CHALMERS

Methane slip prevention in the combustion chamber

Finding the biggest methane slip problems for 4-stroke dual fuel marine engines

Bachelor thesis for Marine Engineering Program

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PREFACE

This is a bachelor thesis, regarding the marine merchant sector. The bachelor thesis is a mandatory part of the 4-year marine engineer program at Chalmers university of technology. A lot of companies owning ships operating in the close-by bays and oceans of the university located in Gothenburg Sweden, are ordering more and more ships with LNG as fuel. The same area is also an emission control area (ECA), where marine pollution is often talked about and evaluated. LNG is an upcoming and becoming a more common fuel here, and the new emissions connected to it is also an important subject in the change. Since the marine engineer study is partly focused on engine design and operating conditions, this thesis is focused on that as well, and not so much about logistics and economical aspects. This thesis is written during the peak of the global covid-19 outbreak, which has been a weighing factor in the choice of method for this study.

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SAMMANDRAG

LNG är ett alternativ till de konventionella marina bränslena. Det består till huvuddelen av metan, som har ett betydligt högre" global warming potential" (GWP) ekvivalent än koldioxid. GWP20 är 86 och GWP100 är 28 enligt (IMO, 2020). På grund av de lägre NOx, svavel, och partikelutsläppen, så ses LNG som ett renare bränsle. Men om metanutsläpp sker, så är det tydligt att påverkan på den globala uppvärmningen kommer att öka. Metanutsläpp sker och det är oreglerat, men arbete görs för att minska metanutsläppen. Den här tesen handlar om vad som kan göras inom interna förbränningsmotorer som släpper ut metan p.g.a. ofullständig förbränning, även känt som metan-slip. I resultatet syns det vad som orsakar metan-slip från det vanligaste motor konceptet, "4-stroke medium speed low pressure dual fuel engine".

Den största utmaningen med att minska metan-slippet sker under låg last. Och den största källan under låg last är överlägset "quenching", slocknande av flamman under förbränning. Genom att granska litteratur har det visat sig att det finns fortfarande mycket möjlighet till förbättring. Genom att reducera skrevor, optimering av kolvgeometrin, timing av ventiler och genom att hitta lösningar till att reducera luft- och bränslerationen under låg last.

Nyckelord: Methane-slip, Marine engines, LPDF, crevices, combustion chamber, quenching. Methane emission, Gas engine.

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ABSTRACT

LNG is an alternative to conventional marine engine fuels. It consists mainly of methane which has a significantly higher global warming potential (GWP) equivalent than carbon dioxide. GWP20 is 86 according to (IMO, 2020). Due to the lower carbon dioxide, NOx, sulphur, and particulate matter (PM) emissions, it is seen as a cleaner fuel. But if methane emissions occur the global warming impact will rise. Methane emissions do occur and are unregulated. But work is done to decrease it. This thesis is regarding what can be done regarding internal combustion engines releasing methane due to incomplete combustion, also known as methane slip. In the results it is shown what is causing the methane slip from the most common engine concept 4-stroke low pressure dual fuel engines.

The major challenge in reducing methane slip is during low engine load and the major contributor during low load is by far quenching in the combustion. By reviewing literature, it has been shown that there are still possibilities for improvement in the combustion chamber, by reducing crevices, optimizing the piston geometry, timing the valve operation and by finding solutions to reduce the air fuel ratio during low load.

Keywords: Methane-slip, Marine engines, LPDF, crevices, combustion chamber, quenching. Methane emission, Gas engine.

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ACRONYMS AND TERMINOLOGY

ATDC	After Top Dead Centre
BDC	Bottom Dead Centre
BTDC	Before Top Dead Centre
CA	Crank-angle
DNV-GL	Det Norske Veritas-Germanischer Lloyd
DSO	Diesel Spray Oriented
ECA	Emission Control Area
GWP	Global Warming Potential
HPDF	High Pressure Dual Fuel
IMEP	Indicated Mean Effective Pressure
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization of Standardization
LBSI	Lean Brun Spark Ignited
LNG	Liquified Natural Gas
LPDF	Low Pressure Dual Fuel
MOC	Methane Oxidation Catalyst
NECA	Nitrogen Emission Control Area
OPD	Original Piston Design
TDC	Top Dead Centre
UN SDG	United Nations Sustainable Development Goals
VVT	Variable Valve Timing
WMS	Wavelength Modulation Spectroscopy

1. INTRODUCTION

Liquefied natural gas (LNG) as a fuel in marine application has become very popular in recent years. Partly it's because LNG as a fuel has many benefits compared to conventional oil-based fuels such as heavy fuel oil, marine diesel oil and marine gas oil emission wise (DNV-GL, 2015). It is a cleaner option, and in many cases, it does not need any aftertreatment systems. It has a good potential for complying with future IMO emission regulations and is also possible to mix with biogas for even further environmentally friendly use.
LNG has a significant reduction in air pollution such as sulphur oxide (SOx), Nitrogen oxides (NOx), carbon dioxide (CO2) and particle matter (PM) (Stenersen & Thonstad, 2017). Using LNG as fuel can reduce the NOx emissions up to 90% and carbon dioxide emission up to 25% and can comply with current IMO Tier 3 NOx regulations in NOx emission regulated areas (NECA), depending on which engine concept used (Ushakov et al., 2019). High pressure dual fuel (HPDF) engines do not comply with NECA emission levels set by IMO tier 3.

Methane emissions from vessels are not included in any regulation yet, and methane slip has been recognized as one of the major challenges for lowering the global warming emissions from LNG driven ships. An aftertreatment system for methane could be a solution but has not been tested in marine operation yet (Raj, 2016). The challenge is related to low temperature in the exhaust gas for an efficient catalytic reduction and from sulphur deactivation of the methane oxidation catalyst (MOC).

The first challenge to manage the methane emissions is by choosing the appropriate fuel system and engine arrangement. Since the different engine types pollute different amounts of methane and for different reasons, lowering the methane emission from each engine type is also made differently. There are mainly three different internal combustion engine types used for natural gas (NG)-combustion with marine application today (Ushakov et al., 2019). Lean burn spark ignited engines (LBSI), low pressure dual fuel engines (LPDF) and high-pressure dual fuel engines (HPDF). The latter is recognised to have the lowest methane emission but struggles to comply with IMO Tier 3 NO_x regulations (Ushakov et al., 2019), this option is the least common among the three. The most common option right now is LPDF due to the convenience of being able to switch from NG-combustion to using only the pilot fuel injection as fuel in case there is shortage or lack of LNG suppliance. This thesis will further describe the technical challenges and possible future solutions for reducing the methane emissions onboard while at the same time complying with IMO tier 3 NOx regulations.

1.1 Background

Methane emissions are not yet regulated, but there is extensive research and data that demonstrates that methane slip exists, as shown in the results of this report. The GWP is high for methane and there is a possibility that future regulations will form. GWP is a tool used for comparing global warming potential between different gasses, using CO2 as an equivalent. GWP is measured during a 20-year time span and a 100-year span because gasses have different lifetimes in the atmosphere. Since many consider LNG to be a future fuel. According to UNs SDG nr 13 there is a goal to lower global warming emissions by 7.6% each year starting in 2020 until 2030 (UN, 2020). Since it is also described that the goal has not been met the first year, regulating methane slip from the marine shipping sector might soon be looked upon by regulators and lawmakers.

1.2 Aim of the study

LNG as a fuel is considered clean and is chosen as an environmentally better option than other conventional marine fuels. Norway is even using the NOx fund to support the choice of LNG marine engines (DNV-GL, 2015). But there is an issue of unburned methane from these engines. In recent years there have been a lot of questions about methane slip and its environmental impact. Because methane emission into the atmosphere is a strong greenhouse gas significantly more potent than CO_2 (ICCT, 2020). There are several actions to be made to lower the environmental effects of using LNG, such as securing the supply chain from leakage, evaluating the well-to-tank emissions etc. But what can be done by the shipping industry is to start with reducing the methane slip from marine combustion engines.

Methane emissions have increased by 151-155% over the period 2012 to 2018 (IMO, 2020). The LPDF four stroke engine has the majority of the market share for marine engines, 40% in 2017 according to (IMO, 2020). The LPDF four stroke engine also has the highest methane slip among the gas engine concepts available (Ushakov et al., 2019). The CO_2 reduction from using 4-stroke LPDF engines is therefore cancelled out by the methane slip. But whether the total GWP from choosing LPDF over conventional diesel engines is lowered or heightened, depend highly on which time horizon is being used for the comparison. The GWP over a 20-year timespan for methane is 86 $gCO_2eq./gCH_4$, and 28 $gCO_2eq./gCH_4$ over a 100-year timespan (IMO, 2020). Because the GWP for methane is significantly higher during a 20-year timespan, the calculated total GWP from LPDF engines will be significantly higher when using a 20-year timespan rather than a 100-year timespan. Since the UNs SDGs is set to 2030, the authors have chosen to focus on measurements and comparisons made with a 20-year GWP rather than a 100-year GWP.

The aim of this study is to examine methane slip from LPDF 4 stroke engine to find the most suitable method to reduce methane air emissions in a combustion and design perspective. And pinpoint the biggest challenges regarding the engine design that needs further research.

1.3 Research questions

- Which are the most important challenges in the engine design that causes or can reduce methane slip from four stroke LPDF engines?
- How to reduce the methane slip by internal engine design for four-stroke LPDF engines?

1.4 Delimitations

Methane slip from other combustion than commercial shipping marine engines, such as steam boilers, incinerators, and gas turbines have not been further investigated. As well as methane leakage from bunker storage, cargo, and piping.

The study is also limited from comparing difference in LNG quality, because the studies chosen in the results may have been conducted and investigated with different LNG sources. Therefore, an assumption has been made that all engines in the results have been investigated during use of fuel with a compatible methane number for that specific engine. LNG extracted from different reservoirs contain different amounts of methane and other gases. LNG is then sold with a calculated methane number to explain the fuel characteristics for the buyers. The methane number is calculated by the methane content and the total heating value of the mixture. The impacts of receiving variable LNG quality for the ships bunker is further discussed in chapter. 2.2.

This thesis briefly mentions spark ignited engines, but the results are only taken from measurements regarding LPDF medium speed 4-stroke engines. And the discussion and conclusion are only regarding LPDF, because these are the most common engines and with the biggest methane slip problems (Ushakov et al., 2019)

LNG is of main concern in this thesis, and not LBG or CNG, because LNG is the most common fuel in marine engines operating with natural gas. CNG is more common in the road transport sector because of the smaller volumes needed. LBG might be more relevant in the future, but today the main source of natural gas comes from fossil fuel oil reservoirs.

2. THEORY

2.1 Engine types

As mentioned in the introduction there are currently two engine types dominating the market, LBSI and LPDF engines, being more common than engines with high pressure fuel injection systems. The choice between these engine types, might depend on the LNG suppliance, and depending on which area the ship is going to be trafficking (DNV-GL, 2015), which engine effect is required and how the ship will operate. Load pick up and uncontrolled combustion problems are different from the two engine types. It is also important to understand the NOx regulations, especially if the ship is going to operate in an emission control area (ECA), since the engine concepts also have different NOx emissions. The different engine concepts have different advantages and disadvantages, and are available in overlapping engine effects, which makes the choice of engine more complicated (Ushakov et al., 2019).

Engine koncept	ADVANTAGES	DISADVANTAGES
LBSI	Lowest Sox, PM and NOx emissions (g/kWh) Tire 3 compliance Small size	Low total fuel efficiency High main fuel consumption(g/kWh) Sensitive to gas quality No back up fuel system
LPDF 4-STROKE	Tire 3 compliance Diesel as backup fuel system Small size	Highest Methane slip Sensitive to gas quality Poor thermal efficiency at low load Low total fuel efficiency High main fuel consumption(g/kWh),
LPDF 2-STROKE	Tire 3 compliance High total fuel efficiency Low main fuel consumption(g/kWh)	Sensitive to gas quality Poor thermal efficiency at low load Big size
HPDF	Close to no methane slip High total fuel efficiency Low main fuel consumption(g/kWh) Not sensitive to gas quality	Highest NOx emission (g/kWh) Highest PM emissions Tire 2 compliance not Tier 3

Table 1:Engine concept comparison

2.1.1 Lean burn spark ignited engine

LBSI operates in the otto-cycle with infused fuel-air mixture through the intake during the compression cycle and ignites close to TDC with a spark plug (Ushakov et al., 2019). The principle clearly follows the otto-cycle but with a higher lambda value than conventional otto-engines. The lambda value is often around 2, to reach a lower temperature during combustion to prevent high emissions of NO_x. Due to the high lambda value the spark plug cannot operate directly inside the combustion chamber, and a pre-chamber is designed together with a second injector to ignite a richer air-fuel ratio. Another advantage of using a prechamber is the achievement of a higher rate of flame propagation, which results in less unburned fuel (Stenersen & Thonstad, 2017).

2.1.2 Low pressure dual fuel engine

LPDF engines also operate in lean conditions, turbocharged. Since this engine type is self-ignited by a pilot fuel like diesel, but also has port injected gas fuel (Stenersen & Thonstad, 2017), it is a CI engine following the otto cycle. The pilot injection will improve the ignition, and it will lower the chance for misfiring and make a fast combustion inside the combustion chamber (Königsson et al., 2013). Natural gas is pre-mixed like an otto-cycle, with a lean fuel-air mixture in the intake stroke. Because the injection of natural gas is made in the intake port, and then introduced in the combustion chamber together with the intake air, the valve overlap can be a problem since it will cause unburned fuel to escape through the exhaust valve because of the turbocharged intake manifold pressure exceeds the exhaust manifold pressure.

For 4-stroke medium-speed engines the NG injection is made in the intake port, but more often for low speed 2-stroke LPDF engines, injectors are placed in the lower part of the cylinder liner. Less equipment in the combustion chamber will lower the possibilities for crevices. And the small valve overlap will not be a cause for methane slip, since there is no NG-injection in the intake port in the low speed 2-stroke LPDF engine.

The LPDF 4-stroke engine ignition principle is the same as conventional diesel four stroke engines. This means that LPDF gas engines could use diesel as a backup fuel. Two different fuel options in one engine. That is one of the main reasons why LPDF is preferred as a solution for international shipping (Ushakov et al., 2019).

The main problem still exists, there are high unburned methane emissions at low loads, and relatively low methane emission at high loads. Low thermal efficiency at low load and the thermal efficiency increasing with increased load(Ushakov et al., 2019).

2.1.3 High pressure dual fuel engine

HPDF engines are also worth mentioning even though it is not yet as big in the market yet. This engine concept is the most like the conventional diesel cycle since it does not induce any gas in the compression cycle (Stenersen & Thonstad, 2017). To be able to induce the gas together with the pilot fuel close to the TDC it requires a high-pressure gas system. The natural gas is injected with around 300 bars and ignites from the self-ignited pilot fuel.

2.2 LNG

LNG is natural gas, condensed from gas to liquid by colling it down to minus 162 degrees Celsius(McGuire & White, 2006). Natural gas reduces 600 times in volume when condensing from gas to liquid. This makes it more efficient to transport in liquid.

Methane is the main component in liquefied natural gas, but the content can vary depending on the source. The fuel has a calculated methane number that is calculated depending on the amount of methane and from which other components are present. One example is shown in (Ushakov et al., 2019) where the methane number varied from approx. 76 to 86 and the methane content between 91% and 96% between five different sources. The methane number is a measurement used for the quality of the natural gas, and it affects the combustion characteristics. In (Feist et al., 2010) testing showed that lower methane number required a lower lambda value. This was established by measuring the oxygen content in the exhaust in different testbed engines running on NG with different methane number. This indicates that the stoichiometric value decreases with decreasing methane number. The testing in (Feist et al., 2010) also showed that running on fuel with decreasing methane number results with increased NOx emissions. The increased formation of NOx is due to a higher combustion temperature, caused by a higher content of propane and ethane in lower methane number fuels according to (Feist et al., 2010). The lower quality natural gas has lower knock resistance, since the methane is a good antiknock component compared to other heavier hydrocarbons inside LNG (Stenersen & Thonstad, 2017).

Natural gas is mainly extracted from oil reservoirs, and thus is a fossil fuel. But methane gas can also be produced in renewable ways. Methane gas from such sources is called biogas or liquified biogas LBG. Biogas is possible to mix with LNG and will also reduce the net carbon emission since it has a lower net GWP in the supply chain and production (Balcombe et al., 2017). Therefore, it is also possible for LNG powered ships, if allowed by the industry, to lower its emissions further by mixing in biogas more and more.

There are many aspects to be looked upon when comparing and choosing LNG as fuel. LNG has a potential in lowering CO2 emissions by 25%, since LNG has a lower carbon content compared to conventional marine fuels per energy unit (Pavlenko et al., 2020). And a lower heating value higher than diesel, 48,6 MJ/Kg against 42,5 MJ/Kg (Wei & Geng, 2016). The heating value of LNG will vary depending on LNG quality, but with 100% methane the heating value will be 50MJ/Kg (World Nuclear Association, 2016). According to the Methane main reaction $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ and compare it with Diesel main reaction $C_{12}H_{23} + 71O_2 \rightarrow 48CO_2 + 46H_2O$ the CO2, LNG CO2 emission is lower than diesel.

Unburned fuel results in methane emissions, and methane gas have a high GWP. The GWP is normally measured with a 20- or 100-year timespan since different gases have different lifetime in the atmosphere (Jarraud & Steiner, 2012). Methane has a high GWP, but relatively short lifespan, which gives it a higher GWP in a 20-year lifespan. Since the UNs SDG is time limited to 2030, then GWP20 is most relevant and used in this study.

2.3 Methane slip

Methane slip is the unburned methane escaping from the combustion chamber (Stenersen & Thonstad, 2017). Methane slip is affected by how the NG and air is compressed in the combustion chamber before combustion. The Methane slip is about 1%-5% of the total gas consumption(CIMAC WG 17, 2014). There are three different ways for the unburned methane to escape from the engine. Methane can by-pass through the valve stem seals in the intake and exhaust ports, or the crevice area between the piston and the cylinder liner and pass the piston rings into the crankcase area and then ventilate out through the crankcase ventilation to the atmosphere, if an open system is used (LIGHTHOUSE, 2020). The second way is from incomplete combustion due to several reasons and parameters. And lastly gas fuel escaping via the scavenging air (Jensen et al., 2020). There are several methods to optimize and improve the combustion in the combustion chamber which can reduce the methane slip (Stenersen & Thonstad, 2017). It could be:

- Reducing the crevices area
- Find the balance of variable valve timing, minimize the overlap
- Combustion chamber geometry
- Engine control system, tuning
- piston crown design, air flow under compression stroke

- Piston rings and lubrication, avoiding blow-by

2.3.1 Blow-by

Blow-by is crankcase emissions and there is methane slip occurring because of this. Unsealing piston rings allows the air and fuel mixture to leak out through the anti-polishing piston ring into the crankcase during the compression stroke (Heywood, 2018, p.387-391). Blow-by is caused by the piston clearance to the cylinder wall, the piston ring gap, and the unstable movement of the piston (Delprete et al., 2019). The piston rings' function is to seal and tight the clearance between the cylinder wall and piston, preventing pressure loss from combustion chamber and improve efficiency (Turnbull et al., 2020a). When the gas fuel flow into the crevice area between cylinder wall and piston, then the pressure behind the piston ring will increase, therefore it will push the piston ring against the cylinder wall and increase the tension and sealing against the cylinder wall. The methane slip will be reduced by improving the piston rings tightening and sealing effects, but it comes with consequences that the piston rings' friction against the cylinder wall will increase. Therefore lower the thermal efficiency and increase gas fuel consumption as well as maintenance cost (Turnbull et al., 2020b).

The crankcase needs to be ventilated and depressurized somehow. The crankcase needs to be ventilated both due to build-up of oil fumes and blow-by entering the crankcase. This can be done either through an open crankcase ventilation system or a closed crankcase ventilation system (Golkarfard et al., 2018). An open crankcase ventilation system ventilates out the fumes to the atmosphere, while a closed system ventilates the crankcase to the air intake of the engine.

In this case an oil separator must be fitted to separate the oil, preventing it from contaminating the turbocharger as well as the combustion chamber. Fumes can also leak through the valve stems into the valve house ventilation that is connected to the crankcase through the lubrication (Pavlenko et al., 2020).

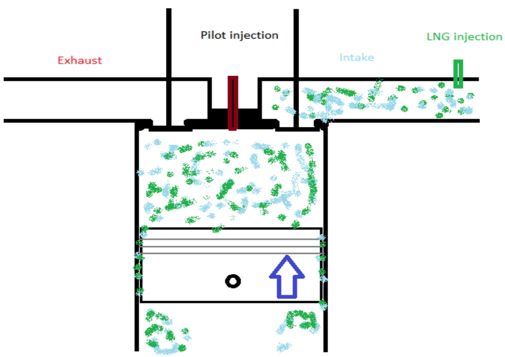

Figure 1:The crankcase emission, The air and fuel mixture blow-by the piston ring into the crankcase

2.3.2 Quenching

Quenching is the failure of the flame propagation, the flame quenches towards an area where combustion is not possible (Heywood, 2018, p. 698-699). It occurs because of a few reasons that will be explained in this thesis.

Air fuel ratio (AFR) is the ratio of the fuel and air mixture introduced into the combustion chamber. A stoichiometric AFR is the theoretically optimum mixture of combustion. Meaning the combustion without any unburned hydrocarbons. Where all hydrocarbons have oxidized into CO2 and the hydrogen into water (Heywood, 2018, p. 88). The stoichiometric value is referred to as lambda equal 1 in calculations. Adding air rises the lambda value and has then become leaner. The opposite, to add more fuel decreases the lambda value and the mixture has now become richer.

The flame propagating in the combustion chamber can be hindered by the geometry, for example by the crevice entry areas, and the size of the crevices themselves (Heywood, 2018, p. 628). It is also and mainly an effect from too low temperatures caused by the cooling from the cylinder walls. (Heywood, 2018, p. 298-299). Reaching further away from the stoichiometric value has a limit until the mixture cannot burn anymore. Quenching usually increases under low load, because of the high air fuel ratio (Stenersen & Thonstad, 2017). Methane is more stable than conventional oil fuels and needs a very high temperature to ignite making it prone to quenching (LIGHTHOUSE, 2020). At low loads, the lambda value will increase because the gas fuel decreases while an excessive air flow remains to secure the combustion of the pilot fuel, (Sommer et al., 2019). When the quenching occurs, it usually means the combustion will not be fully completed, generating potential methane slip to occur(Stenersen & Thonstad, 2017)

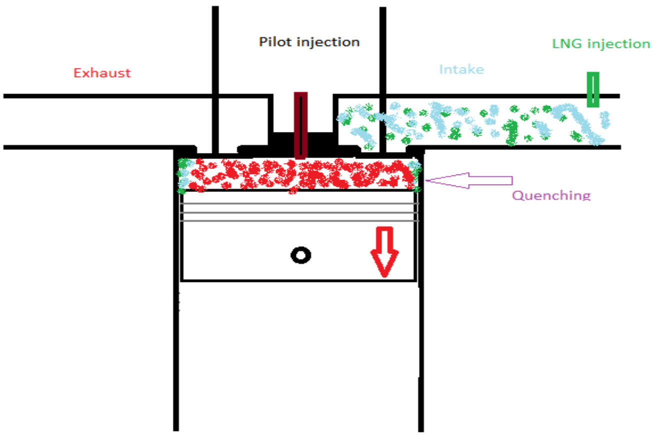

Figure 2: The flame did not propagate properly close to the cylinder liner.

2.3.3 Valve Timing

On exhaust stroke the exhaust valve will open and the piston will move from bottom dead centre (BDC) to top dead centre (TDC). The intake valve will be opened until right before the piston reaches TDC (Heywood, 2018, p. 240-245). The valve opening timing depends on the control settings. The exhaust valve will be closed on the intake stroke and the piston moves towards BDC. The closing of the intake valve overlaps a little into the compressions stroke to maximize the fuel air mixture into the combustion chamber before ignition. During compression stroke the piston moves from BDC towards TDC and the intake valve is closed. The pilot fuel injection will start before the piston reaches TDC. During the expansion stroke, the exhaust valve will open right before the piston reaches BDC. The exhaust valve is timed to open earlier to maximize removal of the exhaust gas.

Due to the early opening of the intake valve, overlap will occur (Heywood, 2018, p. 240-245). The overlap means that the exhaust valve and inlet valve are in open position at the same time. Since the engines are turbocharged, the intake pressure can exceed the exhaust manifold pressure (CIMAC WG 17, 2014) and valve overlap becomes a problem for potential short circuiting to occur. Even though it could be a source for methane slip, it is in modern LPDF engines considered neglectable since the valve overlap is so small (Stenersen & Thonstad, 2017). It is therefore more relevant for older engines that have been retrofitted with LNG equipment for LPDF operation (LIGHTHOUSE, 2020).

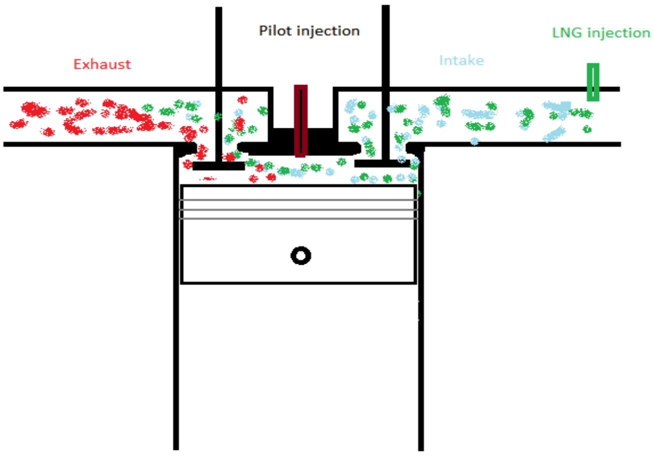

Figure 3: Valve overlap. Intake valve and exhaust valve are opened at the same time just before the end of the exhaust stroke. Some of the air and fuel mixture escaping from the combustion chamber.

2.3.4 NOx emissions

NOx emissions are formed from the oxidation of nitrogen and oxygen present in the air. This occurs from high temperatures and pressures.

The NOx formation is higher in CI engines than in a SI engine (Ushakov et al., 2019), and this is also the case for LPDF engines. The pressure in a LPDF engine follows the principles of a CI with an introduction of fuel just before the TDC. Common knowledge for engine manufacturers is that the pressure can mainly be manipulated by the compression ratio and temperatures can be mainly manipulated from the combustion. (Heywood, 2018, p. 616-622). There is therefore a trade off from engine efficiency and NOx emissions from this perspective (Stenersen & Thonstad, 2017). Although there are aftertreatment systems for NOx emissions this is still highly relevant due to investments and maintenance costs. As further shown in the results and in the conclusion, this is also very important to understand for the methane slip prevention. Since methane is more stable than conventional fuel, and needs more energy to combust (Ushakov et al., 2019).

2.4 Internal engine design

The combustion chamber design is designed for optimum combustion and the dynamic gas motions in the cylinder must be considered. The shape of the piston crown, angle of the valves and ports, prechambers, injectors are all included in the design parameters. The gas motion inside the cylinder is considered and calculated by principles of swirl and squish. Avoiding crevices by engine design and it also affects the chambers' tendencies to make quenching and higher fuel concentrations in crevices possible (Stenersen & Thonstad, 2017). Blow-by must also be considered when preventing methane slip, for this proper lubrication must be achieved with operation of suitable piston rings.

Combustion is affected by the compressed air. To optimize air intake, the air inlet port should be constructed to optimize swirl in the combustion chamber. The shape of the bowl needs to be constructed to optimize the squish area to improve the process of combustion (Heywood, 2018, p. 375-384). Optimize the combustion chamber by redesign bowl shape, increase the squish area and increase the swirl of air in the combustion chamber.

2.4.1 Piston bowl design

The air flow, squish and turbulence is affected by the geometry of the piston bowl, thereby the flow and squish will affect the mixture of fuel and air which will affect the combustion (Mittal & Gwalwanshi, 2021). To increase the efficiency and reduce the emission of the engine, the bowl shape is important for increasing the Swirl and the squish in the combustion chamber. The air inlet port is also designed to cause the air to swirl (Heywood, 2018, p.371-372). It is to create a spiral effect for the air as an extra help to fill up the cylinder and get a better mixture with the fuel before ignition.

The squish is an effect when the piston gets close to the TDC and creates a turbulence of the mixture in the area between the piston top land and the cylinder head (Heywood, 2018, p. 375-384). The goal of the piston geometry is to increase the swirl, and squish, to help reach a more complete combustion(Shen et al., 2021). An alternative to piston bowl design can be a reentrant piston bowl. A reentrant bowl has less homogeneity with increasing swirl or squish the reentrant bowl design can also improve the thermal efficiency and lower the NOx formation of the engine.

This is still relevant even though LPDF engines induces a premixed mixture because the ignition itself occurs with a pilot fuel as a CI engine. The total combustion will still be highly affected by how the pilot fuel mixes and combust in the combustion chamber. The three piston geometries shown in fig. 4, were tested in a test bed LPDF engine, with the diesel spray tilted to 150° C to optimize the surrounding of the diesel spray with NG-air mixture.

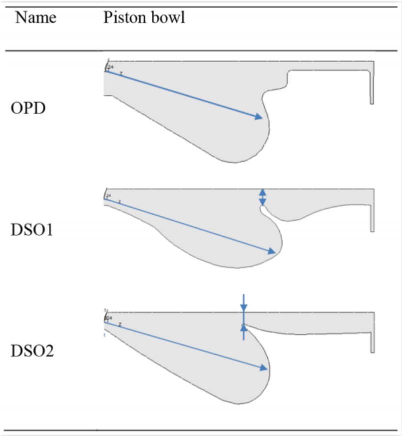

Figure 4: Piston bowl design, reentrant bowl shape by (Shen et al., 2020).

2.4.2 Crevice areas

Crevices are small areas inside the combustion chamber which are not made for optimum combustion. These spaces are between the piston crown and the cylinder liner, inside cracks, uneven surfaces, small areas close to where the valves sit against the valve seat (Heywood 2018, p. 387-391), areas close to where the pilot injector is fitted as well as close to the gasket between the cylinder liner and the cylinder head.

These are also areas where unburned methane gas can be trapped and cannot be reached by the flame after ignition (MAN Energy Solutions, 2020). The fuel-air ratio might also be too saturated in these areas which hinder a proper combustion to occur. The unburned fuel will then leave the combustion chamber during the exhaust stroke out to the atmosphere. This is how methane slip occurs because of crevices. The crevice volume can be reduced by engine design, a minimum of crevice will always remain.

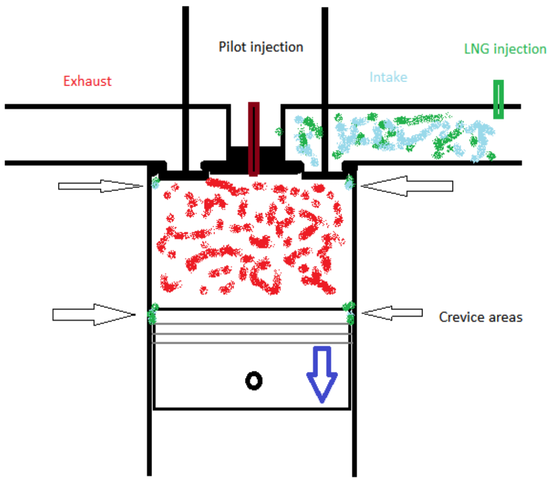

Figure 5: Air and fuel mixture get trapped in the crevice in the Top land. Which fails to ignite during the combustion

2.4.2.1 Piston clearance

The distance between the piston above the first piston ring and the cylinder liner, will determine the piston clearance. Piston rings and lubrication must be selected according to the piston clearance in mind carefully, to make sure the seal between the combustion chamber and crankcase is proof. The size of the piston clearance and the position of the first piston ring will determine the biggest crevice area in the combustion chamber (Rakopoulos et al., 2011). This area is sometimes referred to as Top-land volume.

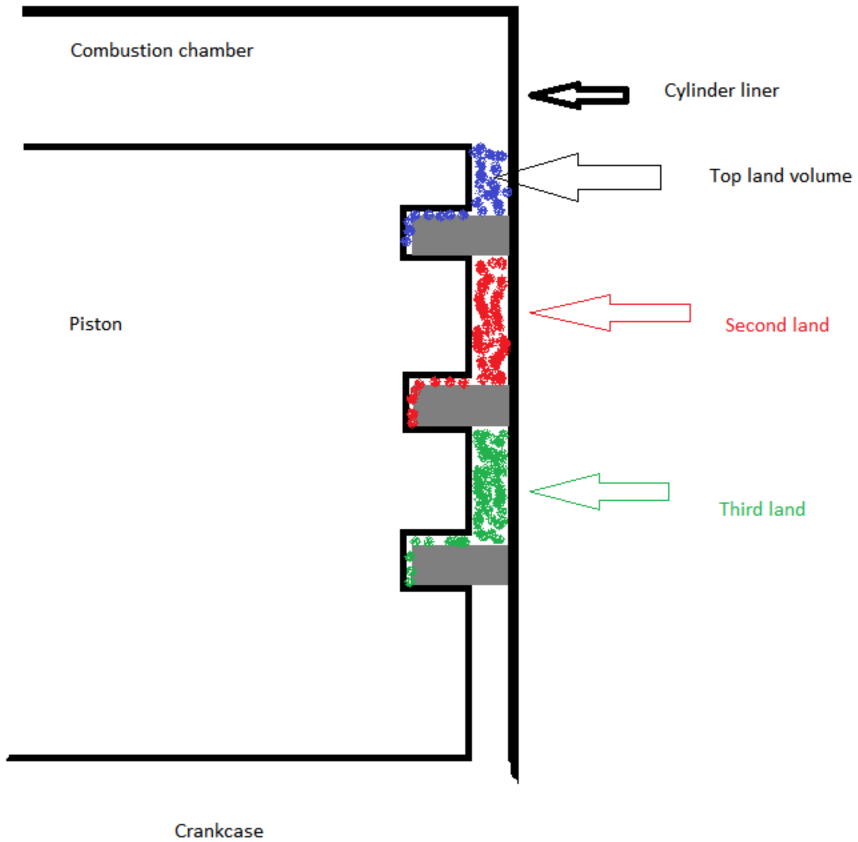

Figure 6: Top land. Those biggest crevices in the combustion chamber.

2.5 Cylinder cut-out

Cylinder cut-outs are not only useful for an engine when a cylinder failure occurs, such as when a fuel pump or a valve fails for a specific cylinder. It can also be an optimization method for a fully working engine. The cut-out is made by simply stopping the fuel injection to the specific cylinder. In a study by (Konrad et al., 2018) it was shown with a predictive modulation that a higher engine efficiency at low loads is possible by cutting out cylinders from operation. The remaining firing cylinders increased in higher indicated mean effective pressure (IMEP), pumping work and a higher turbocharger efficiency (Konrad et al., 2018). This will decrease the unburned hydrocarbons and therefore reduce the methane slip. This method has also been tested in real operation in (Sommer et al., 2019), where the methane emissions were measured during the test.

2.6 CH4 detection instrument

Recently there has been research developing a low-cost methane detector in the exhaust. The detector is called a wavelength modulation spectroscopy (WMS). The test of this sensor was made on two LPDF engines on a marine vessel, while comparing it to a flame ionization instrument to validate the results (Sommer et al., 2019).

The purpose of this Instrument is to identify and improve the operating conditions in real-life use on vessels. By identifying the methane emissions in the exhaust stream the control system formula can be improved with one more variable, to optimize the running conditions for optimum efficiency and minimum methane slip (Sommer et al., 2019).

2.7 Aftertreatment system

Methane oxidation catalysts (MOC) are used for reducing methane emissions. Methane is a stable compound, to break the CH bonds, the methane oxidation catalyst needs to operate at a very high temperature around 500+°C (LIGHTHOUSE, 2020).

Methane oxidation catalyst is not an available choice for 2 stroke engines. It is because 2-stroke engines have a lower exhaust gas temperature, and an oxidation catalyst requires a very high exhaust gas temperature to break the Methane CH bond (LIGHTHOUSE, 2020). Marine 2-stroke engines are slow speed crosshead engines with a longer stroke and higher compression ratio than 4 stroke engines. The fuel energy will convert more efficiently to work rather than thermal energy compared to a 4-stroke engine, and therefore leaving a lower exhaust temperature in the exhaust pipe compared to a 4-stroke engine.

The MOC works better with four stroke engines, because of the higher exhaust temperature (MAN Energy Solutions, 2020). Even though 4-stroke engines are closer to the possibility of a MOC, it is not yet available on the marine market. There are still problems with sulphur deactivation, regeneration of the catalyst and investment costs (LIGHTHOUSE, 2020). But there is still research ongoing to produce cost efficient working MOC for marine 4-stroke engines in the future, such as MAN:s incorporation in the German ministry of economic affairs and energy “IMOKAT” project, which aims to develop MOCs which can reduce 70% of the methane slip in the exhaust (MAN Energy Solutions, 2020).

The technology is available and applied on land-based combustion for road transport industry, the mentioned problems occur because of the big engine size with higher thermal efficiency, giving lower exhaust gas temperatures, and from the higher sulphur content in the pilot fuel, that is available on the marine market.

3. METHODS

3.1 Literature review

Due to the 2020/2021 pandemic, we were not able to go onboard for research nor could any interviews be conducted. Studies were made by investigating earlier field studies and written articles by other authors. By investigating earlier research, we evaluated the basic problems, and potential tools for reducing methane slip from LNG-powered ship engines. The collecting of studies was made qualitatively.

The databases that were used were "web of science" and "Scopus" since these have the most relevant categories and contents for this kind of engineering research, based on the databases available at Chalmers University of technology. Firstly, keywords used were as following:

- LNG marine engine
- methane
- Methane slip
- Methane slip prevention
- Methane slip marine engine.
- Emissions LNG
- Gas fuelled engine
- LPDF engine
- Blow-by
- Quenching
- Crevice
- Engine bowl

Then the selection was made by filtering by citations to catch the most acknowledged research. And from accessing those literatures' relevance, further search of the citing literature was considered. Since

Marine combustion engines with LNG are relatively new on the market. Therefore, the assumptions were made that the technology is developing and the publication year of the literature from the databases were considered and preferred to be as up to date as possible. The less cited articles in the search results were therefore considered due to a newer publication date, these articles were assessed and if any citations, some of the citing articles were also considered to include in the result. Research using smaller gas engines were also included, such as research from the road transport industry. Since this industry is also big and in the front line of development. And because the working principles of the engines are the same it is also relevant for understanding developing marine engines.

Relevant IMO studies were also investigated through the IMO website, mainly to support the theory with comprehensive summarized emission data. To give an understanding of the relevance of emissions coming from the marine sector. And understanding which regulations are today set to limit the emissions.

The biggest marine engine developers were also used for collecting general information about what type of engines are used today and what challenges that have been recognized by the manufacturers. Selected engine handbooks publicly available were downloaded and any further presentations found on the developer's website were examined.

3.2 Survey

A survey was sent out to four manufacturers to investigate which areas of improvement of methane slip has been the most important and recognized by the manufacturers. The survey was offered to be filled out anonymously.

The survey contains 10 close questions and 1 open question, see appendix. The balance between close and open questions was based on the possibility to collect necessary information about methane slip by making it easy and time saving for manufacturers to answer the survey. And not having to release any company secrets, that will make the manufacturers lose their competitive edge.

The survey was designed to find out how the manufacturers reduce the methane slip on their LPDF four stroke engines. And what the main challenge with the reduction of methane slip the manufacturers has been facing.

Step 1: Find the contact information of suitable response personnel in the four stroke engines department on manufacturers Website.

Step 2: Introduce our work and survey to our mentor.

Step 3: Send the survey PDF file to the main response personnel and wait for response.

4. RESULTS

4.1 Theoretical comparison of the global warming impact of Methane and carbon dioxide

Emission data from (Peng et al., 2020) of a LPDF engine, run on E2 test cycles according to (ISO, 2020a) on both diesel mode and NG mode can be compared with their GWPs for each emission species during specific loads. The GWPs for methane and CO2 from table 2 and 3 are compared in both a 20- and a 100-year time horizon in fig. 7.

CO2 emissions from LPDF running on LNG		CO2 emissions from diesel mode	
Engine load [%]	gCO2/kWh	Engine load [%]	gCO2/kWh
25	572	25	588
50	567	50	657
75	490	75	613
100	468	100	613

Table 2: CO2 Emission data from (Peng et al., 2020)

Engine load [%]	gCH4/kWh	Methane GWP20 [gCO2eq/kWh]	Methane GWP100 [gCO2eq/kWh]
25	25.5	2193	714
50	12.8	1100	358.4
75	5	430	140
100	3.7	318.2	104

Table 3: Methane emission data from (Peng et al., 2020)

The GWPs for methane slip in table 3 is calculated by multiplying the GWP with the emission data as following: Methane GWP20/100 at certain engine load, equals to emission data at certain engine load times 86/28. This result is compared in fig. 7 against same equation for CO2 emission data from diesel operation.

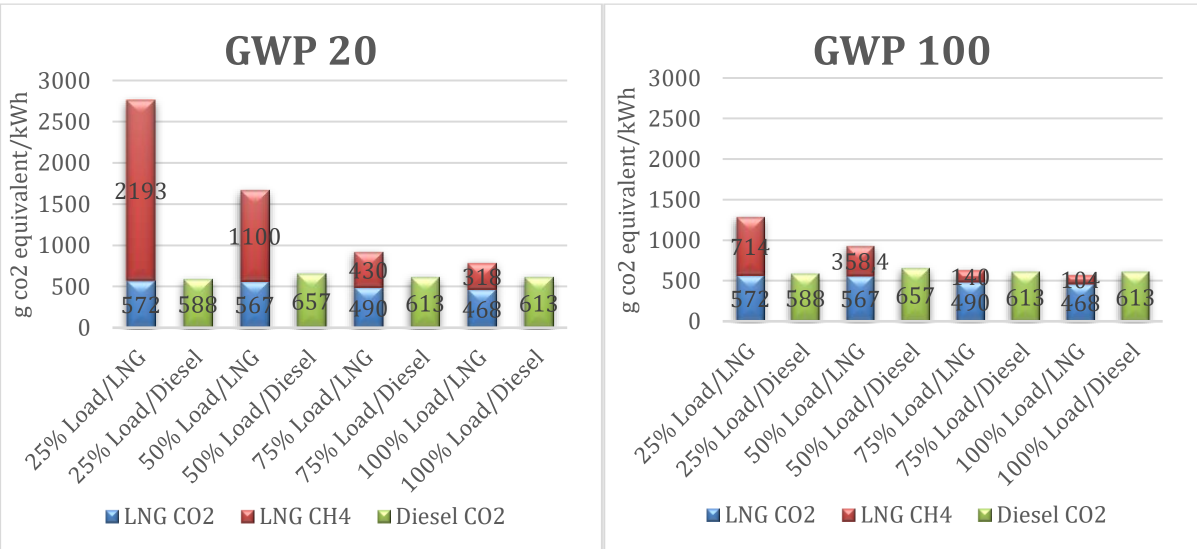

Figure 7: GWP20 and GWP100 comparing LPDF on gas mode and diesel mode. Emission data from (Peng et al., 2020)

As shown in fig. 7 the choice of time horizon is crucial for evaluating the GWP difference from running on LNG or conventional diesel. The significant increase of methane slip at lower engine load than 50% shows the clear difference between running on LPDF LNG operation and diesel operation. Especially at a 20-year time horizon. The only positive result shown from LPDF LNG operation from this calculation is during 100% engine load using a 100-year time horizon.

4.2 GWP20/100 calculation

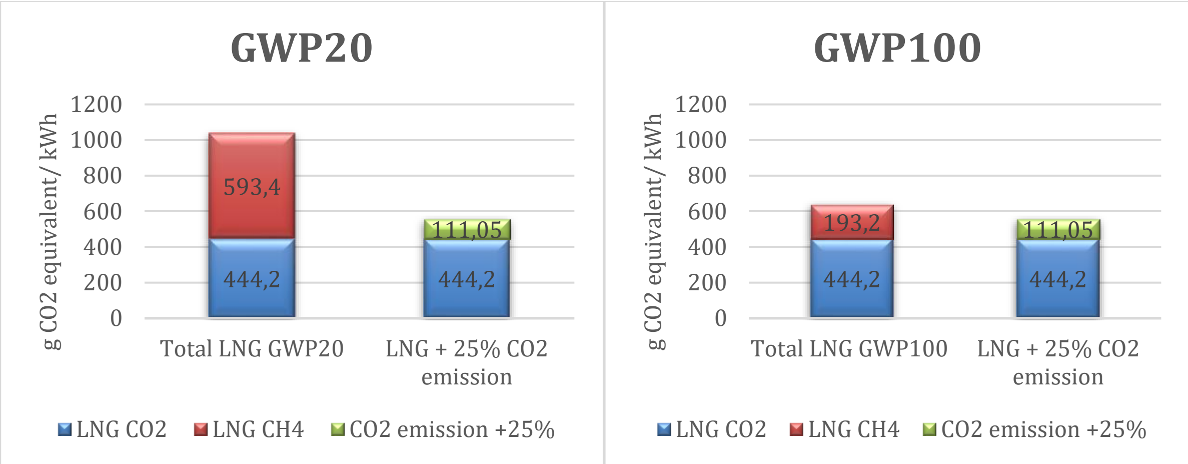

Figure 8: GWP20, emission factors from (Ushakov, 2019) LPDF and CO2 x 1.25

Emission factors are taken from the summarized measurements in (Ushakov et al., 2019) where the average methane emission factor is 6.9 gCH4/kWh and average CO2 emission factor is 444.2 gCO2/kWh.

4.2.1 GWP20 calculation

CO2 emission factor plus 25% = Best-case scenario difference from LPDF to diesel: 444,2 x 1.25 = 555,25 gCO2eq/kWh. If all LPDF engines, make a 25% CO2 reduction comparing to diesel operation.

Methane emission factor from LPDF engines is 6,9 g/kWh.
Methane emission factor GWP20 = 6,9 x 86 = 593,4 gCO2eq/kWh.

Total gCO2eq/kWh from LPDF engines minus the best-case scenario difference from LPDF to diesel CO2 equivalent results in an increase of 482.05 in total gCO2eq/kWh if LPDF gas mode is used.
(593,4 + 444,2) - 555,25 =482.05 gCO2eq/kWh.

Estimated diesel mode gCO2eq/kWh emission divided by total gCO2eq/kWh emission from LPDF = Total GWP20 difference.
555,25 / (593,4 + 444,2) = 0.535
0.535-1 = 46.5%
Calculated with GWP20, the result show that using LNG as fuel will the give a 46.5% higher GHG impact than diesel.

4.1.2 GWP 100 calculation

Methane emission factor from LPDF engines is 6,9 gCH_4/kWh.
Methane emission factor GWP100= 6,9 x 28 = 193,2 gCO_2eq/kWh.

Total gCO_2eq/kWh from LPDF engines minus the best-case scenario difference from LPDF to diesel CO_2 equivalent results in an increase of 82,12 gCO_2eq/kWh if LPDF gas mode is used.
(193,2+ 444,2) - 555,25 = 82,12 gCO_2eq/kWh.

Estimated diesel operation gCO_2eq/kWh divided by total gCO_2eq/kWh from LNG = the difference.
555,25 / (193,2 + 444,2) = 0.87
0.87-1 = 13%

Calculated with GWP100, the result show that using LNG as fuel the GHG impact is 13% higher than Diesel in a methane, CO_2 analysis.

4.2 Numerical analysis and prediction

A Prediction made by (Jensen et al., 2020) using numerical analysis of a medium speed 4-stroke LPDF engine, shows the methane-slip source distribution of quenching, crevices, and short circuiting. The results from the model in (Jensen et al., 2020)shows:

- Crevices: 5.2 - 9.0 g/kWh
- Quenching: 1.3 - 54.1 g/kWh
- short-circuiting: 8.0 - 10.3 g/kWh

The results of the methane slip source distribution from (Jensen et al., 2020)shows the data in four engine load cases. 25%, 50%, 75% and 100%.
The short-circuiting source for methane-slip is much more constant compared to the crevices and quenching sources. With an emission difference of 2.3 compared to crevice 3.8 and quenching 52.8. This shows that the quenching source varies highly by engine load.
The quenching is by far lowest at 75% and by far highest at 25% load. While short-circuiting is peaking at 75% load and crevices peaking at 25% load. The methane emissions due to crevices and quenching decreases from 25% load to 75% load, and then increases to full load. The cause of the increase from 75% load to 100% load is mentioned as unknown in (Jensen et al., 2020).
The diagram Figure 7 below shows the methane emissions with the three emission sources added on top of each other and compared between 25% and 75% load.

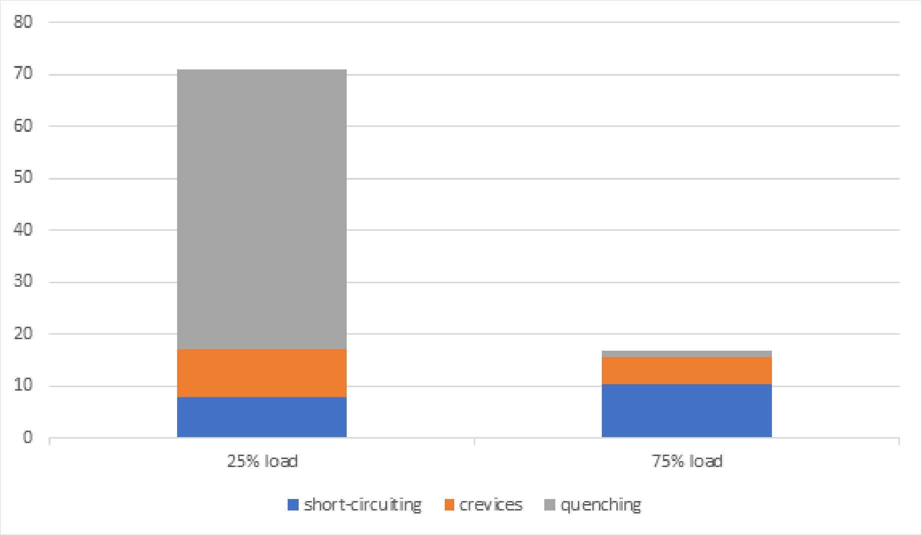

Figure 9: Distribution between the methane slip sources and load (Jensen, 2020).

In Figure 9 and 10 the methane emission distribution from (Jensen et al., 2020) is compared between the engine load with peak methane emissions and with the lowest methane emissions: On 25% load, 76% of the total methane slip occurs by quenching, 13% by crevices and 11% by short circuiting.

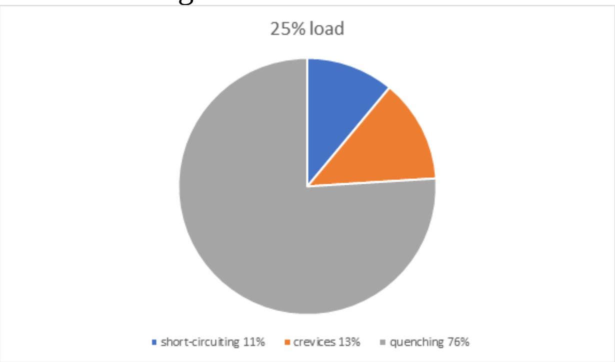

Figure 10: percent between the methane slip sources and load(Jensen et al., 2020).

On Figure 11, 8% of the total methane slip occurs by quenching at 75% engine load, 31% by crevices and 61% by short circuiting.

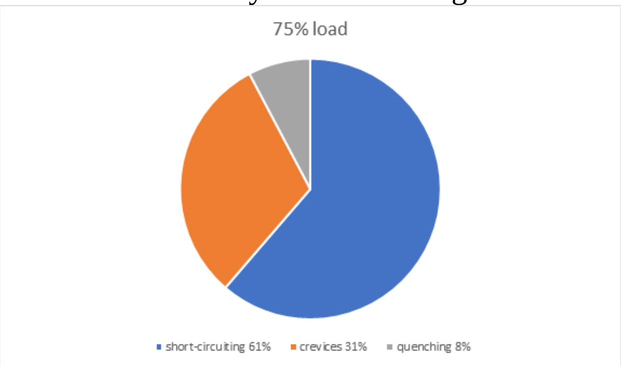

Figure 11: percent between the methane slip sources and load (Jensen et al., 2020).

4.3 Blow-by

Blow-by was not considered as a methane slip source in the (Jensen et al., 2020) prediction, but it is very well a present methane slip source if an open crankcase ventilation system is used, which still is the norm in today's marine engine installations (Pavlenko et al., 2020). Because blow-by methane will ventilate through the crankcase ventilation and oil separator out to the atmosphere it will not be detected in the exhaust gas, therefore measurements need to be made in the crankcase ventilation system. In (Johnson et al., 2017) measurements were made in an open crankcase ventilation in heavy duty well drilling dual fuel engines. The engine operation was not in control of the research team, but their measurements suggested that 2% of the LPDF engines methane slip was caused from blow-by. This very well indicates the possibility of blow-by in marine LPDF engines as well. The closed crankcase ventilation manufacturer UT99 (2021) claims a 99% oil separation efficiency and an increased fuel efficiency of 0,7% for marine engines, which indicates a blow-by of 0,7% of total fuel consumption.

4.4 Crevice area reduction

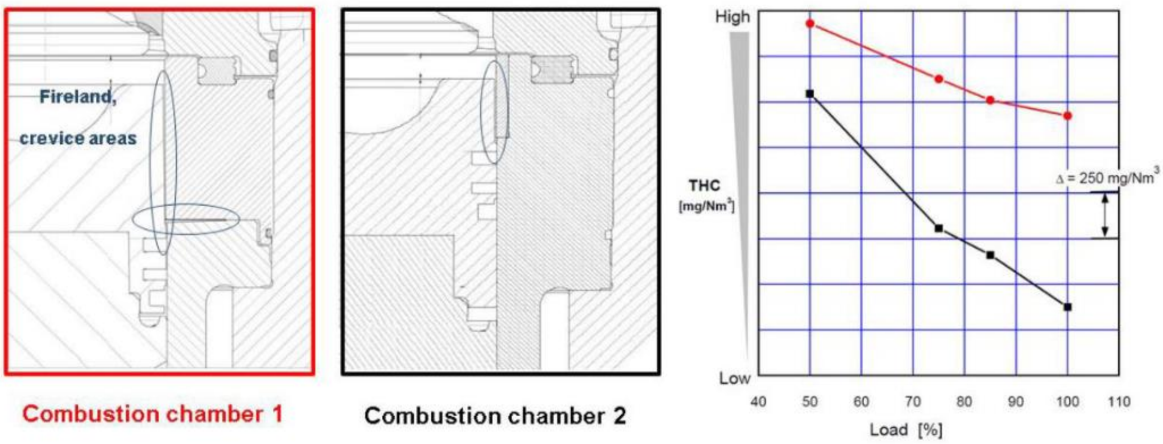

Figure 12: Crevice reduction (Stenersen & Thonstad, 2017)

Replacing the anti-polishing ring further up to reduce the biggest crevice in the combustion chamber, the top land volume. Methane slip caused by crevices can be significantly reduced, especially at higher loads.

4.5 Measurement data from engines before 2010

Here is measurement data summarized from (Nielsen & Stenersen, 2010). These are measured emission data from real engines and not a prediction. The methane slip is 40.4 g/kWh at 25% load, 22 g/kWh at 50% load, 13,4 g/kWh at 75% load and 12.7 g/kWh at 100% load.

This also shows clearly that the engine load is a major problem releasing methane slip in the atmosphere. These measurements are a relatively old comparison to today's made engines, see Figure 15.

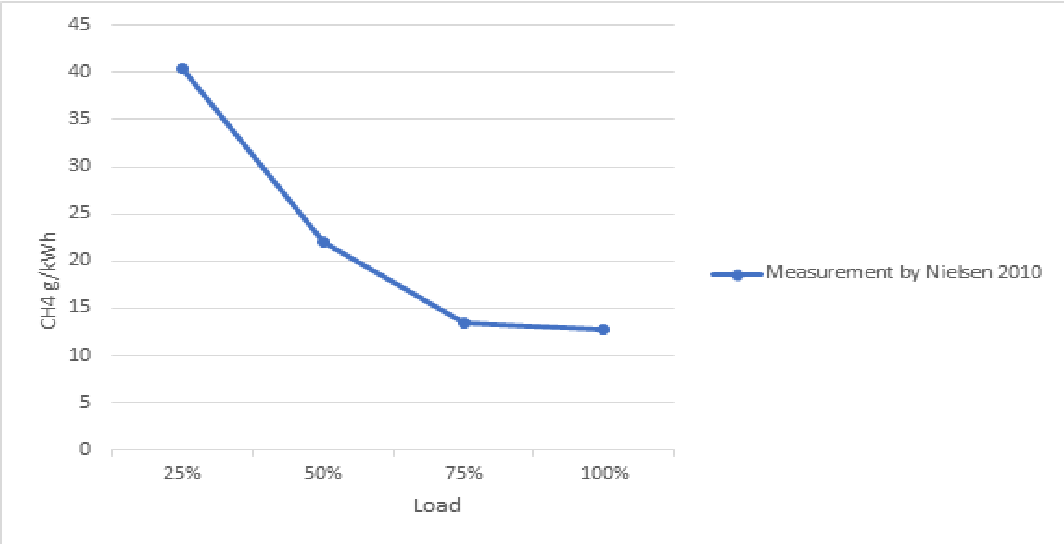

Figure 13: Methane slip measurement for engine before 2010(Nielsen & Stenersen, 2010).

4.6 Measurement data from engines after 2010

Measurement data summarized in Figure 14. Figure14a is from (Ushakov et al., 2019), they show methane slip from different LPDF engines in CH4 g/kWh and engine load ratio. Figure 14b is the ratio between NOx g/kWh and engine load.

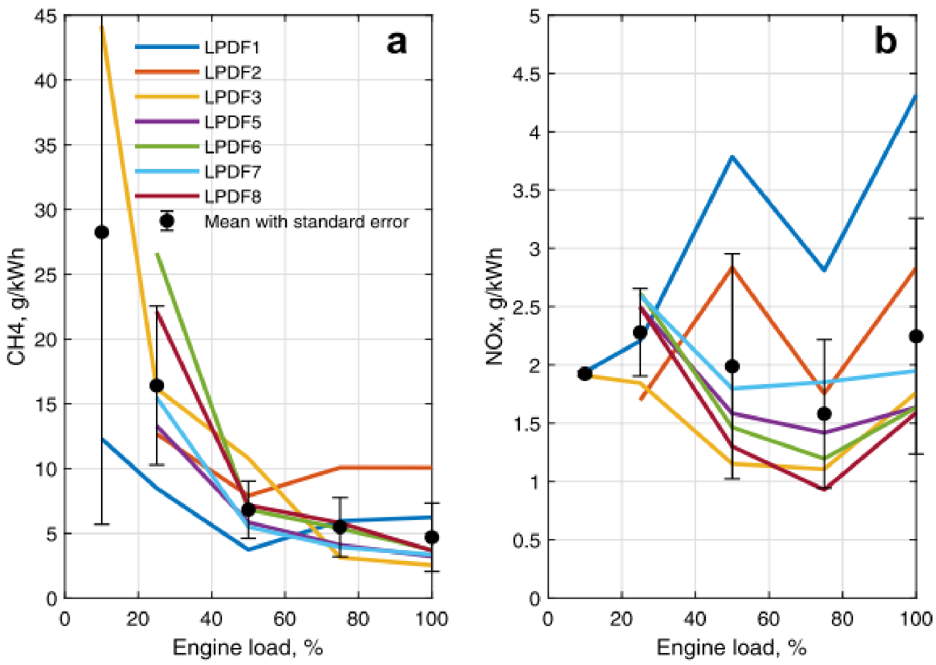

Figure 14: Methane slip measurement for engines after 2010 (Ushakov et al., 2019)

4.7 Comparison methane slip for engines before and after 2010

Figure comparison is average measurement data about methane slip for engines before 2010 and engines after 2010 in different loads.

	25% Engine load	50% Engine load	75% Engine load	100% Engine load
Engine before 2010 CH4 g/kWh	40.4	22	13.4	12.7
Engine after 2010 CH4 g/kWh	16.5	7.5	5.5	4.5
CH4 Reduction in %	59%	65%	59%	65%

Table 4: Methane slip measurement data in g/kWh in different engine load (Nielsen & Stenersen, 2010) and (Ushakov et al., 2019).

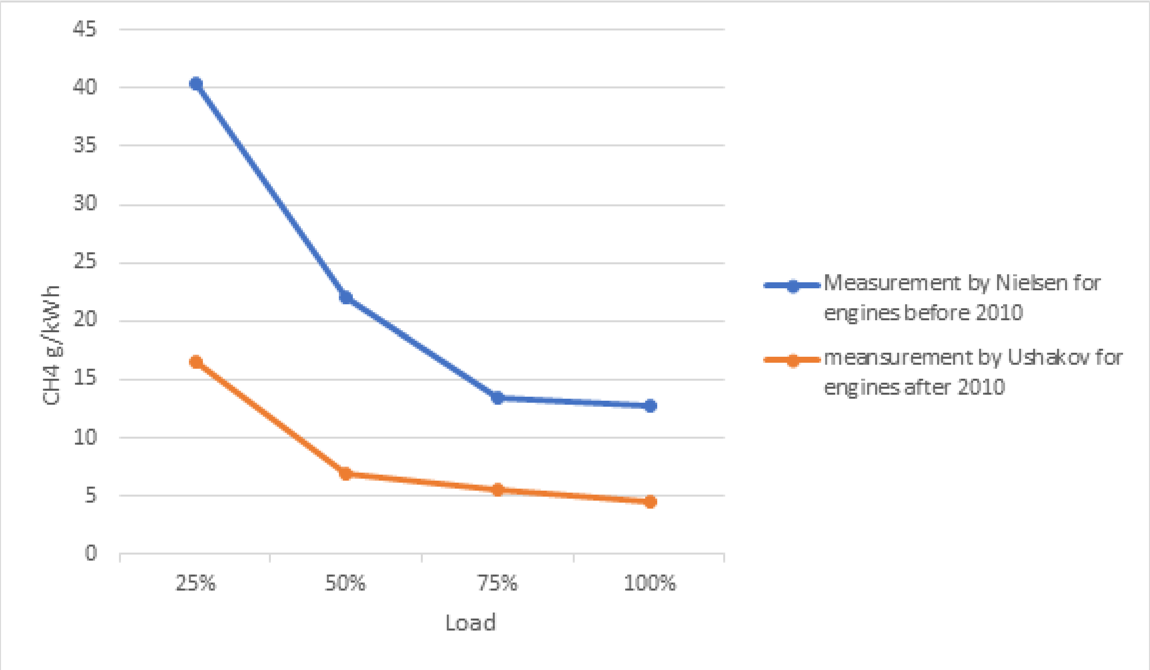

Figure 15: comparison between methane slip (Nielsen & Stenersen, 2010) and (Ushakov et al., 2019).

Figure 15 shows the comparison of methane slip from engines built after 2010 and engines built before 2010. Engines after 2010 have an approximately 62% lower methane slip than engines before 2010.

4.8 Lambda value

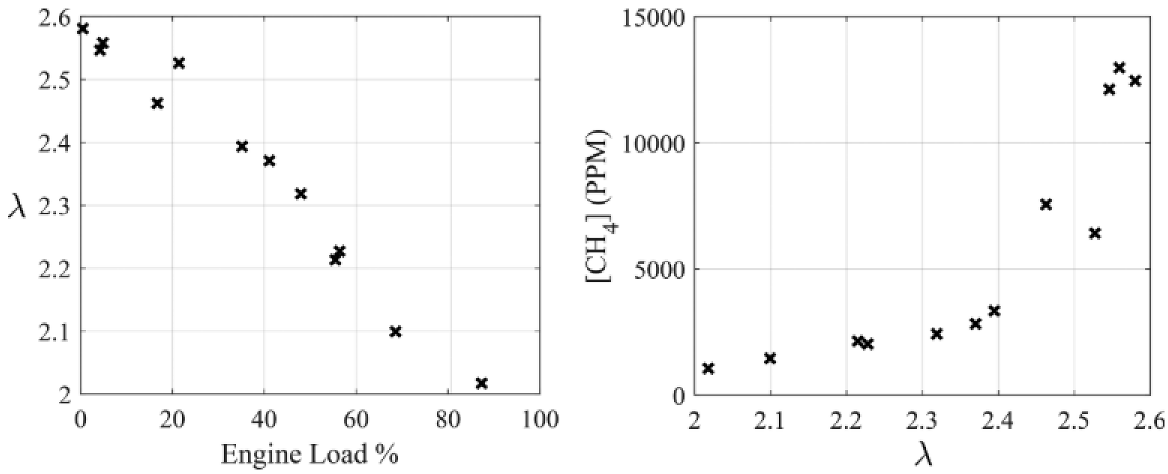

Figure 16: Effects of load and lambda value on methane slip (Sommer et al., 2019).

By the research in (Sommer et al., 2019) the methane slip is also significantly increased during low loads. The lambda value in several engine loads were estimated. And they successfully show that the methane slip increasing by decreasing load, follows the increase of lambda value.

4.9 Piston bowl geometric design

Piston bowl test on different geometric design by (Shen et al., 2020).

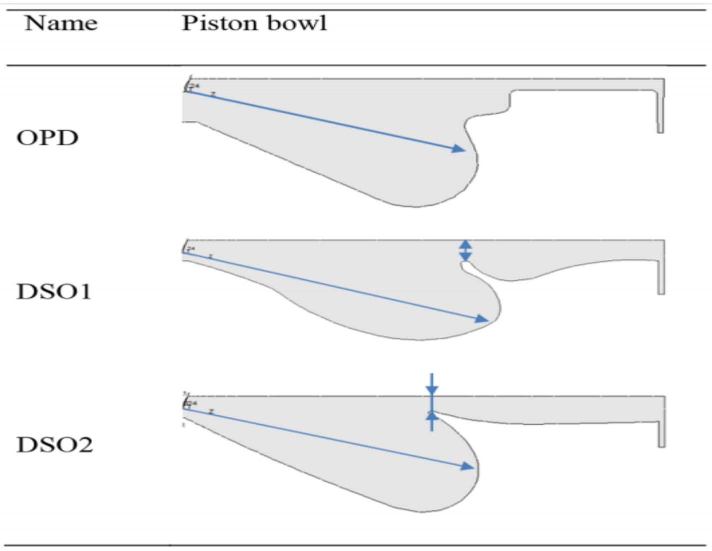

Figure 17: piston bowl geometric design (Shen et al., 2020).

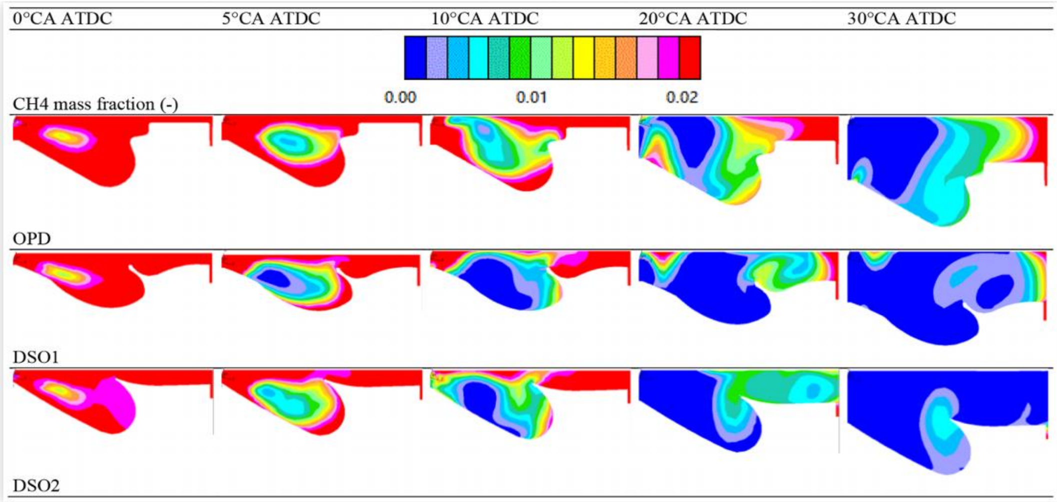

Figure 18: Contours of CH4 mass fraction by (Shen et al., 2020)

Alternating the piston geometry is a fundamental designing factor for the flame propagation and optimizing the combustion. Figures 17 and 18 are demonstrations of alternatives for piston geometry designs. The Figure shows half the combustion space, dividing the piston by half showing the right side, with colours visualizing the mass fraction.

Figure 18 shows the distribution of methane mass fraction with different piston geometries, between 0-30° crank angle (CA) After top dead centre (ATDC). The mass fraction distribution is similar in the first 5 degrees (Shen et al., 2020). At 10°CA ATDC the squish area for Diesel spray oriented 1(DSO1) and DSO2 starts to ignite. The whole squish area is then burned through at 20% CA ATDC for DSO2. Compared to the original piston design (OPD), that has not yet reached the cylinder liner at 30°CA ATDC for OPD. The result of this model clearly shows a faster flame propagation in the second geometry alternation (DOC2), especially in the squish area. It also shows a more burned mass fraction in the top land volume crevice.

4.10 Manufacturers

4.10.1 Survey

The surveys sent out to engine manufacturers were not answered. Therefore, no diagram results are presented from the survey. Even though manufacturer details were left out from the survey it was still considered to be a risk to fill out the survey. Some of the manufacturers answered that revealing this information would compromise their competitive edge. This indicates that the LPDF development is constantly developing and potentially improving.

4.10.2 Literature

The engine handbooks and product guides did not contain much information in methane slip handling. The information from the Wärtsilä 50DF product guide describes the solution of separating the control of the intake valve and the gas injection valves in the intake ports (Wärtsilä, 2019), to make them independent. Allowing the scavenging air not to contain fuel gas the first moment the intake opens. Making the small amount of intake air that escapes through the exhaust during scavenging to contain the minimum amount of fuel gas. This is clearly a method to reduce short circuiting.

5. DISCUSSION

5.1 GWP calculations and comparisons

Running 4-stroke LPDF engines on LNG with minimum pilot fuel have the potential of lowering the CO2 emissions, but does also emits methane gas to the atmosphere. Therefore, the methane slip as a GHG will outweigh the reduction in CO2 emissions. With a best-case scenario assuming a 25% CO2 reduction from all LPDF engines showed in (Ushakov et al., 2019), the methane slip impact as a GHG can be calculated against the CO2 reduction. The CO2 reduction potential is assumed from the energy value per carbon atom in methane compared to other conventional marine fuels. And the assumption of a potential 25% reduction in CO2 for LPDF engines is taken from assumptions from several credible reports; (Stenersen & Thonstad, 2017), (Ushakov et al., 2019), (LIGHTHOUSE, 2020), (Pavlenko et al., 2020) and as described in chapter 2.2.

With this assumption together with the measurement data summarized in (Ushakov et al., 2019) measured by (SINTEF, n.d.) and manufacturers testbed measurements where the average methane slip factor for 4-stroke LPDF engines was calculated to 6.9 gCH4/kWh, from experiments running on E2 and E3 test cycles following (ISO, 2020b). This shows the importance of lowering not only CO2 but more importantly methane slip from LPDF with today's emission averages. Since methane stands for more than half of the GWP on a 20-year time horizon compared to CO2.

Clearly the LPDF engines running on gas has a bigger impact on average on GWP in a 20-year time horizon. In best case scenario of 25% CO2 reduction, LPDF engines emits in average 482.35 gCO2eq/kWh (46.5%) more than engines running on conventional diesel, with methane and CO2 accounted for.

Using the same calculation with GWP100 = 28 (IMO, 2020), the result will still give a negative impact of using LPDF engines running on LNG. Running LPDF engines on LNG would in average emit 82.15 CO2eq/kWh (13%) more than engines running on conventional diesel fuel. And as seen in fig. 7, even if an assumption is made that a specific ship would emit lower methane because operating on higher load than weighted in E3 and E2 cycles, would still not make a big enough difference to argue that it would emit lower GHGs impacting giving lower GWP20/100 than a diesel engine. The only result that shows that kind of suggestion is the 100% load comparison from fig.7, which does not show a big enough difference to reliably support that argument.

5.2 Comparison between methane slip measurement data for engines before 2010 and after 2010

Figure 15 shows the comparison of methane slip from engines built after 2010 and engines built before 2010. Engines after 2010 have an approximately 62% lower methane slip than engines before 2010.

5.3 What causes the methane slip and how to reduce it

	Methane slip by Quenching	Methane slip by Crevices	Methane slip by Short-circuiting
Methane slip at 25% engine load	76%	13%	11%
Methane slip at 75% engine load	8%	31%	61%

Table 5: Numerical analysis prediction (Jensen et al., 2020)

According to prediction using a numerical analysis model by (Jensen et al., 2020) 76% of the total methane slip at 25% engine load caused by quenching, 13% by crevices and 11% by short-circuiting. At 75% engine load there is only 8% of the total methane slip that is caused by quenching, 31% by crevices and 61% by short circuiting. The results from the prediction by (Jensen et al., 2020) is logical because engine efficiency, pressures and temperatures are generally higher at higher loads such as 75% compared to lower loads, such as 25%.

It is important while looking at figure 9, 10 and 11 to realize that the predicted measurement data shows the peak methane slip at 25%, this is not necessarily the case. Because other studies and the results in figure 3 shows that the methane slip increases further with decreasing load below 25% load. So, what the result in figure 9, 10 and 11 is indicating is only the lowest and peak emissions for 4 modelled engine loads as 25%, 50%, 75% and 100%.

5.3.1 Quenching

This is common knowledge for engine designers. And that also indicates a confirmation of (Jensen et al., 2020) results that quenching increases at low loads and decreases at high loads. According to the figure 9, 10 and 11. The total methane slip caused by quenching at 25% engine load is significantly higher than 75% engine load. At low load, the temperature is not high enough for methane to reach a complete combustion, and the effect of quenching decreases with increasing engine load. That is why at 25% engine load 76% of the methane slip is caused by quenching but just 8% methane slip caused by quenching at 75% engine load.

The solution for quenching is to try to reduce the quenching conditions such as rising the engine load, temperature or use other fuel at low load and switch to LNG again at high load. As the results from (Sommer et al., 2019) also indicates, the quenching is caused by a change of AFR and temperature. The solution in their work also proves this effect, by cutting out cylinders during low load operation to change the AFR in the remaining operating cylinders. Cutting out cylinders forces the remaining cylinders to receive more load and consume more fuel to achieve the same engine effect, thus decreasing the lambda value in the firing cylinders.

5.3.2 Crevice

According to figure 9, 10 and 11. The total methane slip influenced by crevices has a bigger share at high load than low load. 13% of the total methane slip at 25% engine load, is caused by crevice and 31% at 75% engine load. Crevice areas can be reduced by optimizing the piston clearance between the cylinder liner or reducing the top land volume. Top land volume is the total volume of the crevice defined by the piston clearance and the length from the first piston ring to the upper edge of the piston top land. The reduction can be done by moving the piston ring upward as far up as possible. The combustion efficiency will increase while the crevice area decreases.

5.3.3 Short-circuiting

Figure 9, 10 and 11 shows short circuiting is quite constant with load as shown in the results, and short circuiting as shown has the biggest influence for methane slip at high load. Because the short circuiting is constant with load, the influence of quenching and crevices decrease at high load. The valve overlap has the biggest impact for short circuiting, and it can be reduced by reducing the overlap times. Though removing the exhaust gas by scavenging is important there is a balance between sufficient scavenging and excess scavenging. Techniques as described in the Wärtsilä 50DF product book is also a way of optimizing the scavenging with the intention of minimizing methane slip by short circuiting.

5.3.4 Blow-by

Methane slip caused by blow-by can be eliminated completely if a closed crankcase ventilation is fitted. This not commonly used on regular diesel engines because the risk of contaminating the turbocharger if the oil separation is not sufficient. But there are plenty closed crankcase ventilation systems available, for example, systems from (UT99, 2021), that also suggests a good cost efficiency due to the saved LNG fuel.

5.4 Design with indirect influence on methane slip

The piston crown geometry also has a big impact on the combustion. The swirl, tumble and squish are directly affected by the piston bowls geometry (Heywood, 2018, p. 364-384). According to figure 18, the DSO2 phenomenon is caused by the pistons' geometric design to increase the swirl inside the combustion chamber, and because of the increased squish area that increases the turbulence of the mixture inside the combustion chamber as well. Which leads to the whole cylinder propagating faster than OPD.

5.5 Method discussion

The method of searching for literature and reviewing research has been reliable since the measurements and cited articles are relatively few and connected to legitimate institutes. Meaning it has been easy for the authors to come by acknowledged and relevant research online. Some articles and facts have also been gathered from the road transport research, this of course has a major difference, for example engine speed and size, and emission regulations and incentives. Since the research is certainly extensive and the working principles are the same as for marine engines, it has still been relevant for detailed information such as ideas for piston bowl design, piston clearance research. And looking at problems that have already been solved in the road transport industry that still is a challenge for marine engines.

Manufacturers have not been successfully contacted, which are the ones with state-of-the-art engine design information. This would certainly have given this thesis more extensive information, with the reason that the manufacturers do not want to risk losing their competitive edge, they have not accepted answering our survey. The improvements of the manufacturers design work have certainly improved the engines according to the measurement data, see Figure 15. Which compares measurement data newer than from 2010 from (Ushakov et al., 2019) and older data from (Nielsen & Stenersen, 2010).

Collecting results from manufacturers would probably be more effective by performing interviews leaving the opportunity to leave out sensitive information for the manufacturer even greater. Or reaching out with the surveys more efficiently through stronger connection channels.

6. CONCLUSION

Methane is a strong GWP emission. According to figure 7 and 8, using LNG is not reducing the GHG impact neither on a 20-year nor 100-year time horizon. LPDF running on LNG will reduce CO2, NOx, SOx, and other emissions, but LNG as fuel will increase the methane slip so significantly that it does not lower the global warming impact, unless methane slip can be significantly reduced mostly in low load operation but also in high load operation.

The figures 7, 14 and 15 show that the methane slip increase rapidly with low load. There is a possibility that IMO sets up a regulation requirement for methane slip in the future, to find a solution for reducing methane slip.

The main solution in reducing methane slip from LPDF engines is to avoid operating the engine at low load to reduce quenching of the flame. Quenching is the major problem. This is shown in the methane source distribution prediction in Figure 9, and from the lambda change in variable loads shown in figure16. Quenching is caused by lean mixture at low loads, and it can be reduced, if the engine operates with a mixture closer to stoichiometric mixture, (Stenersen & Thonstad, 2017). The result in this thesis also confirms this.

Crevice area emission can be reduced by lowering the total crevice area by positioning the top piston ring as high as possible, see figure 12. A minimum of crevice will always remain, but the small changes possible to make will still make a relatively great difference. The methane slip reduction potential can be considered by comparing the source distribution in fig. 10 and 11.

Short- circuiting emission can be reduced by controlling the overlap. The newest 4-stroke LPDF engine run almost with not overlap, the problem lies with older LPDF engines and older diesel engines retrofitted to gas operation.

Crankcase emission can be reduced with a closed crankcase ventilation. Closed crankcase ventilation is recommended. The methane emission from crankcase circulating through an oil mist separator and back to intake manifold. According to (UT99, 2021) there closed crankcase ventilation systems will recapture all blow-by methane slip and separate 99% of oil fumes back into the crankcase.

Bowl geometry design to optimize swirl and squish to optimize the turbulence and flame speed in the combustion chamber. Leads to a more complete combustion, which indirect reduce the methane slip.

It should be possible to tune with the engine control system by decreasing the air intake mass flow, even though NOx emissions should also be avoidable during this load when a richer mixture is induced, it should be possible since the pressure and temperatures are lower than when running on higher loads. Also, other methods like cylinder cut-out also seem to be an effective way to enrich AFR at lower loads to reduce quenching.

6.1 Recommendations for further research

Research in NOx and methane emission and how it could affect the tuning of the engine control system could help finding an operating balance in the in-use of the control system. Therefore, further research in tuning the engine control system is recommended.

Further research in piston bowl geometry is also recommended for reducing the crevice area, potential bulk quenching area and for optimizing the flame propagation with help of swirl, and squish. This could be done with test cylinders and measuring the Rate of heat release, NOx, and methane emissions.

Further research in more advanced control systems can be a solution to eliminate the over-tuning shown in (Ushakov et al., 2019). An advanced engine control system could be able to optimize the running conditions better to keep the knock-/misfiring-/methane slip balance at an optimum at all loads and during load pick up. And by adding methane emission detection, potentially reach an even more optimized control system. Cylinder cut-out is also an option for dealing with the biggest problem, quenching. Further testing and research are needed to secure the operating safety and ware of the engine to make this into an acknowledged standard operating mode.

REFERENCES

Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2017). The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions. In *ACS Sustainable Chemistry and Engineering* (Vol. 5, Issue 1, pp. 3–20). American Chemical Society. https://doi.org/10.1021/acssuschemeng.6b00144

CIMAC WG 17, G. E. (2014). Methane and Formaldehyde Emissions of Gas Engines. *Cimac, 17*. http://www.cimac.com/cms/upload/workinggroups/WG17/CIMAC_Position_Paper_WG17_Methane_and_Formaldehyde_Emissions_2014_04.pdf

Delprete, C., Selmani, E., & Bisha, A. (2019). Gas escape to crankcase: impact of system parameters on sealing behavior of a piston cylinder ring pack. *International Journal of Energy and Environmental Engineering*. https://doi.org/10.1007/s40095-019-0296-x

DNV-GL. (2015). *LNG as ship fuel: Latest developments and projects in the LNG industry*. 52. www.dnvgl.com

Feist, M. D., Landau, M., & Harte, E. (2010). The Effect of Fuel Composition on Performance and Emissions of a Variety of Natural Gas Engines. *International Journal of Fuels and Lubricants*, *3*(2), 100–117. https://doi.org/10.2307/26272923

Golkarfard, V., Subramaniam, R., Broughton, J., King, A., & Mullins, B. (2018). Comparative Performance of 12 Crankcase Oil Mist Separators. *SAE International Journal of Engines*, *12*(1), 3–12. https://doi.org/10.4271/03-12-01-0001

Heywood, B. J. (2018). *Internal combustion engine fundamentals* (2nd ed.). McGraw-Hill Education.

ICCT. (2020). *New IMO study highlights sharp rise in short-lived climate pollution | International Council on Clean Transportation*. https://theicct.org/news/fourth-imo-ghg-study-finalreport-pr-20200804

IMO. (2020). Fourth IMO GHG Study 2020. *Angewandte Chemie International Edition*.

ISO. (2020a). *ISO - ISO 8178-1:2020 - Reciprocating internal combustion engines — Exhaust emission measurement — Part 1: Test-bed measurement systems of gaseous and particulate emissions*. https://www.iso.org/standard/79330.html

ISO. (2020b). *ISO - ISO 8178-1:2020 - Reciprocating internal combustion engines — Exhaust emission measurement — Part 1: Test-bed measurement systems of gaseous and particulate emissions*.

Jarraud, M., & Steiner, A. (2012). Summary for policymakers. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change* (Vol. 9781107025). https://doi.org/10.1017/CBO9781139177245.003

Jensen, M. V., Cordtz, R. F., & Schramm, J. (2020). Numerical analysis of methane slip source distribution in a four-stroke dual-fuel marine engine. *Journal of Marine Science and Technology (Japan)*. https://doi.org/10.1007/s00773-020-00760-3

Johnson, D. R., Heltzel, R., Nix, A. C., Clark, N., & Darzi, M. (2017). Greenhouse gas emissions and fuel efficiency of in-use high horsepower diesel, dual fuel, and natural gas engines for unconventional well development. *Applied Energy*, *206*, 739–750. https://doi.org/10.1016/j.apenergy.2017.08.234

Königsson, F., Kuyper, J., Stalhammar, P., & Angstrom, H. E. (2013). The Influence of Crevices on Hydrocarbon Emissions from a Diesel-Methane Dual Fuel Engine. *SAE International Journal of Engines, 6*(2), 751–765. https://doi.org/10.4271/2013-01-0848

Konrad, J., Lauer, T., Moser, M., Lockner, E., & Zhu, J. (2018). Engine Efficiency Optimization under Consideration of NOX- and Knock-Limits for Medium Speed Dual Fuel Engines in Cylinder Cut-Out Operation. *SAE Technical Papers, 2018-April*.

https://doi.org/10.4271/2018-01-1151
LIGHTHOUSE. (2020). *Aftertreatment of methane slip from marine gas engines*.
MAN Energy Solutions. (2020). Managing methane slip. *Man*. https://www.man-es.com/marine/campaigns/methane-slip
McGuire, & White. (2006). *T Anker S Afety*. *I*.
Mittal, G., & Gwalwanshi, M. (2021). Influence of reentrant piston bowl geometry on combustion in CI engine. *Materials Today: Proceedings*, *xxxx*, 2–5. https://doi.org/10.1016/j.matpr.2021.02.098
Nielsen, J. B., & Stenersen, D. (2010). *Emission factors for CH4, NOx, particulates and black carbon for domestic shipping in Norway, revision1*.
Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). *The climate implications of using LNG as a marine fuel*. www.theicct.org
Peng, W., Yang, J., Corbin, J., Trivanovic, U., Lobo, P., Kirchen, P., Rogak, S., Gagné, S., Miller, J. W., & Cocker, D. (2020). Comprehensive analysis of the air quality impacts of switching a marine vessel from diesel fuel to natural gas. *Environmental Pollution*, *266*. https://doi.org/10.1016/j.envpol.2020.115404
Raj, A. (2016). Methane emission control. *Johnson Matthey Technology Review*, *60*(4), 228–235. https://doi.org/10.1595/205651316X692554
Rakopoulos, C. D., Kosmadakis, G. M., Dimaratos, A. M., & Pariotis, E. G. (2011). Investigating the effect of crevice flow on internal combustion engines using a new simple crevice model implemented in a CFD code. *Applied Energy*, *88*(1), 111–126. https://doi.org/10.1016/j.apenergy.2010.07.012
Shen, Z., Wang, X., Zhao, H., Lin, B., Shen, Y., & Yang, J. (2021). Numerical investigation of natural gas-diesel dual-fuel engine with different piston geometries and radial clearances. *Energy*, *220*, 119706. https://doi.org/10.1016/j.energy.2020.119706
Shen, Z., Wang, X., Zhao, H., Shen, Y., & Yang, J. (2020). Numerical Investigation of Diesel-Spray-Orientated Piston Bowls on Natural Gas and Diesel Dual Fuel Combustion Engine. *SAE Technical Papers*, *2020-April*(April), 1–10. https://doi.org/10.4271/2020-01-0311
SINTEF. (n.d.). *APPLIED RESEARCH,TECHNOLOGY AND INNOVATION - SINTEF*. Retrieved May 18, 2021, from https://www.sintef.no/en/sintef-group/this-is-sintef/
Sommer, D. E., Yeremi, M., Son, J., Corbin, J. C., Gagné, S., Lobo, P., Miller, J. W., & Kirchen, P. (2019). Characterization and Reduction of In-Use CH 4 Emissions from a Dual Fuel Marine Engine Using Wavelength Modulation Spectroscopy. *Environmental Science and Technology*, *53*(5), 2892–2899. https://doi.org/10.1021/acs.est.8b04244
Stenersen, D., & Thonstad, O. (2017). *GHG and NOx emissions from gas fuelled engines*.
Turnbull, R., Dolatabadi, N., Rahmani, R., & Rahnejat, H. (2020a). An assessment of gas power leakage and frictional losses from the top compression ring of internal combustion engines. *Tribology International*, *142*(September 2019), 105991. https://doi.org/10.1016/j.triboint.2019.105991
Turnbull, R., Dolatabadi, N., Rahmani, R., & Rahnejat, H. (2020b). An assessment of gas power leakage and frictional losses from the top compression ring of internal combustion engines. *Tribology International*, *142*(September 2019), 105991. https://doi.org/10.1016/j.triboint.2019.105991
UN. (2020). *— SDG Indicators*. https://unstats.un.org/sdgs/report/2020/goal-13/
Ushakov, S., Stenersen, D., & Einang, P. M. (2019). Methane slip from gas fuelled ships: a comprehensive summary based on measurement data. In *Journal of Marine Science and Technology (Japan)* (Vol. 24, Issue 4, pp. 1308–1325). Springer. https://doi.org/10.1007/s00773-018-00622-z
UT99. (2021). *Oil mist separators of the UPF-CCV product range – UT99*.

https://www.ut99.com/en/upf-ccv-product-range
Wärtsilä. (2019). *Wärtsilä 50DF product guide*.
Wei, L., & Geng, P. (2016). A review on natural gas/diesel dual fuel combustion, emissions and performance. In *Fuel Processing Technology* (Vol. 142, pp. 264–278). Elsevier. https://doi.org/10.1016/j.fuproc.2015.09.018
World Nuclear Association. (2016). *Heat values of various fuels*. Information Library / Facts and Figures. http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

APPENDIX

The survey sent out to the manufacturers is attached in an embedded pdf file below.

Methane slip prevention

1. **Which of the following factors/areas has been the most important for reducing methane slip in your latest 4-stroke LPDF model?**
   Tick one of the boxes for each factor/area. 1 = insignificant 5= of most importance

	1	2	3	4	5
Reduction of crevices in the combustion chamber	☐	☐	☐	☐	☐
Prevention of blow-by passing the piston	☐	☐	☐	☐	☐
Design of the piston bowl	☐	☐	☐	☐	☐
Valve timing	☐	☐	☐	☐	☐
Tuning of engine control system	☐	☐	☐	☐	☐
Improvement of injection system	☐	☐	☐	☐	☐
Others :	☐	☐	☐	☐	☐

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