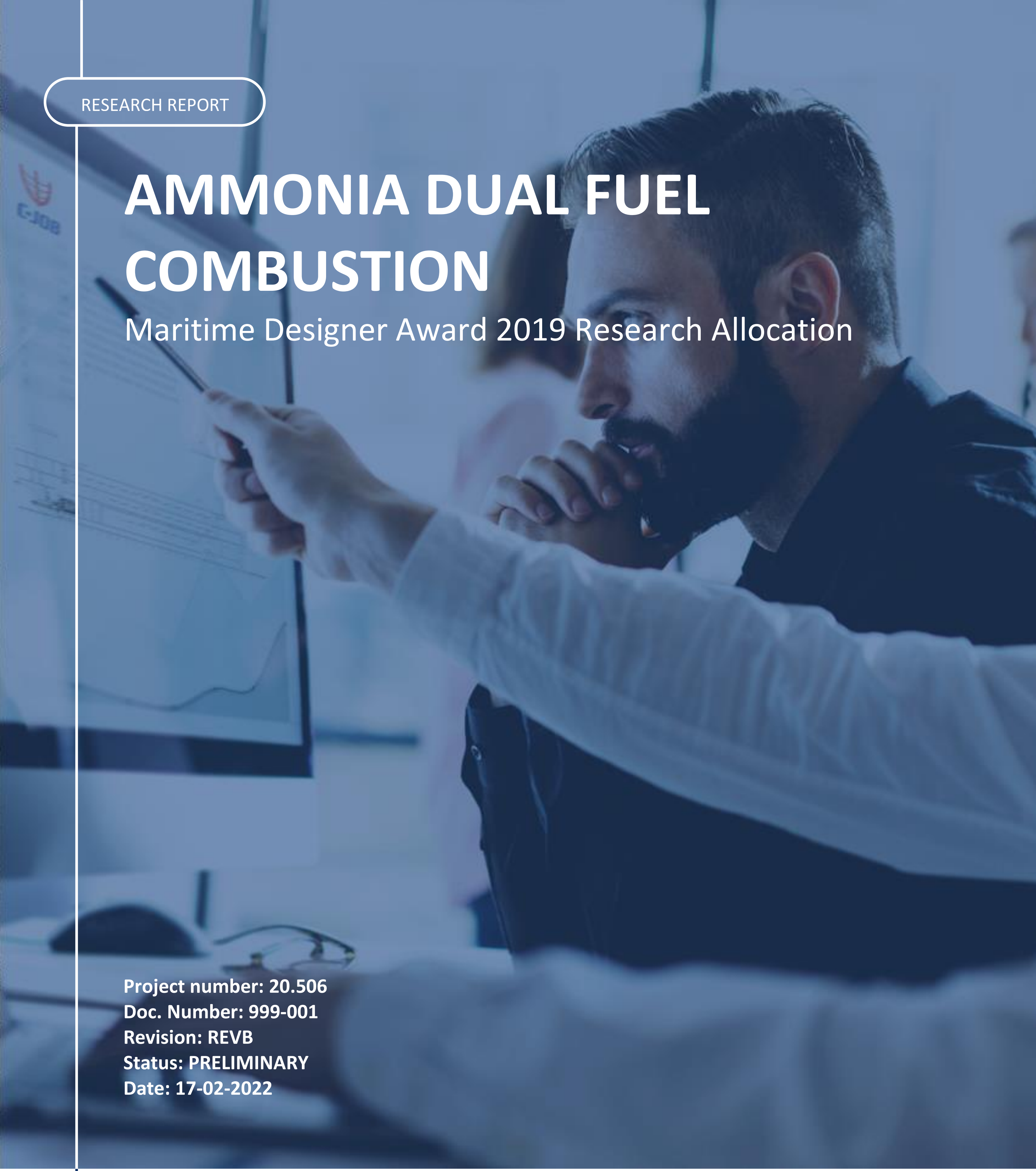

RESEARCH REPORT

AMMONIA DUAL FUEL COMBUSTION

Maritime Designer Award 2019 Research Allocation

Project number: 20.506
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Status: PRELIMINARY
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Stichting Timmerprijs & Progression-Industry

NETHERLANDS MARITIME TECHNOLOGY
NMT Designer Award
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1 INTRODUCTION

As part of the goal of C-Job Naval Architects 'driving the global maritime industry towards sustainability by dedication and ingenuity' the research and development of renewable fuels is vital. C-Job believes the future will hold a mix of renewable fuels, which will reduce and ultimately eliminate harmful emissions. Ammonia has a lot of potential as one of these renewable fuels for the maritime industry.

In line with that, C-Job has conducted research into safe and effective application of ammonia as a marine fuel. This research has been awarded with the Maritime Desginer Award 2019. With the award, additional funds (€24,000.-) were made available by Stichting Timmersprijs to perform follow-up research. These funds have been utilized to accommodate research into ammonia + diesel combustion in an internal combustion engine. This research has been executed by Progression-Industry and covered in a separate full report. This report presents a summary of the main results of the research into ammonia + diesel combustion in an internal combustion engine.

The goal of the research is an initial exploration of ammonia diesel combustion on experimental level to obtain more fundamental knowledge of ammonia diesel combustion. As acknowledgement, C-Job would like to thank Stichting Timmersprijs for providing the funds and Progression-Industry for executing this research with the limited resources.

2 ABBREVIATIONS

General:

ECU	Engine Control Unit
HRR	Heat Release Rate
HC	Hydrocarbons
IMEP	Indicative Mean Effective Pressure
LPG	Liquefied Petroleum Gas
MEP	Mean Effective Pressure
PM	Particulate Matter
SOC	Start Of Combustion
TDC	Top Dead Centre

Chemicals:

NH_3	Ammonia
CO_2	Carbon Dioxide
CO	Carbon Monoxide
NO_x	Nitrogen Oxides
N_2O	Nitrous Oxide

3 TEST SETUP

To test the performance of ammonia in compression ignition engines a Hatz E89G one cylinder 4-stroke diesel engine is used. The engine is connected to an electric machine, together forming a diesel generator. The properties of the diesel engine are shown in Table 3.1.

Property	Value	Unit
Cylinders	1	[-]
Bore	91	[mm]
Stroke	105	[mm]
Stroke volume	683*	[cm^3]
Compression ratio	21:1	[-]
Maximum power	6.6	[kW]

Table 3.1: Engine properties

*The original engine was rebored, increasing its bore and stroke volume from 90 mm to 91 mm and from 668 to 683 respectively.

Figure 3.1 gives a schematic overview of the test setup. Liquefied Petroleum Gas (LPG) or ammonia (NH_3) can be selected by means of a three way valve. The LPG or NH_3 are evaporated and injected into the air intake of the engine (port fuel injection). No means to measure temperature and pressure of the LPG/ammonia injection where available. The LPG/ammonia injector is coupled to an Engine Control Unit (ECU) which determines the injection timing and duration based on the engine speed and a throttle input by means of a potentiometer. A pressure sensor measures the in-cylinder pressure, the emissions are measured with multiple sensors. The engine power and torque can be determined by the in-cylinder pressure or with the generator coupled to the engine.

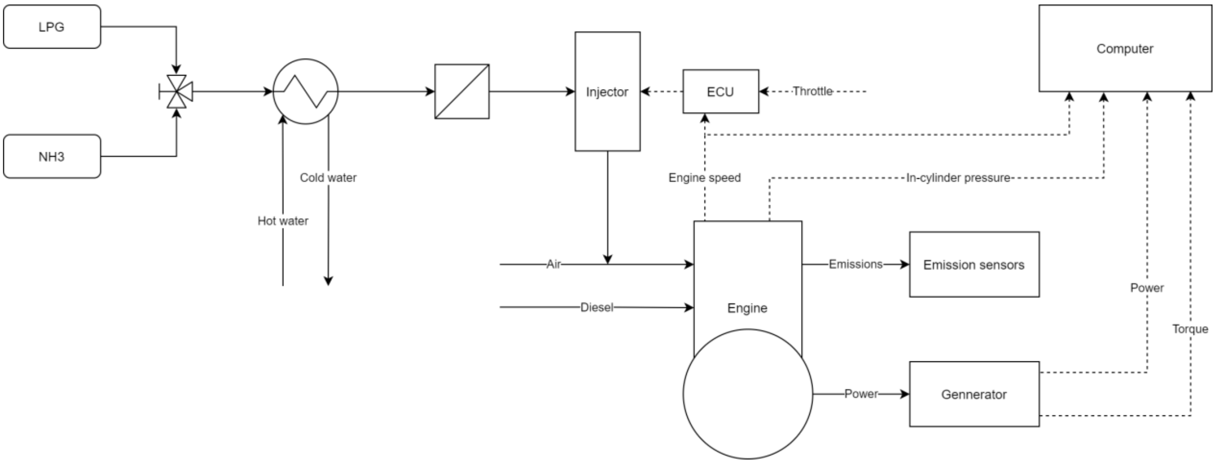

Figure 3.1: Test setup schematic

4 TEST PROTOCOL

The power during the experiments is calculated using the maximum Mean Effective Pressure (MEP) in the cylinder. The mean effective pressure is the average pressure on the piston during the combustion process, which is independent of the cylinder volume. In this experiment the Gross Indicated Mean Effective Pressure ($IMEP_g$) is used, which is based on the mean pressure during compression and expansion strokes. The experiments are performed at 1200 RPM, which is lower than the maximum engine speed of 1800 RPM, therefore the maximum achievable power is lower. The formula below is used to calculate the maximum power at 1200 RPM.

$$P_{i,g} = IMEP_g \cdot V_d \cdot \frac{n_e}{k \cdot 60}$$

$P_{i,g}$ is the calculated power in Watt, $IMEP_g$ is the average pressure in pascal, V_d is the stroke volume of the cylinder in cubic meter, n_e is the engine speed in revolutions per minute (RPM), and k is a factor 2 for the number of effective strokes per cycle (4-stroke). The maximum power at 1200 RPM is 4.1 kW or 6 bar $IMEP_g$.

Because NH_3 and LPG have relatively high self-ignition temperatures, a small amount of diesel fuel is injected to ignite the NH_3/LPG. The diesel fuel injected to ignite the alternative fuel is called the pilot fuel.

Four individual tests have been carried out, a reference test with 100% diesel fuel, a test with LPG, and two tests with NH_3 (low and high pilot). During the tests, the engine is started on 100 % diesel, to run the engine without stalling at 1200 RPM, a minimum $IMEP_g$ of 0.6 bar is required. Subsequently the engine power was increased stepwise by adding LPG or NH_3, increasing the power output. Table 4.1 shows the four test cases and the corresponding power by pilot fuel, overall power range and mass fraction pilot fuel range.

Fuel condition	$IMEP_g$ based on pilot fuel only [bar]	$IMEP_g$ based on pilot and main fuel [bar]	Power based on pilot and main fuel [kW]	Pilot fuel range [% of mass]
Diesel (reference)	N.A.	0.5 – 4.6	0.2 – 3.0	N.A.
LPG (low pilot)	0.6	0.7 – 4.8	0.4 – 3.2	60 – 42
NH_3 (low pilot)	0.6	0.6 – 2.5	0.4 – 1.7	73 – 39
NH_3 (high pilot)	1.6	1.6 – 3.0	1.1 – 2.1	64 – 34

Table 4.1: Fuel scenarios

Because the amount of injected pilot fuel remains constant, but the power output increases during a test run, the relative share of pilot fuel decreases when the engine power increases. This can be seen in the right hand side column of Table 4.1 and in Figure 4.1. It should be noted that the LPG curve in Figure 4.1 contains an error at 3.7 bar IMEP$_g$ because a fault in the LPG flow measurement.

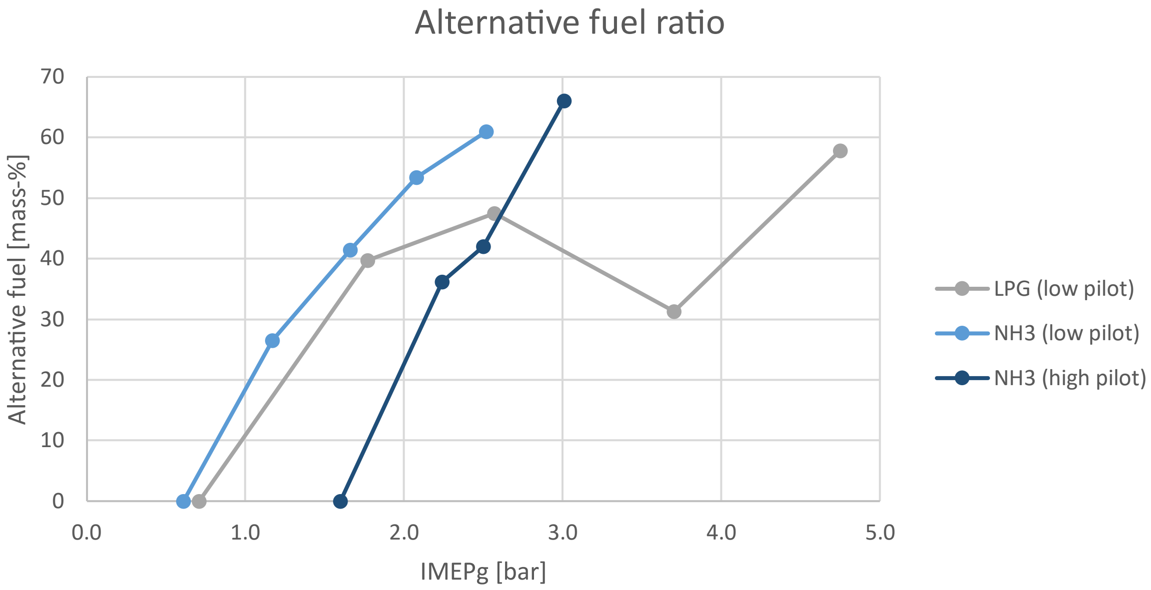

Figure 4.1: Alternative fuel ratio

5 COMBUSTION

The in-cylinder pressure is measured for all four test conditions. These measurements help to better understand the combustion process and the impact of LPG or NH_3 on the process. The results of these measurements are discussed in this chapter.

The fuel pressure is measured in order to confirm that engine power increase is caused by adding LPG or NH_3 and not by the pilot fuel. These measurements confirm that the amount of injected pilot fuel remains the same while the $IMEP_g$ increases. This proves that the increase in power is caused by the injected LPG or NH_3.

In-cylinder pressure

Figure 5.1 shows the in-cylinder pressure for the LPG (low pilot) test case and the Diesel (reference) test case at 2.2 bar $IMEP_g$ and an engine speed of 1200 RPM. When LPG is injected, the in-cylinder pressure is noticeably lower at the start of combustion (about 0 degree crank angle). It is suspected that the decrease in pressure is caused by the cold LPG subtracting heat from the cylinder during the compression.

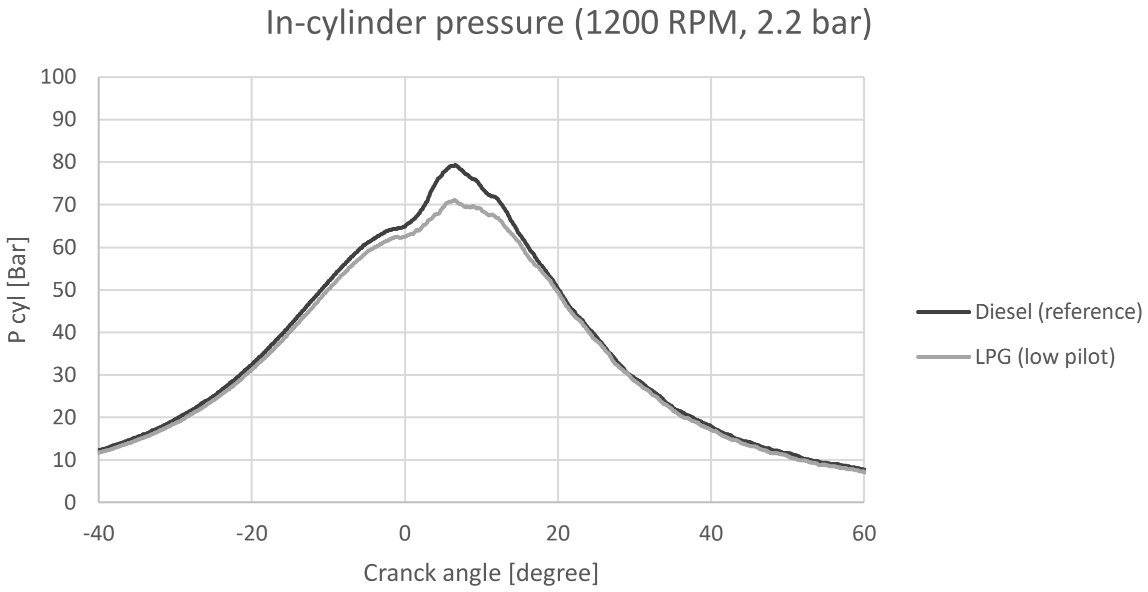

Figure 5.1: In-cylinder pressure during LPG injection at 1200 RPM and 2.2 bar $IMEP_g$

Figure 5.2 shows the in-cylinder pressure for the NH_3 (low pilot) and NH_3 (high pilot) test case at 1200 RPM and 2.1 bar $IMEP_g$. The figure shows that the peak pressure is higher when more pilot fuel is injected. This could also be caused by the cold ammonia subtracting heat from the cylinder during compression, because less ammonia is injected when more pilot fuel is used. The higher flame speed of diesel compared to ammonia could also explain the increase in peak pressure when more pilot fuel is used. The combustion duration will be shorter because of the higher flame speed which increases the peak pressure. Lastly, the figure shows that the combustion starts later when less pilot fuel is used. This causes lower peak pressures because the combustion takes place when the in-cylinder volume is bigger. The tests from (Reiter & Kong, 2011) show similar results, they also suspect that the lower peak pressure is caused by the lower flame speed of ammonia.

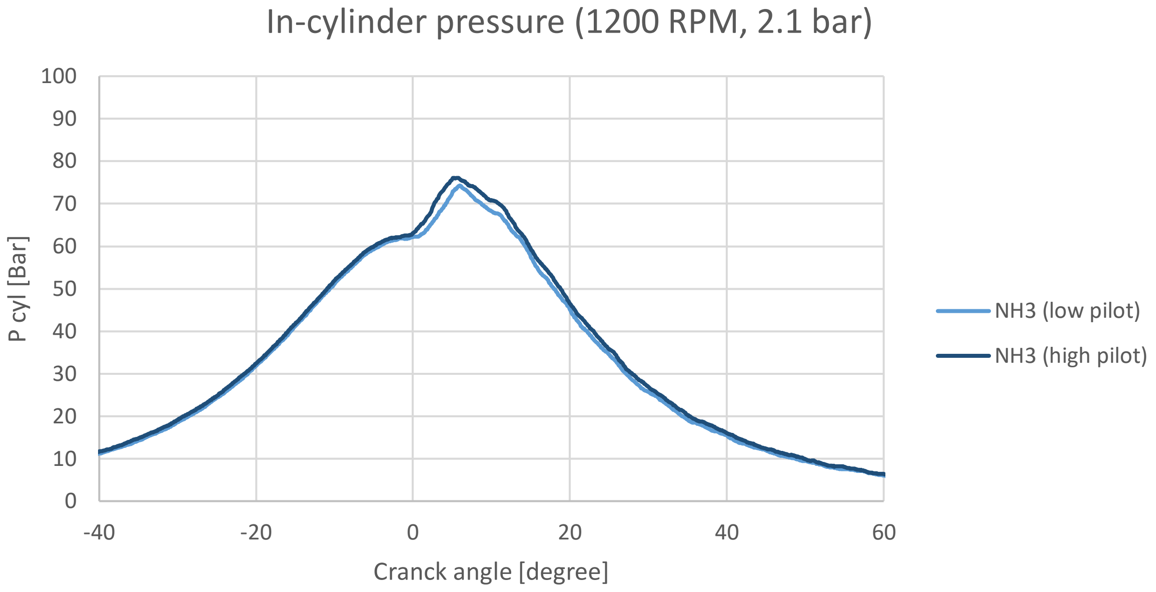

Figure 5.2: In-cylinder pressure during ammonia injection at 1200 RPM and 2.1 bar $IMEP_g$

Heat release rate

Figure 5.3 shows the Heat Release Rate (HRR) of LPG with the HRR of diesel as reference. A lower peak pressure could be the result of a lower heat release rate when LPG is used as fuel. A lower HRR means that the release of heat is distributed over a longer period of time. The figure shows that LPG has a lower HRR which corresponds with the lower peak pressure in Figure 5.1.

Furthermore, the figure clearly shows a later start of combustion when LPG is used. This is possibly because the LPG is ignited after the diesel fuel is ignited. The difference in Start Of Combustion (SOC) is smaller at higher load conditions, this is possibly caused by the higher temperatures when the engine operates at higher engine loads.

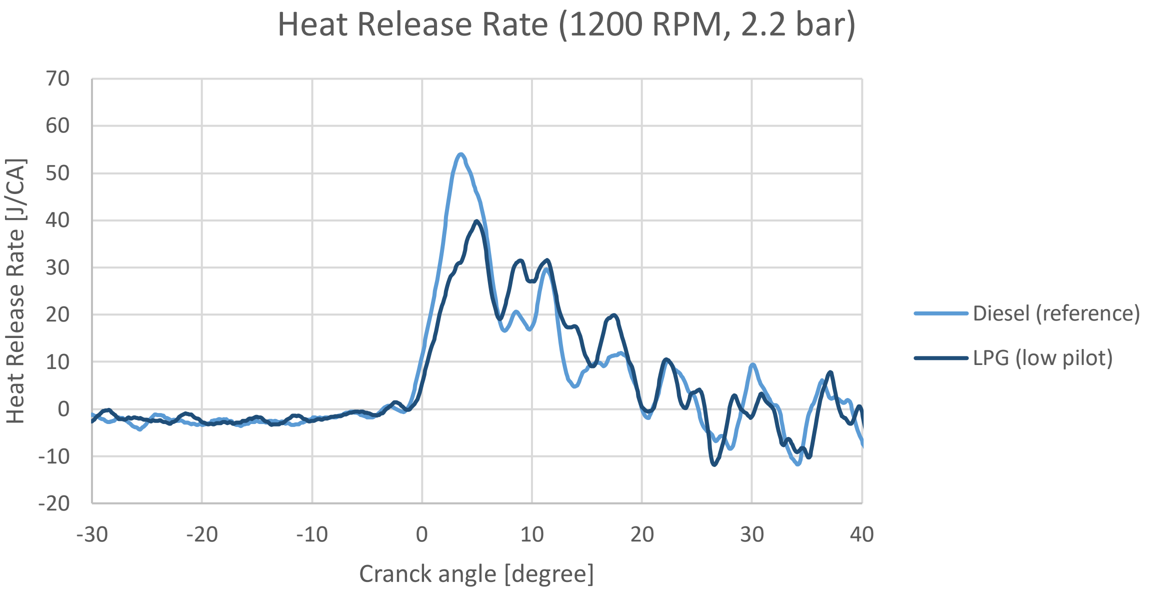

Figure 5.3: Heat Release Rate for LPG at 2.2 bar power

Figure 5.4 shows the HRR during the combustion of ammonia at 1200 RPM and 2.1 bar IMEP$_g$. The figure shows that the combustion starts earlier when more pilot fuel is used. With more pilot fuel a bigger ignition source is created, which results in higher temperatures, promoting the combustion of ammonia.

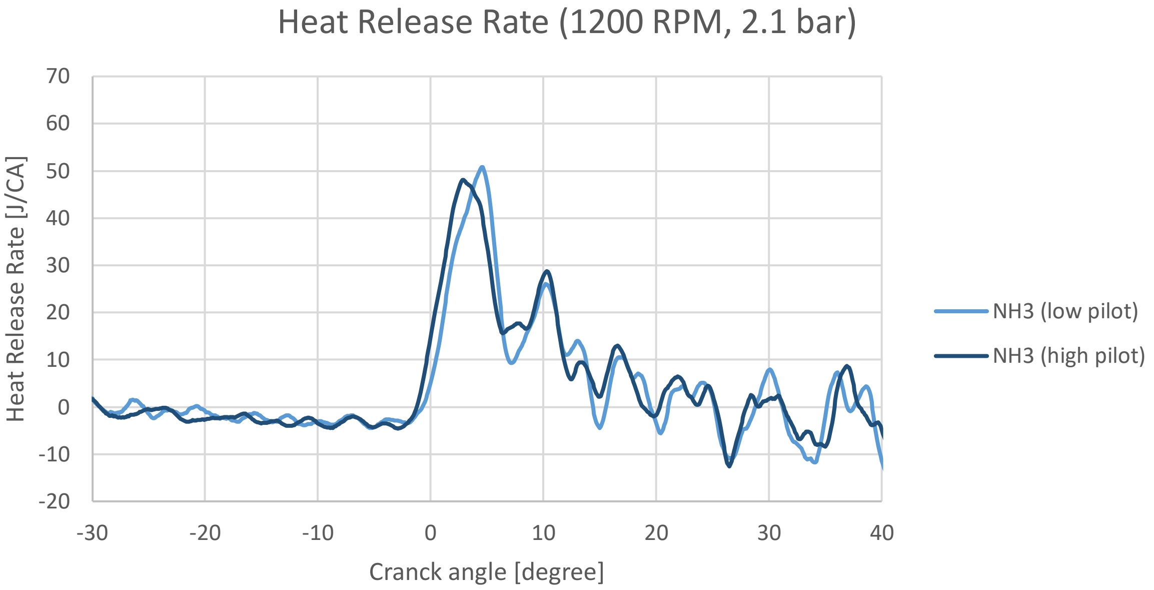

Figure 5.4: Heat Release Rate for ammonia at 2.1 bar power

When the engine load is increased by injecting more ammonia, the relative amount of pilot fuel is reduced. This negatively effects the combustion at higher engine loads.

Reiter and Kong performed similar tests wherein the pilot fuel injection remains constant and the power was increased by adding more ammonia. They expect that there are two causes for the delayed combustion at higher ammonia mass ratios. The first cause is a reduced diesel fuel spray, decreasing the fuel momentum for effective atomization and mixing leading to ignition. The second cause is the high resistance of ammonia to autoignition, making it harder to ignite the mixture when more ammonia is used.

Minimum pilot fuel mass ratio

Because the engine started to run poorly at higher LPG and NH_3 ratios the maximum engine power was not obtained with LPG or with NH_3. It is suspected that the poor running of the engine is caused by the pilot injection timing or a lower pilot fuel ratio. The maximum achieved engine power and corresponding mass fraction pilot fuel are shown in Table 5.1.

Fuel condition	Max IMEP [bar]	Percentage of max power [%]	Pilot fuel [mass-%]
Diesel (reference)	6.0	100	N.A.
LPG (low pilot)	4.8	77	58
NH_3 (low pilot)	2.5	42	61
NH_3 (high pilot)	3.0	51	66

Table 5.1: Maximum obtained power for multiple fuels

Reiter and Kong performed similar experiments with ammonia in diesel engines. They achieved significantly lower pilot fuel mass concentrations down to 7% on mass basis, while the table above shows that a minimum pilot fuel mass percentage of 61% was required for ammonia. The difference between these values can be explained by the different test setups. Reiter and Kong used a 4.5 litre 4-cylinder diesel engine with turbo charger. Because the engine has a greater volume a greater absolute amount of pilot fuel is used, which will improve combustion of the ammonia air mixture. Furthermore, the turbocharger increases the oxygen concentration in the cylinder, which to some extend compensates for the air that is replaced with gaseous ammonia, improving the combustion.

Engine efficiency

The efficiency of the engine was measured during the experiments. The results of the efficiency as function of the engine power are shown in Figure 5.5. Because the engine power was increased by adding the alternative fuel the alternative fuel ratio also increases with the power. The engine efficiency for LPG is faulty because an error in the LPG flow measurements.

The figure shows that the efficiency of the engine is within the same order of magnitude for all 4 cases. However, the ammonia measurements are not completed because of issues with the valve within the vaporizer. Therefore, there is no data for ammonia at higher engine power. It is possible that the engine efficiency will drop at higher power because the injected ammonia allows less oxygen in the cylinder.

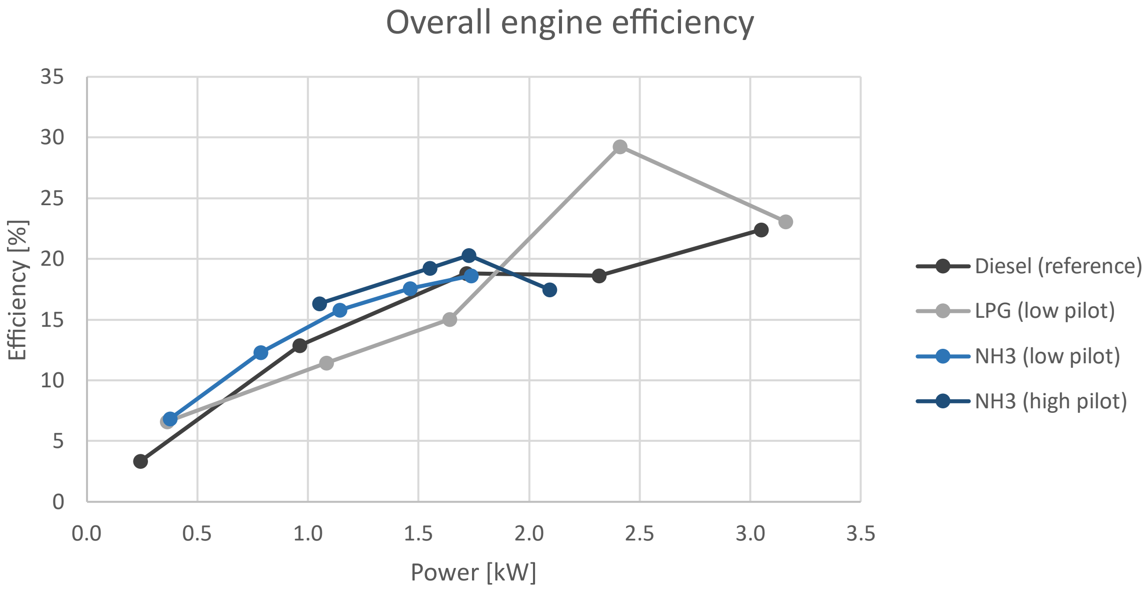

Figure 5.5: Overall engine efficiency

Combustion efficiency

The combustion efficiency cannot be measured directly. However, both high CO and Hydrocarbons (HC) concentrations indicate incomplete combustion. Figure 5.6 shows that the CO concentrations increase when more LPG or ammonia is added. Figure 5.7 shows an increase in HC emissions when more LPG is added. Both the increase in CO and HC indicates an increase in incomplete combustion.

The HC emissions are relatively constant and similar for the diesel and ammonia case. Therefore, the amount of unburned diesel during ammonia operation is similar to the amount of unburned diesel in regular operation.

When ammonia is used, the increase in CO emission is less than with LPG, ammonia does not contain carbon, and therefore less CO can be formed during the combustion.

Relative to the NH_3 (low pilot) scenario, the NH_3 (high pilot) scenario has les CO an HC emissions. This indicates that there is better combustion when more pilot fuel is injected. The improved combustion is likely caused by the larger amount of pilot fuel creating higher temperatures in the cylinder.

The research from Reiter and Kong shows similar results, when less pilot fuel is used at constant engine power, the CO and HC emissions increase. Reiter and Kong explain that this effect is caused by the lower flame temperature of ammonia. When more ammonia is used to replace diesel fuel, the overall combustion temperature goes down, creating more CO and HC emissions.

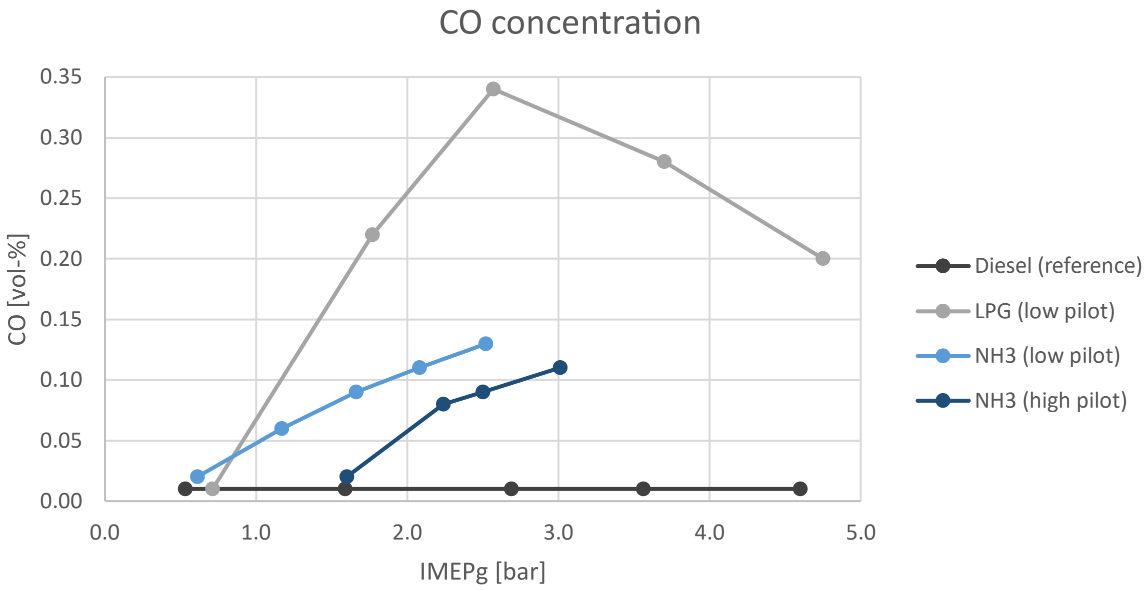

Figure 5.6: CO concentrations in the exhasut gasses

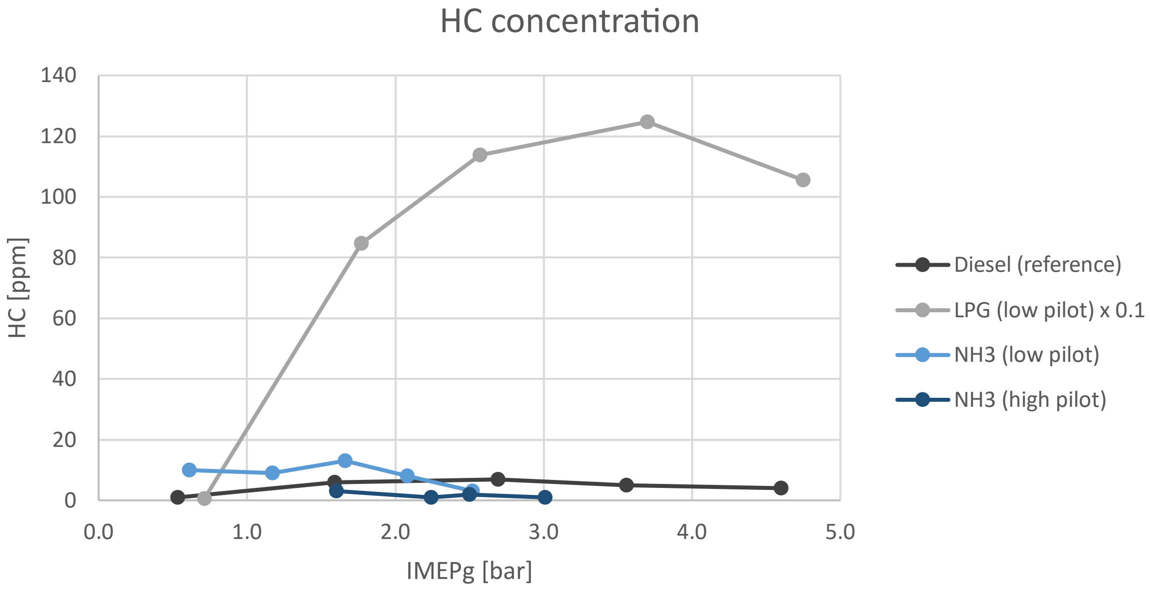

Figure 5.7: HC concentartions in the exhaust gasses

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6 EMISSIONS

In this section the results regarding the emissions of the engine are discussed. Because of issues with the equipment for measuring N_2O concentrations, there are no useful results regarding the N_2O emissions.

Greenhouse gas emissions

The main reason to use ammonia and LPG is to reduce the CO_2 emissions, Figure 6.1 shows the CO_2 concentration in the exhaust gasses for multiple test cases. LPG has a higher H/C ratio and therefore the CO_2 emissions increase slower when the engine power is increase in comparison to diesel. Ammonia does not contain any carbon, and therefore it is expected that the CO_2 concentration will remain constant when the engine power in increased by adding ammonia. However, the figure shows that the CO_2 emissions decreases when the power is increased by adding more ammonia. The decrease in CO_2 emissions is presumably caused by the poor combustion of the pilot fuel due to the higher ammonia concentrations. Figure 5.7 confirms this, the figure shows that the HC emission increase when the engine power is increased by adding ammonia, indicating incomplete combustion of the pilot fuel.

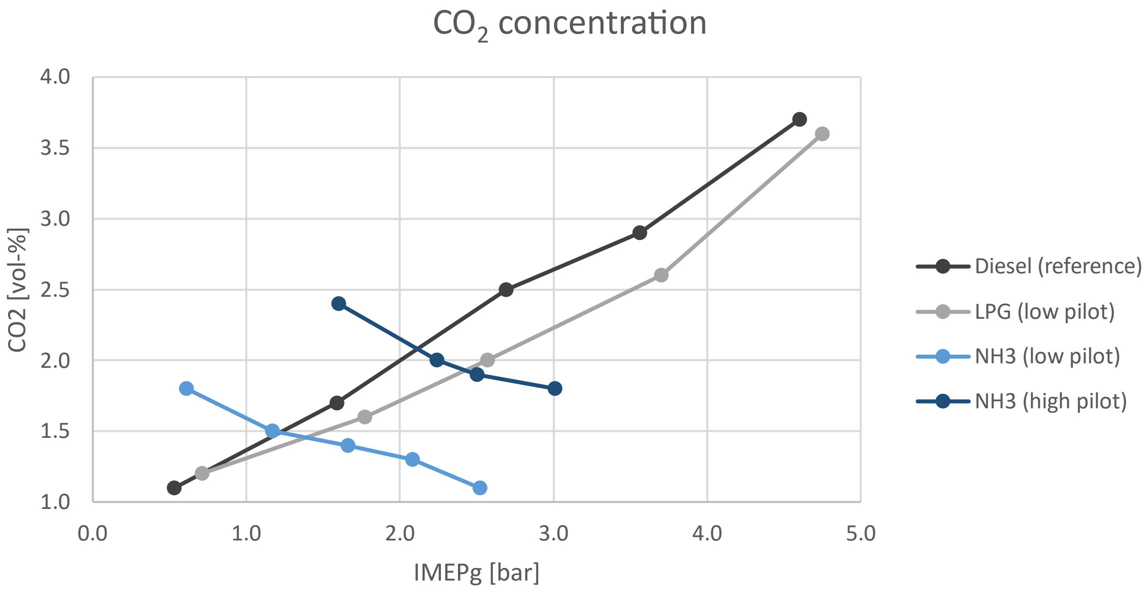

Figure 6.1: CO_2 concentration in the exhaust gasses

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Air pollution emissions

The NO_x emissions are shown in Figure 6.2. The use of LPG and diesel fuel significantly decreases the NO_x emissions. NO_x is created under high temperatures, therefore, the decrease in NO_x emission is probably caused by the relatively low flame temperature of LPG with respect to diesel. When the engine power is increased, the NO_x emissions also increase, this is because the in-cylinder temperatures increase with the engine power.

Even though ammonia has the lowest flame temperature of all three fuels, the NO_x emissions are increased. This is possibly caused by the nitrogen bound to ammonia. At higher loads the NO_x emissions decrease again, this is possibly because the lower flame temperature is outweighing the extra introduced nitrogen. Alternatively, the negatively affected combustion at higher loads could also play a part in this. Additional investigation is required to clarify this further.

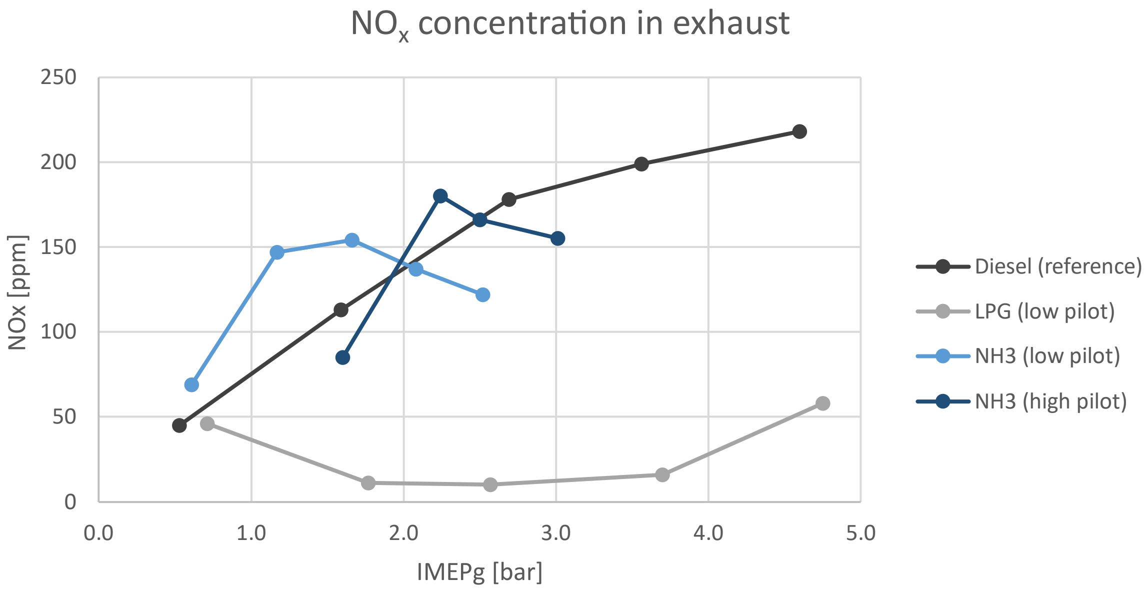

Figure 6.2: NO_X emissions in the exhasut gasses

Figure 6.3 shows relatively low and constant Particulate Matter (PM) emissions for LPG with respect to diesel. Because of the chemical composition of LPG, less particulate matter is produced when LPG is burned. Soot is produced by the incomplete combustion of fuels containing carbon, ammonia does not contain carbon and therefore, will not produce any soot. The higher PM emissions with ammonia is possibly caused by the higher pilot fuel injection and the incomplete combustion of the pilot fuel. The incomplete combustion of the pilot fuel could be caused by the ammonia replacing air in the cylinder, creating low oxygen areas, which creates the soot emissions.

Reiter and Kong measured the PM emissions at constant power while changing the ratio between ammonia and pilot fuel. Their measurements shows a constant increase in PM when the mass fraction diesel is increased. They measured PM emissions higher than regular diesel operation when more than 60% diesel is used. The authors expect that this is caused by the decrease in cylinder temperature, which is caused by bad combustion. The same phenomenon can be seen in Figure 6.3, where part of the ammonia measurements have higher PM emissions than the regular diesel measurements.

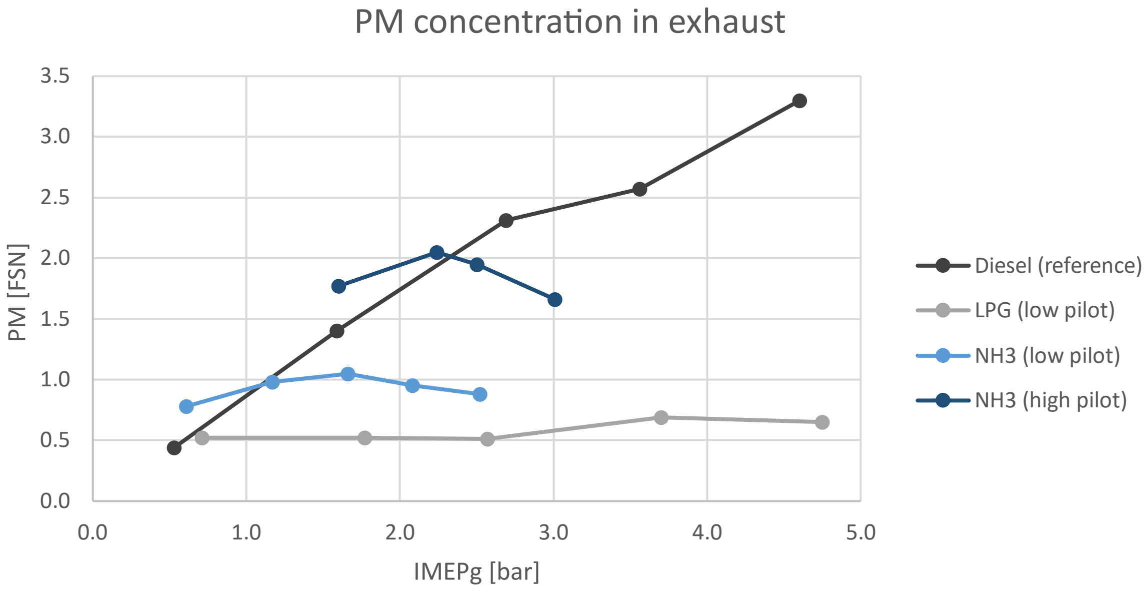

Figure 6.3: PM emissions in the exhaust gasses

Figure 6.4 shows the ammonia concentration in the exhaust gasses. Because of issues with the measuring equipment there is only data available for the NH_3 (high pilot) fuel condition. The figure clearly shows that the ammonia concentration increases when the engine power is increased by injecting more ammonia into the engine.

Reiter and Kong did similar measurements and concluded that the combustion efficiency increased when the engine power was increased by injecting more ammonia, and therefore the ammonia emission decreased. The authors suspect that the poor combustion efficiency alt lower ammonia mass ratios is caused by a very lean ammonia air mixture, that will not allow proper flame propagation.

The difference between de measurements can be explained by the ammonia mass fractions used in both experiments. Reiter and Kong used an ammonia mass fraction between 86% and 93%, in this research a mass fraction ammonia between 27% and 66% was used. The high pilot fuel fraction used in these experiments creates high combustion efficiency at lower loads, which decreases when the ammonia mass fraction increases.

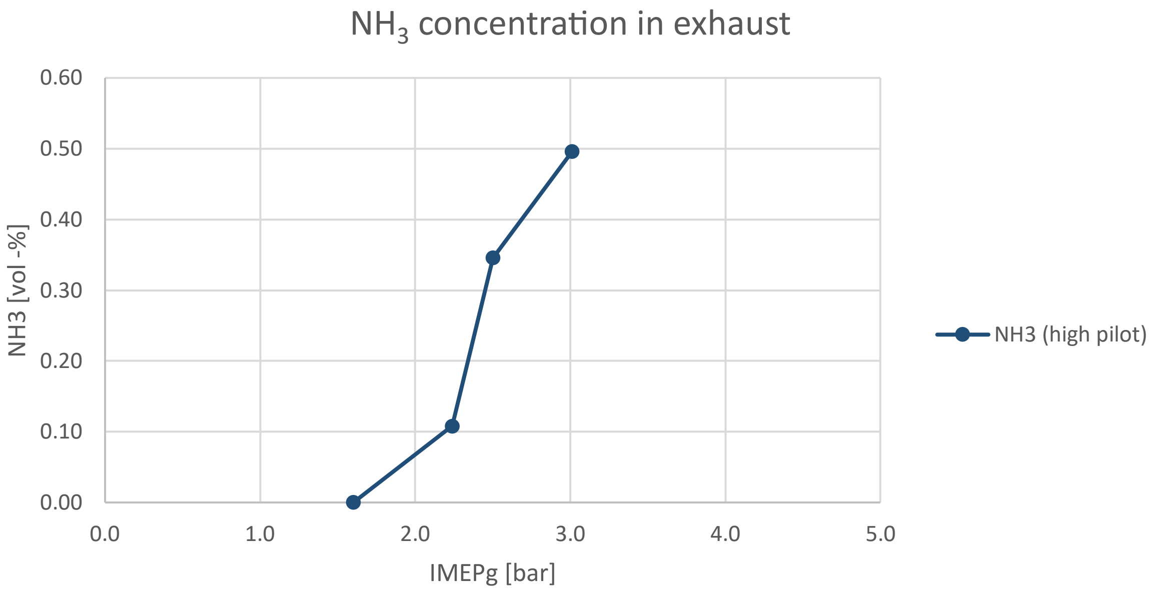

Figure 6.4: NH_3 concentration in exhaust gasses

7 CONCLUSION AND RECOMMENDATIONS

Main conclusions about ammonia diesel combustion in general:

-HRR

- It appears that the injection of LPG or ammonia subtracts heat from the cylinder, which decreases the in-cylinder pressure at the start of combustion. Furthermore, when the mass fraction ammonia is increased, the SOC is delayed and the peak pressure decreases.

-Combustion Efficiency

- When more LPG or ammonia is added, the CO emissions increase, which indicates incomplete combustion. The HC emissions are also relatively high when LPG is injected. The HC emissions indicate unburned diesel and LPG. However, the HC emissions are relatively similar for diesel and ammonia operation. Therefore, the amount of unburned diesel during ammonia operation is similar to the amount of unburned diesel under regular operating conditions at the investigated loads.

-Engine Efficiency

- The engine efficiency is within the same range for all 4 fuel conditions. However, because of issues with the valve within the vaporizer, there is no data for ammonia at higher engine power. In comparison to other studies, mainly Reiter and Kong, it is clear that a turbo charger is essential to increase the oxygen concentration in the cylinder, which to some extend compensates for the air that is replaced with gaseous ammonia, improving the combustion.

-NO_X

- When LPG is injected into the engine the NO_x emissions decrease. This is possibly caused by the flame temperature of LPG, which is relatively low compared to the flame temperature of diesel. When low amounts of ammonia are injected the NO_x emissions are relatively high, this is possibly caused by the ammonia-bound nitrogen. When more ammonia is injected the NO_x emissions start to decrease, which could be explained by the lower flame temperature of ammonia.

-CO_2, PM

- When the mass fraction LPG or ammonia increases the PM emissions decrease, because ammonia and LPG do not contain carbon. Furthermore, even though the absolute amount of injected pilot fuel remains constant when the mass fraction ammonia is increased, the CO_2 emissions decrease. This is most likely caused by the incomplete combustion of the pilot fuel.

-NH_3

- When ammonia is injected into the engine part of the ammonia is not combusted and expelled through the exhaust. When the engine load is increased the ammonia emissions are also increased. This is caused by the lower pilot fuel fraction at higher engine loads. To determine the combustion efficiency of ammonia further research is required.

Based on this research with its main conclusions about ammonia diesel combustion in general it is clear that additional research is required to translate these into results representative for marine engines. These results provide preliminary indications and general knowledge about ammonia diesel combustion as basis for further development in marine engines. Therefore, the following research recommendations are provided:

-N_2O

- Because of problems with the N_2O sensor there are no usable measurements of the N_2O emissions. For future test it is recommended to solve the issues with the N_2O sensor in cooperation with the manufacturer of the sensor.

-Alternative injection

- The tests have proven that ammonia with diesel as pilot fuel does work. However, the test also showed that dual-fuel with port fuel injection has its limits because the gaseous fuel replaces the air going into the engine, which reduces the air/fuel ration. This could lead to poor combustion performance at higher engine loads. Therefore, it is recommended to do further testing with direct liquid ammonia injection.

-Overall performance/General engine performance increase

- Reiter and Kong performed similar test but achieved much higher ammonia fractions. During their experiments they used a turbocharged engine with a greater volume. The greater engine volume allows for larger absolute amount of pilot fuel, which improves the combustion of the ammonia air mixture. Furthermore, the turbocharger increases the oxygen concentration, which improves the combustion, especially at higher loads. Therefore, it is recommended to use larger turbo charged engines for the combustion of ammonia air mixtures.

8 CLOSE OUT

Despite the limitations of the available budget and the test setup, the results are another step in the development of ammonia as a marine fuel showing the preliminary state of the potential and challenges. As per recommendation the next step would be to further research ammonia diesel combustion in a turbo charged engine, with direct liquid ammonia injection, preferably at a larger scale. This will lead to more representative results for marine engines.

As acknowledgement, C-Job would like to thank Stichting Timmersprijs for providing the funds and Progression-Industry for executing this research with the limited resources.