficiency, lower emissions and costs in any application (also outside of maritime sector) requires not only the comprehensive modelling and simulation approaches [59, 54], but also the real measurement data, i.e. field data, suitable for verification of these models. The performance and emission data for ship engines is mainly available from test-bed measurements with only few, like for example [58], studies reporting real operational data. This lack of data from on-board measurements makes it difficult for researches to apply correct emission factors for the assessment of emission reduction potential of LNG as marine fuel comparing to some other solutions. On the other hand, it is also difficult to control the development of gas technology within different gas engine concepts that could help shipowners in choosing the most appropriate gas engine type as quantitative data basis is missing. The summary of main advantages and disadvantages for all existing gas engine concepts is given in Table 2.

The main focus of current article is to present the first comprehensive summary of the emission (with special emphasis on methane slip) data measured from different concepts of gas engines installed on-board. This allows comparison of concepts on the fair basis and in real operational conditions. Some data from earlier measurements is also presented providing possibility to evaluate the development of gas technology over the last decade.

3 Materials and methods

To obtain the required emission profile and performance data in real operation a measurement campaign was carried out on six sailing ships and on one test-bed engine at manufacturer premises. The measurements were carried out by SINTEF Ocean that is an accredited institute for exhaust gas measurements, so all the data was collecting according to corresponding standards as described below.

Table 2 Summary of existing gas engine technologies for marine application

Parameter	LBSI	LPDF	LPLSDF	HPMSDF	HPLSDF
Fuel delivery method	Low pressure injection before compression	Low pressure injection before compression	Low pressure injection before compression	High pressure injection during combustion	High pressure injection during combustion
Gas supply pressure, bar	4-5	4-5	10-12	>300	>300
Ignition source	Electrical spark plug	Pilot diesel fuel injection	Pilot diesel fuel injection	Pilot diesel fuel injection	Pilot diesel fuel injection
Thermal efficiency	High[a]	High at high load Poor at low load	High at high load Poor at low load	High[b]	High[b]
NO_x emissions level	Tier III	Tier III	Tier III	Tier II	Tier II
CO_2 reduction,[c] %	20-30	20-25	20-25	20-25	20-25
Sensitive to gas quality	Yes[d]	Yes[d]	Yes[d]	No	No
Methane slip	Yes[e]	Yes[e]	Yes[e]	No	No
PM reduction,[c] %	>99	95-95	95-95	30-40	N/A

[a] At high load higher than diesel counterpart
[b] Similar to diesel counterpart
[c] Compared to operation on conventional MGO fuel
[d] Require fuels with high methane number, MN>70
[e] Need to be minimized by optimal combustion chamber design and better combustion control

3.1 Measurement instruments and data acquisition system

The exhaust gas measurement system used is composed of HORIBA PG-350 and JUM 3-200 instruments with the detailed specification provided in Table 3. All the instruments were checked and calibrated according to national procedures for accredited measurement equipment prior every measurement intervention.

The layout of the typical measurement setup that was used is shown in Figure 4. The gas sample was extracted from the exhaust gas system with the help of ISO-standard sampling probe equipped with heated PM pre-filter to avoid excessive particulate loading of the measurement instruments [60]. The sample is then transported to the measurement devices with the help of heated transport lines to avoid condensation. Pressure relief column together with bypass valve were used to avoid overpressure in the sampling lines that potentially can be damaging to the gas analyzing cells. Real time emission data with 1 Hz frequency were collected from the instruments with the help of specially designed data acquisition system consisting of 8-channel analog input module Adam 4017 and interface module Adam 4520. Data has been collected on the laptop with the help of DASYLab data acquisition software and later analyzed in Microsoft Excel and MATLAB. Additionally, ambient temperature, relative humidity and ambient pressure were also measured during the measurement campaign.

3.2 Measurement procedures

All on-board measurements were carried out according to ISO 8178 [61] standards using either constant-speed E2 cycle for generator operation or E3 cycle for propeller-law-operated main engines depending on the machinery configuration. In certain

Table 3 Specification of emission measurement system

Gas component	Measurement instrument / principle	Measurement range
NO_x, ppm	Horiba PG-350 / Chemiluminescence (CLD) method	250 ppm / 500 ppm
CO, ppm	Horiba PG-350 / Non-Dispersive InfraRed (NDIR) absorption method	500 ppm
CO_2, %	Horiba PG-350 / Non-Dispersive InfraRed (NDIR) method	10 %
O_2, %	Horiba PG-350 / Paramagnetic method	25 %
THC, ppm	JUM 3-200 / Heated Flame Ionization Detection (HFID) method	1000 ppm
Methane,[a] ppm	JUM 3-200 / Heated Flame Ionization Detection (HFID) method	1000 ppm
Ambient conditions	KIMO AMI 300 / Barometric pressure (bar), relative humidity (%) and inlet air temperature (°C)	

[a] There are no measurement procedures provided by Norwegian Accreditation for methane

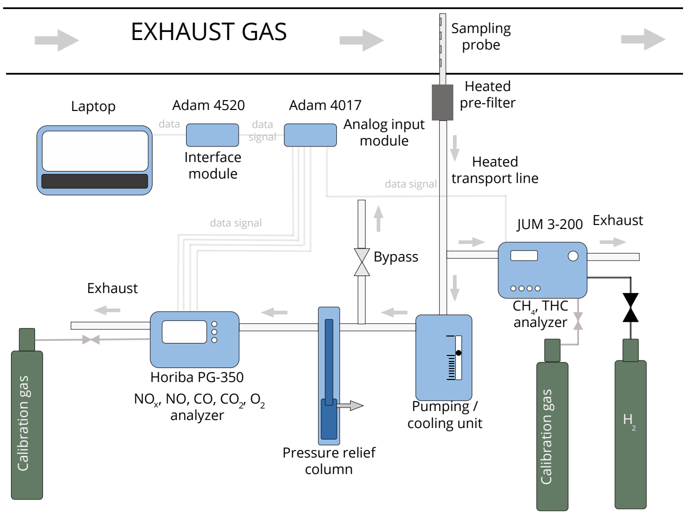

Fig. 4 Measurement setup schematics

cases the actual engine speed and load level could not meet the specified values according E3 cycle due to load variations caused by changing propeller pitch without changing the engine speed. In these cases, the load was decided by readings from the load calculator of the engine control system, and deviation in engine speed compared to standard was neglected in the calculations of specific emission factors.

As both E2 and E3 cycles are steady-state ones, for each load point a stable operating conditions were established before the measurements commenced. This step required around 5-10 minutes. After that a logging of emission data was carried out for a period of 15-20 minutes with a data sampling frequency of 1 Hz. The last 7-10 minutes of the sampling period, the JUM 3-200 hydrocarbon analyzer was switched from THC mode to CH_4 mode operation. Readings of engine operational data as engine load, engine speed, air receiver pressure and temperature, etc. were taken from the engine control system in the engine room. Average values from both emission logging and readings from ship control system were used to calculate the required emission factors.

Ambient data (ambient temperature, relative humidity and barometric pressure) were measured by a hand-held KIMO AMI 300 instrument in location close to engine inlet filter. All emission measurement instruments were calibrated prior every measurement sequence. During long continuous measurements the instruments are required to be re-calibrated after two hours of operation which was done without stopping the cycle sequence. Before every re-calibration the drifting since last calibration was calculated and written to the log to ensure the drifting value being within acceptable limits. No measurements were rejected due to drifting error of the instruments in current campaign.

The overall engine stability during the measurements normally depends on cycle-to-cycle stability of engine itself and on load variations due to the effect of propeller and other equipment. The stability was verified by calculating the standard deviation of the measurement series for THC and CH_4.

4 Results and discussion

The measurement results presented here are based on measurements performed on six ships (for one of the ships the measurements were performed for two engines) and one test-bed engine. For the test-bed engine four separate measurements were done: two by SINTEF Ocean (E2 and E3 cycles) and two in parallel with engine manufacturer. Moreover, the data from the measurements on two other ships carried out within different project were also included into the data pool. Some data was also available from the manufacturer test-bed measurements documented in technical files for the considered vessels. Overall 18 separate measurement series created a basis for current study. The data from two older engines of those 18 were not used for calculation of the desired emission factors due to the recent developments in gas technology that took place during the last 5 years.

Only LBSI and LPDF engines were considered during the measurements due to very limited number of marine vessels with other gas engine concepts employed. With further development in LPLSDF and high pressure dual fuel engines, these technologies should be also included in the scope of similar studies in the future.

To avoid unnecessary advertisement and/or possible negative effect on the reputation of any of the engine manufacturers for the engines involved in current study, no engine manufacturer details are given in the report. Each of the considered engines receives a corresponding gas technology tag LBSI or LPDF with a certain ID number, for example LBSI3 and LPDF7.

4.1 LBSI engines summary

Data from 9 single measurement series was used to calculate the desired emission factors for LBSI engines. The main emphasis is paid to CH_4 as being the main goal of the study, but the values for NO_x, CO, THC and CO_2 are also provided supplementing the results and providing additional proof for making necessary conclusions. The calculated emission factors are shown in Table 4.

Table 4 Weighted average emission factors for LBSI marine engines (built after 2010) in accordance to E2 and E3 test cycles

Data source	NO_x		CO		THC		CH_4		CO_2		Number 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 Ocean measurements[a]	7.1	1.29	10.3	1.86	27.3	4.82	25.0	4.42	2677	480.5[b]	7
Manufacturer measurements[c]	8.3	1.35	8.0	1.31	18.8	3.07	17.0	2.77	2722	444.0	2
Average (all sources)	7.3	1.30	9.8	1.74	25.4	4.43	23.2	4.05	2687	472.4	9

[a] Based on on-board and test-bed measurements
[b] High- and medium-speed engines considered together
[c] Based on test-bed data only

First of all, one can observe that there is a pretty good agreement between independent measurement data and one provided by the engine manufacturers when it comes to the regulated emissions of NO_x (by Tier II/Tier III standards [62]) and CO_2 (by Energy Efficiency Design Index (EEDI) [63]). The difference is within 10%, which is rather low considering all possible uncertainties related to the measurements and calculations. At the same time the unregulated emissions show a huge difference reaching almost 40 % for methane. Obviously there is a number of reasons for that including the absence of clear and detailed measurement standards for THC and methane, difference in engine operating conditions between laboratory and at sea, variation in fuel quality, possibilities for engine tuning in laboratory and so on.

At the same time, all LBSI engines (with the exception of LBSI1 utilizing somewhat older (prior 2010) gas engine technology) and considered in current study confirmed the compliance with strict Tier III NO_x emission standard without any aftertreatment systems. For considered medium-speed engines the Tier III limit would be around 2.5 g/kWh. The drawback of LBSI technology is clearly indicated by high emissions of unburned hydrocarbons (THC), majority of which (more than 90 %) corresponds to methane. More detailed data from the measurements is given as function of engine load in Figure 5 namely for methane slip (a) and NO_x (b). The large standard error in measured NO_x is explained by LBSI1 results clearly showing offset from the rest of the data sets.

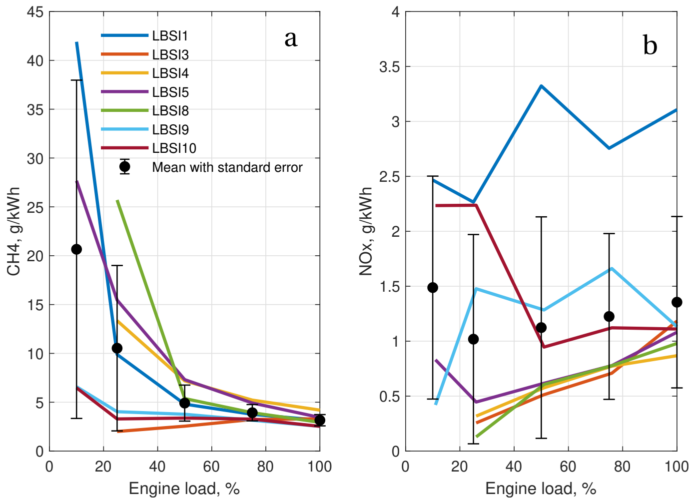

Fig. 5 Methane slip (a) and NO_x emissions (b) measured for LBSI marine engines

As can be seen NO_x emissions increase with the load, while methane emissions substantially decrease. This is quite a natural behaviour as fuel-air ratio increase with the load providing more efficient and complete combustion at medium and higher loads comparing to low load operation. Combustion at these loads is rather steady and complete, hence methane emissions are basically only due to unburned fuel escaping from the crevices volume which is also supported by the data from Figure 5 (a) indicating methane levels almost not changing at loads above 50 %. At low loads too lean operation results in unstable and incomplete combustion (even misfire) with correspondingly very high methane slip and proportionally higher fuel consumption [36]. In this situation it can be proposed to perform low-load NO_x tuning of the engines as at low loads there is still a substantial NO_x margin until Tier III limits are reached. Somewhat richer operation can help to reduce methane slip substantially at the same time fulfilling emission standard requirements.

Two older LBSI engines were also included in the measurement campaign to indicate the gas technology development over the last decade, but were not included in calculation of emission factors as are not representative for state-of-the-art LBSI gas technology. This data adds substantially to the standard error as shown in Figure 5, but is important as indicates variability in methane slip data among so-called "gas engines" as well as shows the achievements available through the recent developments in gas engine technology.

Quite an interesting observation was found studying the data from the same engine models, but installed in different vessels. As can be seen from Figure 6 an impressive agreement (considering on-board measurements) in methane slip is registered for medium and high loads, while at lower loads the deviation in data sets starts to increase rapidly. Again an unsteady nature of combustion at low loads due to too lean conditions is the main factor here. A contribution of other factors such as difference in fuel composition (methane number), engine operational state and conditions, etc. should be also taken in account.

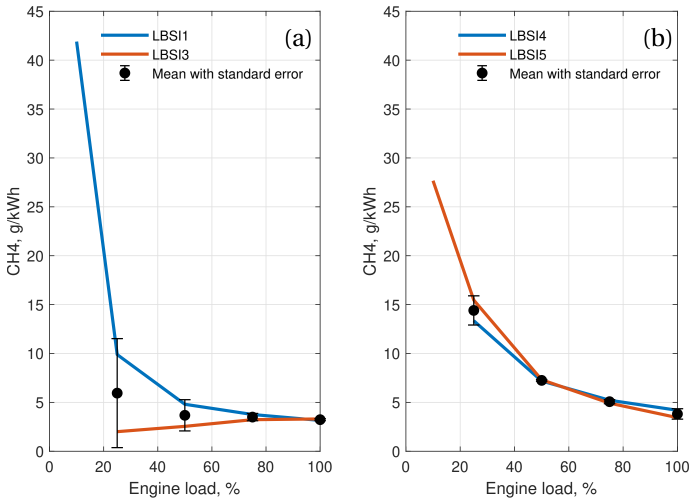

Fig. 6 Comparison of methane slip data from the same engine model installed on different ships

The measured emission data from the same engine model collected on-board was also compared to that collected in laboratory test-bed measurements as shown in Figure 7. As can be easily seen the agreement is rather good at loads > 50 %, while results are simply incomparable at 25 % load. At first look the difference in more than 400 % at 25 % load can be due to the measurement error or (and) poor calculations, but returning back to 5 one can clearly observe that the difference between different measurements at low loads can be tremendous and difference in hundreds or even thousands of percent is not an exception [32]. Again the main reason is bulk quenching due to too lean conditions [27, 64] resulting in large amount of gas (i.e. fuel) leaving the combustion chamber simply unburned.

In addition to this purely physical reason in current case there might be some other factors that are involved and probably even dominating over the specified bulk quenching phenomenon. They may include the effect of "ideal" laboratory conditions, possibility for tuning of the engine on test-bed stand, different health conditions of the engines, difficulties for fuel control system to deal with unsteady conditions at sea and others [36]. The effect of each of the specified factors is not

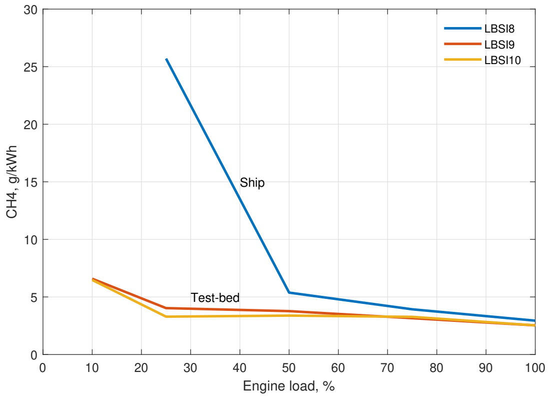

Fig. 7 Comparison of methane emissions from on-board and test-bed measurements for the same engine model

known and hardly can be evaluated, but all they should be taken into consideration.

4.2 LPDF engines summary

Data that makes basis for the assessment consists of measurements done on two ships equipped with state-of-the-art engines from different manufacturers. It is supplemented by the data provided by the engine suppliers from their own test-bed measurements. Emission factors for LPDF engines based on the available data are summarized in Table 5. As can be seen methane slip comprise 92-97 % of measured THC emissions proofing to be of the main concern in regards to unburned hydrocarbons.

Table 5 Weighted average emission factors for LPDF marine engines (built after 2013) in accordance to E2 and E3 test cycles

Data source	NO_x		CO		THC		CH_4		CO_2		Number 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 Ocean measurements[a]	13.7	2.32	9.8	1.65	33.8	5.70	31.2	5.26	2683	452.1	2
Manufacturer measurements[c]	10.3	1.74	11.5	1.95	47.0	7.92	44.8	7.56	2609	441.1	5
Average (all sources)	11.3	1.90	11.0	1.86	43.2	7.28	40.9	6.90	2630	444.2	7

[a] Based on on-board measurements
[b] Based on test-bed data

In contrast to the case of LBSI engines, there is a pronounced difference between NO_x emissions measured by independent institution and that provided by the manufacturer for LPDF engines. The difference is 25 % and might be partially explained by difference in engine operational condition in laboratory and at sea. The difficulties providing proper emission statistics based on only two measurements on-board can also have an impact here. The difference in other measured emission types is significant especially in case of THC and CH_4 emissions comprising 28 % and 32 % respectively. Nevertheless lower methane slip measured by SINTEF Ocean at the same time showing higher NO_x levels in contrast to the data from the manufacturers may indicate the laboratory tuning of engine for lower NO_x which is the only directly regulated emission type [62] and is of primary concern. In such case it might be advised to utilize the margin between actual measured NO_x level and limits specified by Tier III for reduction of excessive methane slip emissions. It is sufficient with the intervention in control settings of the engines providing changes in the valve timing and/or pilot injection timing. It should allow somewhat less lean combustion at low loads that are the primary contributor to the overall methane emissions [64]. Here it should be also pinpointed that, even despite of the use of pilot injection significantly contributing to overall NO_x emissions [41], the Tier III emission standards were fulfilled for the considered engines (with the exception of LPDF1) without use of exhaust gas treatment.

As can be seen from Figure 8 there is a rather good agreement in the measured methane slip data down to 50 % load, while for 25 % load there a substantial spread, stretching between 8.5 g/kWh and 26.5 g/kWh, that can be observed. Again a number of factors that can be used here in explaining the difference is for example difference in engine operational conditions, control settings, fuel composition, load variation, amount of pilot fuel used and so on. Basically all these factors affect the combustion stability. At low loads the combustion may be unstable due to lean operational conditions [27], hence incomplete fuel combustion and even misfire can occur leading to sudden increase in unburned fuel, i.e. in registered methane slip. In case of LPDF engine this can be normally avoided by increasing amount of pilot fuel used [65, 66], hence increasing overall combustion efficiency. This matter allows to save the fuel which in other case will pass through the combustion chamber unburned resulting in environmentally harmful emission. Only two data sets (both from on-board measurements) are available for very low load operation providing poor statistics as data shows a tremendous variation. These results at the same time highlight the complexity of combustion phenomenon at challenging low load operating conditions and possible issues that this implies for further data analysis.

As was mentioned above, only LPDF1 engine was not able to fulfill Tier III as can be seen from part (b) of Figure 8 with NO_x emission curve lying above the bulk of the data with substantial margin at medium and high loads. At the same time at low loads this engine shows one of the lowest NO_x levels among the tested engines. This engine has a potential to achieve Tier III levels by proper adjustment of the engine control and regulation system, i.e. by incorporation of so-called low NO_x tuning. It is believed that such tuning should take place after the engine has been installed and tested in a vessel, not on a test-bed during the acceptance test, as the engine real operation condition at sea cannot be completely reproduced in laboratory tests. Moreover, it is quite often that engines appear to be "overtuned" resulting in very low nitrogen oxides emission, far below the limit set by the stan-

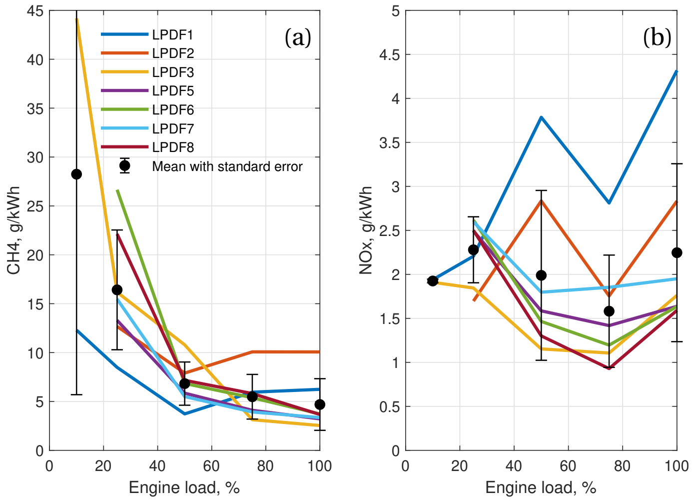

Fig. 8 Methane slip (a) and NO_x emissions (b) measured for LPDF marine engines

dards. Lower combustion temperatures in such cases results in lower NO_x emission [27], but this deteriorates the combustion quality causing reduction in fuel utilization efficiency and hence in higher emitted levels of CH_4 [33]. Such situation was also observed during the measurement campaign and is reflected in Figure 9. As one can see, the engines LPDF1 and LPDF2 clearly shows identical methane slip behaviour with nearly constant offset (around 35-55 %) over the entire measured load range highlighting the above-mentioned concern. Same offset of around 30-60%, but in opposite direction, can be also seen from corresponding NO_x emission plot shown in part (b) of the same Figure 9.

Such behaviour was not observed for every manufacturer as can be seen from Figure 10 where a pretty good agreement between on-board and test-bed emission data can be observed. In such case it is not possible to conclude on existence of any tendency in "overtuning" the engines in regard to NO_x emissions or this being only an exception for LPDF1 and LPDF3. The observed behaviour is planned be double-checked in continuation of current study as more field data has being collected.

The majority of LPDF emission data comes from test-bed measurements as seen from Table 5. This data includes an interesting set of results from the same engine model (and manufacturer correspondingly) with different power rating and engine speed as represented by Figure 11. The variation in cylinder power rating is rather significant (around 20 %) even despite rather modest variation in engine speed, which is quite natural considering the same engine model designed for a specific operational window and application. All the engines show a pretty good agreement over the entire measured load range with some higher variation observed for NO_x emissions at 75 % load. The interesting fact that summarizing information from Figures 5-10 one can notice that NO_x levels have its minimum at 75 % load for all the considered LPDF engines, with LPDF1 and LPDF2 showing a pronounced "deep valley" at this load point. Such behaviour is a direct result of

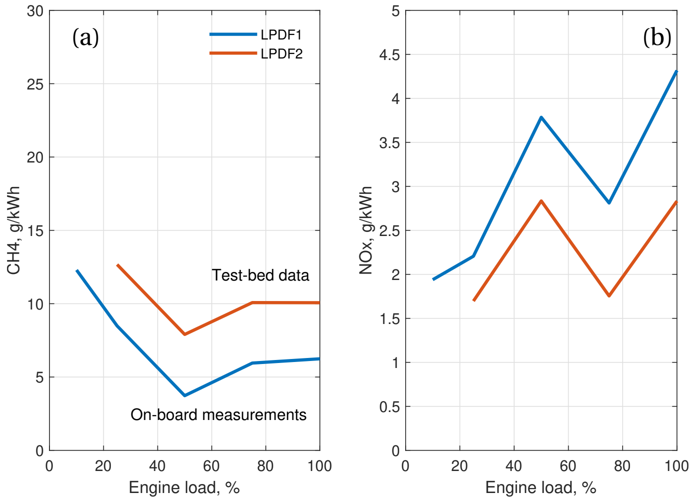

Fig. 9 Comparison of methane slip (a) and NO_x (b) emission data from on-board (ship) and test-bed measurements for the same engine model

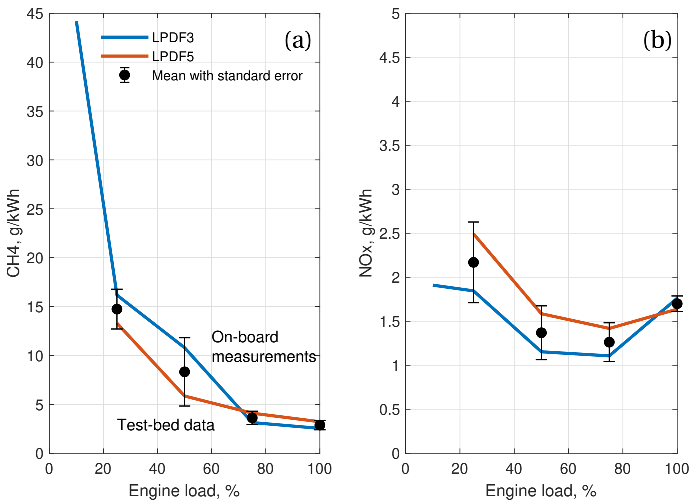

Fig. 10 Comparison of methane slip (a) and NO_x (b) emission data from on-board (ship) and test-bed measurements for the same engine model (different engine manufacturer is considered comparing to Figure 9)

the engine been "tuned" for minimum NO_x emissions exactly at 75 %. This load is typically chosen for such "tuning" as in accordance to E2 and E3 test cycles [62, 61] it has the highest weight factor (50 %) that has to be used in calculation of overall NO_x emission factor for the considered engine to get the required Tier III acceptance. Such approach is not used in on-shore transportation sector where more advanced test cycles (including transient cycles) are employed, but also utilized in some off-road applications with smaller engines where weight factor approach is still being used.

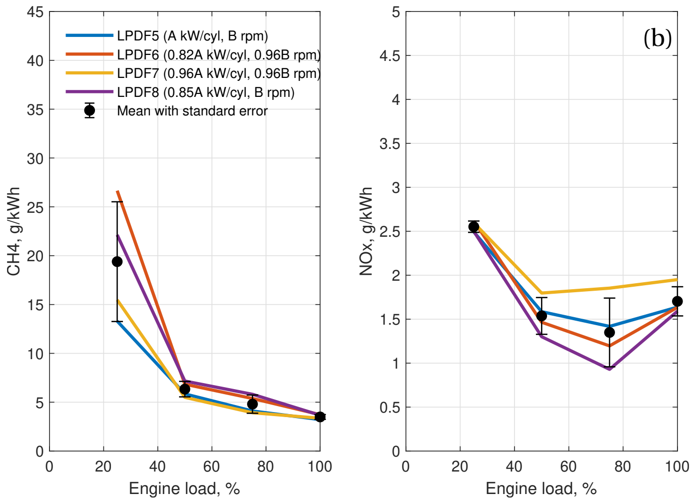

Fig. 11 Comparison of methane slip and NO_x (b) emissions from the same engine model with different power rating and engine speed

4.3 Single LBSI and LPDF engines

In addition to the summary of the analysis for considered LBSI and LPDF engine groups a more deep evaluation of a randomly chosen single engines from each concept was performed to assess the correctness of the measurements performed. The engine on-board always operates in slightly unsteady conditions (even at constant load and calm sea) [58], thus making challenging performing comprehensive emission measurement campaign on board.

Engine LBSI5 built in 2015 and installed on oil/chemical tanker with gross tonnage of 3960 t was used as an LBSI example here. It is a medium-speed engine with maximum power of 1460 kW at 900 rpm used for electricity generation, hence E2 test cycle is considered here [61]. The entire measurement log for four load conditions and measured concentrations of NO_x, CH_4, CO, CO_2 and O_2 was studied carefully. Only the area of most stable operation was considered for computation of mean values. It should be also mentioned that both methane and THC emissions were measured for each load point to find the contribution of unburned methane to overall unburned hydrocarbons.

As can be seen from emissions summary presented in Figure 12 the emissions of methane are very stable over the entire measurement period for all four load points, while other emissions show some variation that is although not statistically significant. Here it can be clearly seen oxygen content decreases over the load indicating reduction in air-fuel ratio and hence more complete and efficient combustion. This results in unburned methane (and CO) emissions substantially decreasing with load while NO_x emissions increase. Increase in registered CO_2 levels also indicates more complete combustion [27]. Somewhat higher variation in NO_x emissions at 100 % is explained by challenging conditions under constant maximum load operation at sea [67, 33] and possible switch on and off of additional power consumers on board to provide maximum load operation conditions.

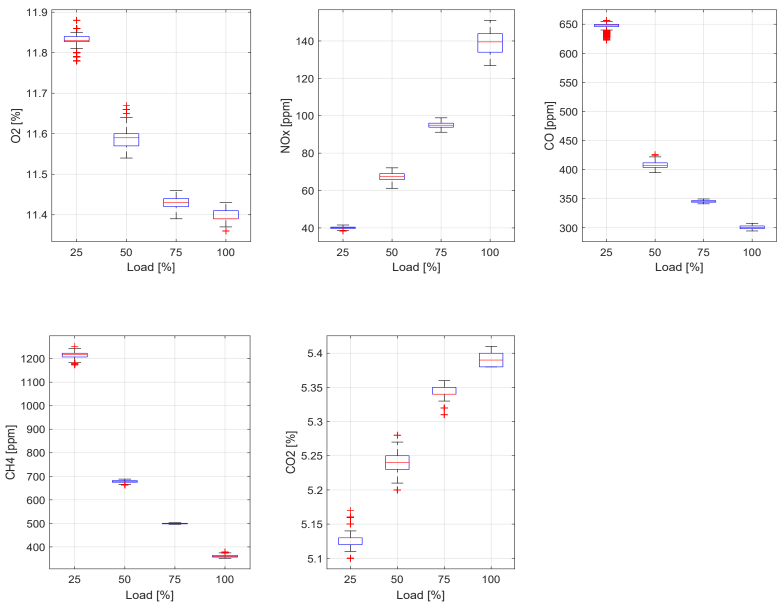

Fig. 12 Exhaust emission summary for LBSI5 engine

In its turn, among the tested LPDF engines, LPDF3 was chosen for more detailed stability analysis of measured exhaust gas emissions. It is also a medium-speed 4-stroke engine and was built in 2016 and installed on a cement carrier with gross tonnage of 4284 t. The engine's speed is 750 rpm and maximum rated power of 3000 kW. In a similar manner to LBSI5 engine, the emission summary of the presented data for LPDF3 is shown in Figure 13. As can be seen the stability of all measured emission types are very good with the only exception of NO_x emissions at higher loading conditions. At 100 % load this behaviour can be due to the difficulties performing maximum load measurements at sea as the engine normally, due to the practical reasons, cannot deliver 100 % of rated power resulting in slight load (fuel consumption) variation at condition with lowest air-fuel ratio and hence highest measured NO_x levels [33]. In its turn 75 % load conditions are very important in case of Tier III compliance verification with weight factor of 50 % and is normally chosen for fine engine tuning for lower NO_x. This can cause over-regulation of fuel gas admission valve with corresponding variation in supplied fuel quantities causing excessive variation in measured NO_x levels.

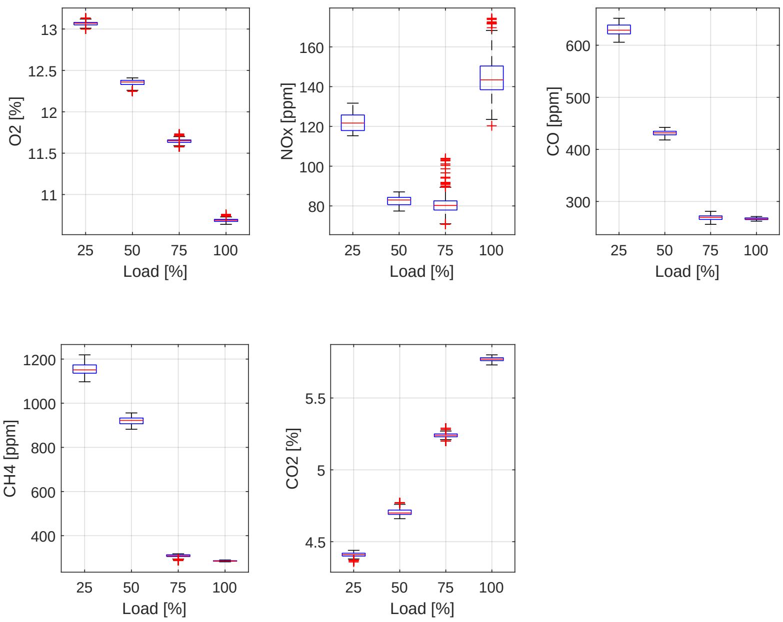

Fig. 13 Exhaust emission summary for LPDF3 engine

Comparing NO_x and CH_4 emission behaviour for different engine concepts from Figures 12 and 13 it is possible to observe another interesting fact, i.e. the contribution of pilot fuel combustion to overall NO_x levels. Both engine concepts exhibit similar behaviour (i.e. decrease) for methane slip over the entire load range, while NO_x emissions increase with the load for LBSI engine and for LPDF concept, but only in 50-100 % load range, in other words excluding low load operation. At this low loads it shows a 50 % increase in NO_x (comparing to higher load point of 50 %). Such behaviour most likely was caused by pilot injection utilizing more fuel to provide stable combustion at challenging low load conditions. This additionally highlights the significance of pilot fuel injection contributing to overall NO_x emissions [42]. For the reference, it can be specified that for LPDF3 engine the pilot fuel injection duration at 25 % load was 35 % longer than at other load conditions (as was set by the manufacturer).

The detailed statistical analysis on the lower level (i.e. for each load point) was also performed for each data set (considering both LBSI and LPDF engines) to reveal possible issues with the collected data and to identify possible outliers. This was done by performing normality check at the same time considering available engine operational data. No data points were excluded from the analysis based on such approach. The consistency in data is probably due to all measurements strictly following the same measurement protocol (standard) and proper instruments conditioning and maintenance.

4.4 Overall summary

The overall results comprising data from on-board and test-bed emission measurements performed by SINTEF Ocean, data from the manufacturers' own test-bed measurements and materials from the engine acceptance tests provided basis for current study and are represented graphically in Figure 14. The same data pool was extended by the data from the earlier SINTEF Ocean's projects/measurements both on-board and in laboratory allowing to provide realistic and reasonable specific emission factors (refer to Table 6) that are advised to be used for performing various estimations and simulations of emissions from LNG-fuelled MDEs. The authors believe that this can be also beneficial in building more precise environmental models for coastal sea areas and can be found useful in further development of environmentally-friendly gas engine technology.

Table 6 Specific emission factors proposed for marine gas engines

Gas engine type	NO_x		CO		THC		CH_4		CO_2	
	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
LBSI engines	5.1	0.9	9.8	1.7	25.4	4.4	23.2	4.1	2687[a]	472.4[a]
LPDF engines	10.4	1.9	11.0	1.9	43.2	7.3	40.9	6.9	2630	444.2
Average (all sources)	7.5	1.4	10.3	1.8	33.2	5.7	31.0	5.3	2662	460.1

[a] Values are based on data from medium- and high-speed engines

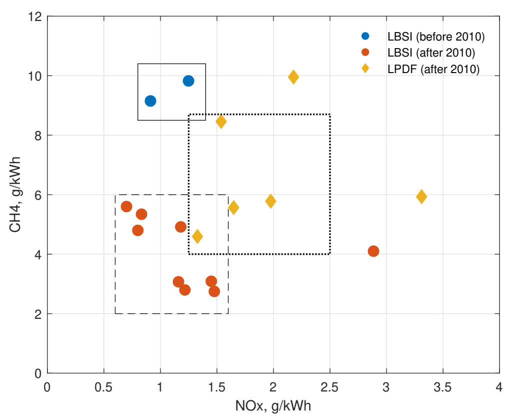

Fig. 14 Overall summary of emissions result from the measurement campaign

On Figure 14 a rather good agreement among the measurement results from LBSI engines allows to group them based on the gas technology maturity, i.e. on the production year, resulting in two distinctive groups: LBSI built before 2010 (solid line rectangular) and those built after 2010 (dashed line rectangular). A rather clear reduction in the emitted methane slip can be observed at the same time keeping NO_x emissions at the same low level. The development in lean-burn gas engine technology (valid commonly for both LBSI and LPDF engines), namely improvements in combustion chamber design (shape optimization and crevice volume reduction), use of variable valve timing and Miller cycle, better throttle valve and gas admission valve control and others [36], can be the main reasons for such "breakthrough". The methane slip reduction associated with the improvements implemented in commercially-available marine gas engines is summarized in Figure 15 constituting 52 % for LBSI engines and 56 % for LPDF engines. The data from some earlier projects [32] were used to estimate the effect of LPDF engines development as no engines of this concept built before 2010 were considered during current study.

It can be also noticed that LPDF engines in general indicate higher levels of emitted NO_x and CH_4 likely due to complexity of the technology incorporating the homogeneous combustion of main gas fuel in Otto cycle with application of diffusion flame from the liquid pilot fuel injection. The precise control is very challenging in such cases as pilot fuel amount should be minimized (down to 1 % of the total supplied chemical energy) for lower NO_x production at the same time having capability to provide almost 100 % power in situations when main gaseous fuel is not available [33]. This also can be one of the reasons explaining somewhat higher variability of LPDF emission results.

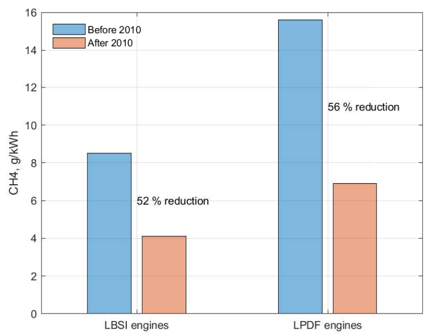

Fig. 15 Emission reduction due to recent development in marine gas engines (2010-2017). Values are weighted average based on E2 and E3 test cycles

5 Conclusions

Methane emissions or, in other words, methane slip do not receive sufficient attention from the environmental researchers and marine gas engine manufacturers most likely because of the absence of direct regulatory requirements and not very wide acceptance of LNG as marine fuel. At the same time the harmful nature of CH_4 both for humans and environment is known for decades and need for lower emitted levels of methane was indicated in various research studies [11, 21]. Such regulatory requirements exist for different industries including transportation. It is believed that international shipping should not be an exception here, especially considering constantly increasing number of vessels utilizing LNG as main fuel. At the same time there are some practical difficulties not allowing to make any final regulatory decisions here such as immaturity of marine gas technology with different concepts available, insufficient amount of available emission data of good quality (especially field data) to set realistic limits, difficult structure of IMO regarding decision making, absence of clear and precise measurement standards and procedures and so on.

Current study is aimed to help in fulfilling the gaps that exist in understanding the methane slip phenomenon providing high-quality measurement data from on-board measurements from both LBSI and LPDF engine concepts. This two gas engine groups combined comprise the majority of all operated marine engines as well as dominating option when it comes to the ordered vessels. The study also provides an updated specific emission factors (separately for LBSI and LPDF engine groups), based on on-board emission measurements, that can be used for more realistic exhaust emission estimations not only by environmental researchers, but also by ship operators/owners when considering different propulsion options for new-build vessels.

It can be summarized based on the performed measurements that there is a significant "breakthrough" in gas engine technology achieved during the last years (2010-2017) with methane emissions reduced by more than 50 % for both LBSI and LPDF concepts at the same time keeping same low levels of emitted NO_x. Due to presence of pilot fuel and complexity of its control [65, 66] (especially at low loads) the LPDF engines show somewhat higher emissions with correspondingly higher variation than LBSI engines. Despite that this engine group is rather popular among the LNG-operated ships due to its option of utilizing diesel fuel in addition to main gas fuel. Moreover, both LBSI and LPDF marine gas engine designs show to fulfill strict Tier III NO_x requirements without application of any aftertreatment systems.

It was also shown that it is quite common among the manufacturers of marine gas engines to perform low NO_x tuning (including injection and valve timing, etc.) with 75 % load being especially important due to its significant weight factor as specified by Tier III E2 and E3 test cycles. It can be addressed here that such "tuning" does help to improve the performance of gas engines in terms of NO_x emissions, but in the expense of CH_4 emissions. The authors especially would like to highlight the importance of avoiding "overtuning" of the engines, i.e. providing lowest possible NO_x with very high levels of methane slip. Tier III levels can be achieved with rather low methane emissions for the considered low-pressure gas engine concepts. Moreover, it is essential to perform the final adjustments of the gas engine control and regulation systems at sea when engine experiences real operational conditions, despite this being a rather challenging work. Finally it should be noticed that weight factors that are specified for each load point in E2 and E3 test cycles cannot represent well the real operational situation of every vessel. For example, large crude oil carrier, passenger ferry and platform supply vessel have very different operational profiles, so it is not correct to utilize same weight factors for them as they spend different amount of time at different loads.

The future work is also planned to improve current study by supplementing it with the real operational data from other gas engine concepts as they are entering maritime market. LPLSDF and high-pressure gas engines has been already tested on ships by still are rather seldom considering immaturity of corresponding gas technologies. It is also important to keep on updating the specific emission factors presented in the study as the rapid development in gas engine is not planning to slow down and it would be beneficial to follow up this development.

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References

1. UNCTAD, Review of maritime transport 2017, Technical Report, Geneva, 2017. URL: http://unctad.org/en/pages/PublicationWebflyer.aspx?publicationid=1890.
2. J. Rogelj, M. den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, M. Meinshausen, Paris Agreement climate proposals need a boost to keep warming well below 2 ÂřC, Nature 534 (2016) 631–639. URL: http://www.nature.com/articles/nature18307. doi:10.1038/nature18307.
3. E. Fridell, E. Steen, K. Peterson, Primary particles in ship emissions, Atmospheric Environment 42 (2008) 1160–1168. URL: http://linkinghub.elsevier.com/retrieve/pii/S1352231007009648. doi:10.1016/j.atmosenv.2007.10.042.
4. V. Matthias, I. Bewersdorff, A. Aulinger, M. Quante, The contribution of ship emissions to air pollution in the North Sea regions, Environmental Pollution 158 (2010) 2241–2250. URL: http://linkinghub.elsevier.com/retrieve/pii/S0269749110000746. doi:10.1016/j.envpol.2010.02.013.
5. J. Tao, L. Zhang, J. Cao, L. Zhong, D. Chen, Y. Yang, D. Chen, L. Chen, Z. Zhang, Y. Wu, Y. Xia, S. Ye, R. Zhang, Source apportionment of PM 2.5 at urban and suburban areas of the Pearl River Delta region, south China - With emphasis on ship emissions, Science of The Total Environment 574 (2017) 1559–1570. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969716318770. doi:10.1016/j.scitotenv.2016.08.175.
6. J. J. Corbett, J. J. Winebrake, E. H. Green, P. Kasibhatla, V. Eyring, A. Lauer, Mortality from Ship Emissions: A Global Assessment, Environmental Science

& Technology 41 (2007) 8512–8518. URL: http://pubs.acs.org/doi/abs/10.1021/es071686z. doi:10.1021/es071686z.
7. P. S. Yau, S. C. Lee, Y. Cheng, Y. Huang, S. C. Lai, X. H. Xu, Contribution of ship emissions to the fine particulate in the community near an international port in Hong Kong, Atmospheric Research 124 (2013) 61–72.
8. I. M. Organization, MARPOL Annex VI and NTC 2008: With Guidelines for Implementation, International Maritime Organization, 2013.
9. K. Cullinane, R. Bergqvist, Emission control areas and their impact on maritime transport, Transportation Research Part D: Transport and Environment 28 (2014) 1–5. URL: http://linkinghub.elsevier.com/retrieve/pii/S136192091300148X. doi:10.1016/j.trd.2013.12.004.
10. S. Brynolf, M. Magnusson, E. Fridell, K. Andersson, Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels, Transportation Research Part D: Transport and Environment 28 (2014) 6–18. URL: http://linkinghub.elsevier.com/retrieve/pii/S1361920913001454. doi:10.1016/j.trd.2013.12.001.
11. S. Brynolf, E. Fridell, K. Andersson, Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol, Journal of Cleaner Production 74 (2014) 86–95. URL: http://linkinghub.elsevier.com/retrieve/pii/S0959652614002832. doi:10.1016/j.jclepro.2014.03.052.
12. C. Deniz, B. Zincir, Environmental and economical assessment of alternative marine fuels, Journal of Cleaner Production 113 (2016) 438–449. URL: http://linkinghub.elsevier.com/retrieve/pii/S0959652615018119. doi:10.1016/j.jclepro.2015.11.089.
13. K. Andersson, Energy efficiency of alternative marine fuels from a life cycle perspective (2017).
14. V. Aesoy, P. Magne Einang, D. Stenersen, E. Hennie, I. Valberg, LNG-Fuelled Engines and Fuel Systems for Medium-Speed Engines in Maritime Applications, Technical Report, SAE Technical Paper, 2011. URL: http://papers.sae.org/2011-01-1998/. doi:10.4271/2011-01-1998.
15. S. Murakami, T. Baufeld, Current status and future strategies of gas engine development, in: CIMAC Congress, Shanghai, May, 2013, pp. 13–16.
16. T. Lauer, Impact of the fuel gas quality on the efficiency of a large gas engine, in: 28th CIMAC World Congress, 2016.
17. P. E. C. IAPH, Existing fleet and current orderbooks, 2018. URL: http://www.lngbunkering.org/lng/vessels/existing-fleet-orderbooks.
18. G. I. E. (GIE), LNG map 2018, 2017. URL: https://www.gie.eu/download/maps/2017/GIE{_}LNG{_}2018{_}A0{_}1189x841{_}FULL.pdf.
19. M. Calderón, D. Illing, J. Veiga, Facilities for Bunkering of Liquefied Natural Gas in Ports, Transportation Research Procedia 14 (2016) 2431–2440. URL: http://linkinghub.elsevier.com/retrieve/pii/S2352146516302940. doi:10.1016/j.trpro.2016.05.288.
20. F. Burel, R. Taccani, N. Zuliani, Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion, Energy 57 (2013) 412–420. URL: http://linkinghub.elsevier.com/retrieve/pii/

S0360544213003861. doi:10.1016/j.energy.2013.05.002.

21. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley, Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1535 pp, 2013.
22. A. Demirbas, Methane Gas Hydrate, Green Energy and Technology, Springer London, London, 2010. URL: http://link.springer.com/10.1007/978-1-84882-872-8. doi:10.1007/978-1-84882-872-8.
23. M. D. Feist, M. Landau, E. Harte, The effect of fuel composition on performance and emissions of a variety of natural gas engines, SAE International Journal of Fuels and Lubricants 3 (2010) 100–117. URL: https://www.jstor.org/stable/26272923.
24. R. A. B. Semin, A technical review of compressed natural gas as an alternative fuel for internal combustion engines, Am. J. Eng. Appl. Sci 1 (2008) 302–311.
25. L. Wei, P. Geng, A review on natural gas/diesel dual fuel combustion, emissions and performance, Fuel Processing Technology 142 (2016) 264–278. URL: http://linkinghub.elsevier.com/retrieve/pii/S0378382015301715. doi:10.1016/j.fuproc.2015.09.018.
26. H. M. Cho, B.-Q. He, Spark ignition natural gas enginesâĂŤA review, Energy Conversion and Management 48 (2007) 608–618. URL: http://linkinghub.elsevier.com/retrieve/pii/S0196890406001919. doi:10.1016/j.enconman.2006.05.023.
27. J. B. Heywood, Internal combustion engines fundamentals, 2nd ed., 2nd. ed., McGraw Hill Education, 2018.
28. E. Bourbon, Clean Cities Alternative Fuel Price Report, July 2015, 2015.
29. B. Dudley, BP statistical review of world energy 2016, 2015.
30. M. S. Eide, Ø. Endresen, Assessment of measures to reduce future CO2 emissions from shipping, Position Paper 5 (2010).
31. B. Curt, Others, Marine transportation of LNG, in: Intertanko Safety, Technical and Environmental Committee (ISTEC) Meeting, Dubai. Google Scholar, 2004.
32. J. B. Nielsen, D. Stenersen, Emission factors for CH4, NOX, particulates and black carbon for domestic shipping in Norway, revision 1, Klima og forurensningsdirektoratet: Marintek (2010).
33. D. Stenersen, O. Thonstad, GHG and NOx emissions from gas fuelled engines, Technical Report, 2017.
34. J. Hiltner, A. Loetz, S. Fiveland, Unburned Hydrocarbon Emissions from Lean Burn Natural Gas Engines–Sources and Solutions, in: 28th CIMAC World Congress, 2016.
35. C. Disch, P. Huegel, S. Busch, H. Kubach, U. Spicher, J. Pfeil, B. Dirumdam, U. Waldenmaier, High-speed flame chemiluminescence investigations of prechamber jets in a lean mixture large-bore natural gas engine, in: CIMAC Congress, Shanghai, China, 2013.
36. V. Krivopolianskii, I. Valberg, D. Stenersen, S. Ushakov, V. Æsøy, Control of the combustion process and emission formation in marine gas engines, Journal of Marine Science and Technology (2018) 1–19. URL: http://link.springer.com/10.1007/s00773-018-0556-0. doi:10.1007/s00773-018-0556-0.

37. Y. Lee, H. Park, K. Kim, J. Son, C. Jung, Newly updated combustion system for HIMSEN gas engine H35/40G, in: CIMAC congress, Shanghai, 2013.
38. M. Ott, I. Nylund, R. Alder, T. Hirose, Y. Umemoto, T. Yamada, The 2-stroke low-pressure dual-fuel technology: from concept to reality, in: 28th CIMAC World Congress on Combustion Engine, 2016.
39. C. Mathey, Valve control management–the possibility of improving gas engine performance, in: 27th CIMAC world congress, Shanghai, People's Republic of China, 2013, pp. 13–17.
40. H. Miyai, K. Iwaya, A. Kikusato, J. Kusaka, Y. Daisho, H. Nakashima, Y. Kawaguchi, D. Mizuguchi, H. Hasegawa, Numerical Optimization of Parameters to Improve Thermal Efficiency of a Spark-Ignited Natural Gas Engine, Technical Report, SAE Technical Paper, 2015. URL: `http://papers.sae.org/2015-01-1884/`. doi:10.4271/2015-01-1884.
41. G. A. Karim, Dual-fuel diesel engines, CRC Press, 2015.
42. C. Kiesling, C. Redtenbacher, M. Kirsten, A. Wimmer, D. Imhof, I. Berger, J. M. Garc\'\ia-Oliver, Detailed Assessment of an Advanced Wide Range Diesel Injector for Dual Fuel Operation of Large Engines, in: 28th CIMAC World Congress 2016, 2016.
43. C. Redtenbacher, C. Kiesling, M. Malin, A. Wimmer, J. V. Pastor, M. Pinotti, Potential and Limitations of Dual Fuel Operation of High Speed Large Engines, Journal of Energy Resources Technology 140 (2017) 032205. URL: `http://energyresources.asmedigitalcollection.asme.org/article.aspx?doi=10.1115/1.4038464`. doi:10.1115/1.4038464.
44. K. Kawase, A. Okada, T. Yamada, Development of the new DAIHATSU 2MW class dual-fuel engine for marine use, in: CIMAC congress, Helsinki Google Scholar, 2016.
45. D. T. Hountalas, D. A. Kouremenos, K. B. Binder, V. Schwarz, G. C. Mavropoulos, Effect of Injection Pressure on the Performance and Exhaust Emissions of a Heavy Duty DI Diesel Engine, Technical Report, SAE Technical Paper, 2003. URL: `http://papers.sae.org/2003-01-0340/`. doi:10.4271/2003-01-0340.
46. L. Yu, E. Song, L. Yang, Research on the influence of diesel injection law to combustion process of micro ignition dual fuel engine, in: CIMAC congress, Helsinki Google Scholar, 2016.
47. H. Schlick, Potentials and challenges of gas and dual-fuel engines for marine applications, Tth CIMAC CASCADES, Busan (2014).
48. D. Strödecke, Two-stroke Dual-fuel Technology Evaluation, MTZ industrial 6 (2016) 38–45.
49. T. Jalovaara, Reliability analysis of a gas-diesel engine's fuel injection system, Käyttövarmuuden ja elinjaksotuoton hallinta (1998) 95.
50. L. Juliussen, S. Mayer, M. Kryger, The MAN ME-GI engine: From initial system considerations to implementation and performance optimization, in: CIMAC Congress, Shanghai, China, May, 2013, pp. 13–16.
51. M. P. Pedersen, Two-stroke engine emission reduction technology, in: CIMAC Congress 2010 Bergen, 2010.
52. D. J. Brusick, Genetic and transforming activity of formaldehyde, 1983.

53. C. Gong, W. Huang, J. Liu, F. Wei, J. Yu, X. Si, F. Liu, Y. Li, Detection and analysis of formaldehyde and unburned methanol emissions from a direct-injection spark-ignition methanol engine, Fuel 221 (2018) 188–195. URL: https://linkinghub.elsevier.com/retrieve/pii/S0016236118302989. doi:10.1016/j.fuel.2018.02.115.
54. O. Schinas, M. Butler, Feasibility and commercial considerations of LNG-fueled ships, Ocean Engineering 122 (2016) 84–96. URL: http://linkinghub.elsevier.com/retrieve/pii/S0029801816300944. doi:10.1016/j.oceaneng.2016.04.031.
55. E. A. Bouman, E. Lindstad, A. I. Rialland, A. H. Strømman, State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping âĂŞ A review, Transportation Research Part D: Transport and Environment 52 (2017) 408–421. URL: http://linkinghub.elsevier.com/retrieve/pii/S1361920916307015. doi:10.1016/j.trd.2017.03.022.
56. A. M. Brownstein, Renewable motor fuels: the past, the present and the uncertain future, Butterworth-Heinemann, 2014.
57. A. Hegab, A. La Rocca, P. Shayler, Towards keeping diesel fuel supply and demand in balance: Dual-fuelling of diesel engines with natural gas, Renewable and Sustainable Energy Reviews 70 (2017) 666–697. URL: http://linkinghub.elsevier.com/retrieve/pii/S1364032116310310. doi:10.1016/j.rser.2016.11.249.
58. M. Anderson, K. Salo, E. Fridell, Particle- and Gaseous Emissions from an LNG Powered Ship, Environmental Science & Technology 49 (2015) 12568–12575. URL: http://pubs.acs.org/doi/10.1021/acs.est.5b02678. doi:10.1021/acs.est.5b02678.
59. H. Thomson, J. J. Corbett, J. J. Winebrake, Natural gas as a marine fuel, Energy Policy 87 (2015) 153–167. URL: http://linkinghub.elsevier.com/retrieve/pii/S0301421515300665. doi:10.1016/j.enpol.2015.08.027.
60. S. Ushakov, H. Valland, V. Æsøy, Combustion and emissions characteristics of fish oil fuel in a heavy-duty diesel engine, Energy Conversion and Management 65 (2013) 228–238. URL: http://linkinghub.elsevier.com/retrieve/pii/S0196890412003251. doi:10.1016/j.enconman.2012.08.009.
61. I. S. O. (ISO), ISO 8178-1:2006. Reciprocating internal combustion engines. Exhaust emission measurement. Test-bed measurement of gaseous and particulate exhaust emissions (2006).
62. I. M. O. (IMO), Annex VI of MARPOL 73/78, Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code, 2005.
63. M. A. N. Diesel, E. Turbo, Energy Efficiency Design Index, 2015.
64. R. Hutter, J. Ritzmann, P. Elbert, C. Onder, Low-Load Limit in a Diesel-Ignited Gas Engine, Energies 10 (2017) 1450.
65. G. A. Karim, K. S. Burn, The combustion of gaseous fuels in a dual fuel engine of the compression ignition type with particular reference to cold intake temperature conditions, Technical Report, SAE Technical Paper, 1980.

66. T. Tagai, S. Gato, T. Mimura, T. Kurai, Development of dual fuel engine 28AHX-DF capable of FPP direct drive, in: 28 th CIMAC Congress Helsinki, 2016.
67. S. Ushakov, H. Valland, J. B. Nielsen, E. Hennie, Particulate emission characteristics from medium-speed marine diesel engines, in: PACIFIC 2012 International Maritime Conference, 2012.