Extended abstract: Analysis of the Combustion Behavior and Emissions of a Fumigated Diesel-Methanol Dual-Fuel Engine

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Extended Abstract submitted for the Journées d'Etudes – March 2022

Abstract

In the past decades, many alternatives have been proposed to improve the sustainability of the transportation sector. One of the potential options, especially valuable for the shipping industry, is the fumigation of methanol in diesel-methanol dual-fuel (DMDF) engines. A literature review studies the effects of fumigating pure methanol and indicates the potential effects of fumigating hydrous methanol. Furthermore, the normal and abnormal combustion behavior as well as some of the notable trends in the emissions are studied based on experimental research.

Keywords

Internal Combustion Engine, Alternative Fuel, Diesel, Methanol, Dual-Fuel, Combustion, Emissions, Pre-ignition, Water

1. Introduction

Although shipping is the most energy-efficient mode of mass transport of cargo, international shipping is respectively responsible for 2.6%, 15% and 13% of the global anthropogenic CO2, NOx and SOx emissions [1]. The rising awareness of climate change and local pollution imposes demanding challenges to the shipping industry, but due to the exceptional requirements of shipping, the era of the internal combustion engine is not over yet [2]. However, even under the most optimistic predictions concerning improvements in efficiency and handling emissions, no significant downward trend in emissions can be met if fossil fuels remain dominant [1]. Because of this, there is a rising interest to use alternative fuels in the shipping sector. Methanol proves to be one of the potential alternative fuels, as it is a liquid, clean burning fuel that can be made in a renewable way [3]. Downsides are the high cost of renewable methanol and the fact that currently most methanol is made in a non-renewable way.

2. Fumigating methanol in CI engines

The shipping industry is most familiar with compression ignition (CI) engines and the rules and regulations primarily aim at them. The use of methanol in a conventional CI engine on the other hand is not straight forward due to the fuel characteristics (Cetane number = 2). The fumigation concept, where methanol is injected in the intake, is the cheapest and least complex solution to use methanol in CI engines [3]. Within this dissertation the combustion characteristics, operating range, efficiency and emissions of a diesel-methanol dual-fuel (DMDF) engine are described, based on the available literature. Followed by an experimental research and data analysis of the normal and abnormal combustion behavior, the efficiency and the emissions.

2.1 Literature review

Many different aspects influence the combustion of a fumigated DMDF engine. The high heat of vaporization and the increase of the heat capacity decrease the in-cylinder temperature during the compression stroke. Around top dead center (TDC) a pilot injection of diesel (acting as a liquid spark) ignites the homogeneous methanol-air mixture, which burns through flame propagation, while the fraction of diesel that did not burn premixed, burns by diffusion combustion. The lower in-cylinder temperature, due to the methanol evaporation, leads to an increased ignition delay and hence more fuel burns premixed.

Partial burn, misfire, roar combustion and knock limit the maximum amount of diesel that can be substituted by fumigating methanol. At lower loads the maximum methanol energy fraction (MEF) increases when increasing the load, while at higher loads the maximum MEF decreases again when increasing the load.

When varying the MEF within the operating range of the DMDF engine, the change of combustion behavior results in a change of the overall efficiency. At lower loads the efficiency decreases while at higher loads it may increase. As methanol has a higher hydrogen to carbon ratio than diesel it offers the possibility of a CO_2 reduction. But as efficiency also influences the specific CO_2 emission, no general conclusion can be taken on the specific CO_2 emissions. Note that the CO_2 emission is almost zero when using renewable methanol.

Using DMDF fumigation also influences the other emissions. There is a general consensus in literature that DMDF decreases the NOx, NO and PM emissions but the NO_2, HC and CO emissions increase.

Although quite some research has been done on the effects of DMDF, some peculiarities remain. Many researchers only evaluated a low diesel substitution, they only examined low break mean effective pressure (BMEP) or their research lacks a profound quantitative analysis of the occurring phenomena. By analyzing self-performed measurements and measurements of previous years, this dissertation fills some of the research gaps.

2.2 Experimental research and data analysis

The engine used for the DMDF research is a Volvo Penta D7C-B TA high speed marine engine, which is converted to a DMDF engine, and which is fully equipped with a data acquisition system. Table 1 lists the main specifications of the engine.

Engine layout	4-stroke 6 cylinder in-line
Aspiration	Turbocharger + aftercooler
Compression ratio	19.0
Bore / stroke	108 mm / 130 mm
Displacement	7.15 l
Diesel injection system	Cam-driven injection pumps
Diesel injection pressure	1200 bar
Maximum torque / speed	904 Nm / 1500 rpm
Rated power / speed	195 kW / 2300 rpm

Table 1: Main specifications of the Volvo Penta D7C-B TA.

2.2.1 Normal combustion behavior and efficiency

A profound analysis of two operating points at 65% MEF compares DMDF at two loads. A prolonged ignition delay characterizes the low load operation (BMEP = 3.5 bar) while an increased intensity characterizes the high load operation (BMEP = 12.3 bar). These differences result in different effects on the pressure, temperature and efficiency. At low load DMDF causes a decrease of the efficiency (-29.7%) due to the less isochoric expansion while at high load the efficiency remains the same. These conclusions are in line with reports in literature at different loads and at lower substitution levels [3,4,6-8].

2.2.2 Emissions in normal operation

When measuring the NOx and NO emissions over a wide range of MEF a parabolic trend (with a local minimum) can be noticed at the higher loads [4]. The dissertation further investigates the parabolic behavior by incorporating reaction kinetics of the Zeldovich reaction mechanism. Figure 1 shows the effect of DMDF on the development of the in-cylinder temperature and the resulting rate constant of the NO production. There is a positive correlation between the development of the global rate constant and the total NOx formation ($R = 0.60$-0.75), and this way the parabolic trend can be explained.

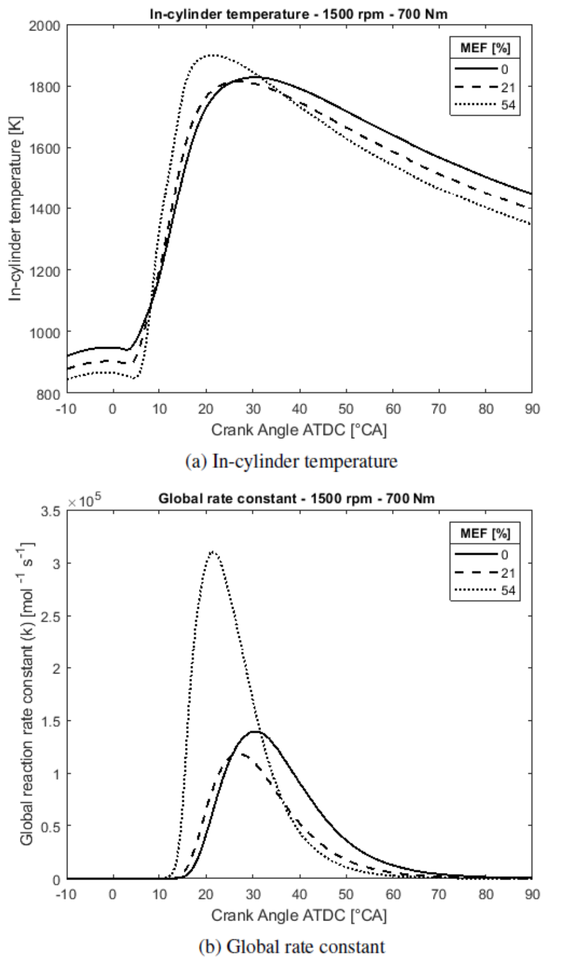

Figure 1: In-cylinder temperature and global rate constant at high load (BMEP = 12.31 bar).

As some part of the NO converts to NO2, the total amount of NOx consists of a blend of NO and NO2. The oxidation of methanol leads to higher concentrations of HO2 radicals, which promote the conversion of NO to NO2. Furthermore, the ratio of NO2/NO also depends on the oxygen availability. The ratio seems to depend approximately linearly on the MEF and quadratically on the air-fuel equivalence ratio (R=0.893). Figure 2 emphasizes the dependency of the ratio of NO2/NO on the MEF and the air-fuel equivalence ratio (i.e. oxygen availability). The contour lines follow a trend as described above till a certain MEF, but for higher substitution levels the effect of the MEF diminishes, for a ratio NO2/NO of one this occurs above 40% MEF.

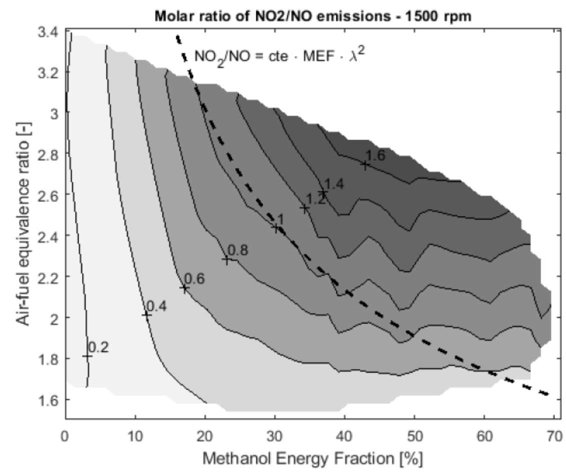

Figure 2: Molar ratio of NO2/NO emissions as a function of MEF and the air-fuel equivalence ratio for different loads at 1500 rpm.

In DMDF operation there appears to be a third order decrease of the specific soot emissions for an increasing MEF, see Figure 3. The low tendency of methanol to form soot (due to its molecular structure) and the increasing amount of fuel burned in the premixed phase are widely accepted explanations. A quantitative analysis indicates that these explanations still underestimate the substantial decrease of the soot emissions. The increasing amount of fuel-bound oxygen in methanol, which enhances the soot oxidation after being formed, is suggested as an extra reason for the considerable decrease of the soot emissions.

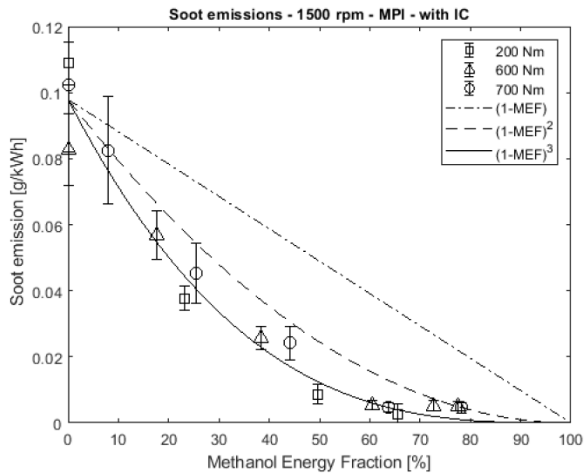

Figure 3: Specific soot emissions at 1500 rpm.

2.2.3 Abnormal combustion behavior

To fully profit the advantages of methanol, only just as much pilot injection of diesel should be used as required to ignite the methanol-air mixture. Different parameters are evaluated on their capability to determine and predict the upper limits of the MEF described above. But no parameter is found to adequately predict them. Depending on the load, several parameters may be used to detect the limit, but no precise values are found to rigorously determine it, as no measurements are done beyond the operating limit of the engine.

The auto-ignition of methanol before the injection and auto-ignition of diesel is called pre-ignition. As it gives rise to knocking conditions, limits the maximum MEF and increases the soot emission, it should be avoided. Pre-ignition did not occur if the in-cylinder temperature before the start of combustion remained below 985K. There is a relation between the in-cylinder temperature around TDC and the intake temperature, but the relation depends on the engine, the operating point and the MEF. Future research is recommended to examine the influence of the air-methanol ratio on the limiting temperature for pre-ignition.

3. Hydrous methanol in DMDF engines

During the production of pure methanol, the dehydration step accounts for a considerable part of the overall cost and energy requirement [9]. Moreover, water injection (WI) in the intake of CI engines also leads to NOx reductions. So fumigating hydrous methanol seems interesting from an economical, an energetic and from an emission point of view.

Therefore, a literature review elaborates about the effects of WI in CI engines and the use of hydrous methanol in DMDF engines. A short overview of the potential injection locations is given, followed by the effects of WI on the combustion characteristics, the operating range and the emissions.

The effects of WI on the combustion behavior can be split up in three groups: the thermal effects, the chemical effects and the dilution effects. Mainly because respectively: the heat of evaporation and the increase of the specific heat capacity cause a cooling effect, a small part of the water molecules dissociate in H and OH radicals and the remaining part can be considered as inert and hence dilutes the mixture.

As water is a knock suppressant, WI in DMDF engines may increase the high load operating limit, but the decrease of reactivity may decrease the substitution limit at the partial burn and misfire boundaries.

WI does not influence the efficiency unless an excessive amount of water is injected, and it does not cause a considerable difference in CO2 emissions. Due to the thermal and dilution effects, WI reduces the NOx emissions but there is a trade-off relation with other emissions such as PM, NO2, HC and CO.

The most interesting characteristics of WI in a DMDF engine are the NOx reduction and the possible increase of the substitution limit at high load.

4. Conclusions

- Based on a vast amount of selection criteria, methanol proves to be a valuable alternative fuel, principally because it is a liquid, clean burning fuel that can be made in a renewable way.
- A prolonged ignition delay mainly characterizes the low load operation while an increased intensity characterizes the high load operation.
- At low load DMDF causes a decrease of the efficiency (-29.7%) due to the less isochoric expansion while at high load the efficiency remains the same.
- The parabolic trend in the NOx and NO emissions (with a local minimum) at the higher loads can be explained by incorporating reaction kinetics of the Zeldovich mechanism.
- The ratio of NO2/NO emission depends both on the MEF as on the oxygen availability.
- There appears to be a third order decrease of the specific soot emission for an increasing MEF. This may be explained by the low tendency of methanol to form soot, the increase of the amount of diesel that burns premixed and the increasing amount of fuel-bound oxygen which enhances the soot oxidation.
- Above an in-cylinder temperature of 985 K, a pre-ignition may occur, which gives rise to knocking conditions, limits the maximum MEF and increases the soot emissions.
- Based on a literature review, the fumigation of hydrous methanol seems interesting to reduce the NOx production and to increase the substitution limit at high loads.

5. Refereces

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