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POMDME-diesel blends: Evaluation of performance and exhaust emissions in a single cylinder heavy-duty diesel engine

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ABSTRACT

Oxygenated fuels produced from methane-based products are characterized by strong capability of reducing soot at the exhaust of internal combustion engines. In addition some oxygenates are characterized by similar physical properties to diesel thus not requiring substantial modifications to the engine infrastructure. Therefore, their production on industrial scale could be proposed to obtain blends with commercial diesel once results on emission reduction and fuel economy would have been experienced.

In the present paper different poly (oxymethylene) dimethyl ethers (POMDME) in diesel blends (5 and 10%) have been investigated in a single cylinder heavy duty diesel engine in order to achieve a complete overview of their impact on engine performance and exhaust emissions. In addition to exhaust soot and gas analysis, the kL calculation has been carried on in order to discuss further details regarding the soot formation/oxidation dominant phases for the different fuels. For this purpose a miniaturized optical light probe (OLP) has been mounted directly in the engine combustion chamber.

The comparison between the POMDME diesel blends and commercial diesel has shown a significant reduction in soot emissions, close to 35%. Moreover no significant increase in NO_X emissions has been found, highlighting as molecular oxygen can be not crucial (at least up to the percentages considered in the present paper) for this pollutant in a premixed plus diffusive combustion mode.

1. Introduction

In order to achieve a reduction in pollutants, several methodologies and measures have been adopted by legislators, academia and industry [1]. Research laboratories and manufacturers are focusing, among others, on the use of fuel blends with a variety of physical and chemical properties. Among these fuels oxygenates have been widely investigated [2–17] because of the possibility of suppressing the C—C bonds and therefore the soot precursor species with the consequence of reducing soot emissions from diesel engines. In particular, poly (oxymethylene) dimethyl ethers (POMDME or OME in abbreviated form) are characterized by a $CH_3{-}O{-}(CH_2{-}O)_n{-}CH_3$ general structure, with a mass fraction of oxygen within the molecule up to 50%. These fuels can be obtained from methanol in a process chain described in detail by Burger et al. [18–20]. The first fuel of the POMDME family, dimethoxymethane (DMM), is characterized by only one $CH_2{-}O$ group and has been studied both blended with commercial diesel and pure. Kenney et al. [3], for instance, investigated a 15% DMM in diesel blend in several speed/load conditions and found a PM reduction at any investigated operative point while no significant reduction in NO_X emissions was detected. Moreover Ogawa et al. [4] achieved ultra-low emission and efficient diesel combustion with pure DMM and a combination of high EGR and a three-way catalyst. Because of its high volatility (boiling point at 42 °C), though, problems related to vapour lock may occur thus modifications to the fuel system are required, as stated by various authors investigating DMM. For example, Sirman et al. [5] investigated a 15% DMM in diesel blend in a direct injection diesel engine and found great benefits in exhaust emission reduction. They state, though, that it is not possible to substitute this fuel into existing engines without modifications to fuel system. In addition Härtl

Abbreviations: 2D2CP, two dimensional two colour pyrometry; BMEP, break mean effective pressure; BSEC, break specific energy consumption; BSFC, break specific fuel consumption; DME, dimethyl ether; DMM, dimethoxymethane; DOC, diesel oxidation catalyst; EGR, exhaust gas recirculation; LHV, lower heating value; NEDC, new European driving cycle; OLP, optical light probe; POMDME, poly (oxymethylene) dimethyl ether; PM, particulate matter; RoHR, rate of heat release; SOI, start of injection.

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et al. [21] tested a pure DMM-fuel with additives to enhance viscosity, lubricity and cetane number. Engine testing proved the possibility of a NOx reduction without a corresponding increase in soot emissions being, however, an increasing methane output near stoichiometric conditions detected. Because of the low cetane number, high volatility and weak viscosity and lubricity of DMM, the authors considered that higher OMEs (n = 3, 4, 5) would be more suitable for application in a diesel engine as neat substance, which has been investigated in [22]. Even Burger et al. [18] considered that, due to their physical properties, POMDMEs with n ranging in between 2 and 5, can overcome the disadvantages given by DME and DMM, particularly regarding injection system modifications due to higher viscosities and higher boiling points. In addition, the authors point out that further long chains (n > 5) could lead to precipitation at low temperatures having as a consequence a clog in filters or other parts of the fuel system. Therefore, POMDMEs with higher viscosity and boiling point than DMM and a molecule with up to 5 CH_2—O groups seem to be more attractive to be blended into commercial diesel. The few papers regarding the use of POMDMEs found in the literature [23–29] highlighted the possibility of achieving a strong reduction in particulate matter (PM). Pellegrini et al. [23], as example, compared a 7.5% POMDME in diesel blend with commercial diesel, at fixed NO_X emission level and showed a significant reduction of PM on the one hand but higher PAH emissions on the other hand. The authors explained this result considering that the higher EGR rate and lower exhaust gas temperature reduced the DOC activity when operating with the oxygenated fuel. Moreover they noticed, with POMDME, a reduction of the number of particles above 30 nm at engine speeds above 2000 rpm. In addition a 3–4% power loss and increase in specific volumetric fuel consumption was noticed. Pellegrini et al. [24], measured and evaluated the emission performance of neat POMDME and a blend of 10% POMDME and 90% commercial diesel fuel in a Euro-2 diesel passenger car engine over the new European driving cycle (NEDC). The authors found, with respect to the reference diesel fuel, a significant reduction in PM emissions with the 10% blend (18%) and with the neat POMDME (77%) with which Euro 4 limit was fulfilled. Possibly due to high frequency of C—O bonds in its molecular structure, the use of the neat POMDME resulted in higher emission of CO and formaldehyde before exhaust gas treatment. The neat POMDME showed also increased NOx emissions while HC was not significantly affected by the fuel type. Iannuzzi et al. [25] investigated dimethoxymethane (DMM), several blends of POMDME in diesel and different pure POMDMEs in a constant volume cylindrical cell in order to apply optical diagnostics, with particular reference to the two dimensional two colour pyrometry (2D2CP). Their results demonstrated a reduction of the soot formation dominated phase and earlier starting soot oxidation phase when increasing the oxygenated fraction in the blend. Moreover fuel jet images showed a reduction of the soot formation area when increasing the oxygen content in the blend. The authors even focused on exhaust emissions by means of a fast particle spectrometer, detecting nearly smokeless combustion for pure oxygenated fuels and a non-linear soot emission reduction with increasing O_2 content in the blend. In fact an addition of just 5% of oxygenated fuel within commercial diesel permitted a reduction in soot of about 30%. Finally the authors provided the distribution of particles diameter for the different fuels showing that particulate matter in oxygenated fuels is characterized by far smaller dimensions probably because of an oxidation effect on nucleation cores.

The aim of the present work is to investigate, in a single cylinder "heavy duty" direct injection diesel engine, a mixture of POMDMEs blended into commercial diesel in order to examine achievable engine performance and exhaust emissions taking into account not only particulate matter but nitrogen oxides and carbon dioxide as well. In particular particulate matter results are discussed through smoke emissions and their in-cylinder formation and oxidation behaviour through the calculation of the in-cylinder kL factor during the combustion process. Since the particular POMDME mixture is characterized by similar physical properties to diesel thus not requiring substantial modifications to the engine infrastructure, it could be of particular interest for the market. A production on industrial scale of POMDME to be blended with commercial diesel would be of interest in order to obtain blends characterized by diesel high energy content and POMDME strong capability of reducing soot formation.

2. Experimental apparatus

2.1. Engine set-up

The experimental activity has been conducted on a single-cylinder DI diesel engine (Fig. 1) located at the ETH Zurich. It is based on a MTU 396 series engine and is equipped with a common rail injector system capable of injection pressures up to 1600 bar and an 8 hole Ganser 218 solenoid injector. The engine is connected to a Zöller – Kiel AG B-300 AC dynamometer characterized by a maximum absorbable power of 260 kW and a maximum speed of 7500 rpm. An external compressor able to supply pressurized air up to 5 bar is connected to the engine intake while a heating/cooling system allows conditioning the intake air in a 17–100 °C temperature range and a roots compressor is used to recirculate exhaust gas. Moreover, the fuel and oil pumps are externally driven and the experimental engine, whose main characteristics are reported in Table 1, is provided with an exhaust gas throttle allowing the exhaust gas back pressure management.

Even though the original cylinder head configuration is a 4-valve design, in order to insert a water-cooled sensor adaptor allowing the placement of an additional optical sensor (optical light probe–OLP), one of the two exhaust valves has been removed. The removal of an exhaust valve did not significantly deteriorate

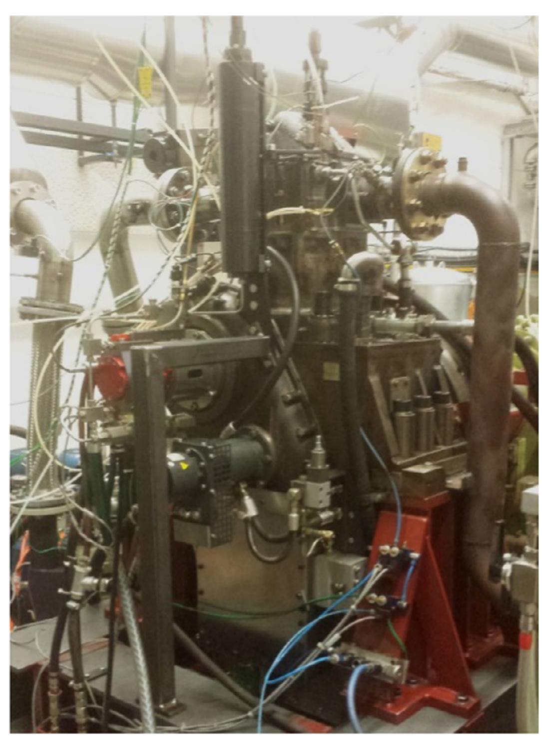

Fig. 1. MTU-396 Single Cylinder Diesel Engine.