



Combustion behavior and soot formation/oxidation of oxygenated fuels in a cylindrical constant volume chamber



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ABSTRACT

Oxygenated fuels produced from methane-based products, are currently being studied in several research centres for their capability of strongly reducing soot at the exhaust of internal combustion engines.

In the present activity different oxygenated fuels were investigated in a constant volume chamber with large optical access. In order to study the combustion evolution and soot formation and oxidation processes, optical techniques such as OH chemiluminescence and two dimensional two color pyrometry (2D2CP) have been applied. Moreover a fast particle spectrometer has been used at the chamber exhaust in order to analyze the soot emissions from the different investigated fuels. Poly(oxyethylene) dimethyl ethers (OME) with a $\text{CH}_3\text{-O-(CH}_2\text{-O)}_n\text{-CH}_3$ general molecular structure have been studied for different temperatures at start of combustion.

The first phase of the investigation included the calculation of the kL factor for three OME2 in diesel blends. The results demonstrate a reduction of the soot formation dominated phase when increasing the oxygenated fraction in the blend. Moreover fuel jet images show a reduction of the soot formation area when increasing the oxygen content in the blend. The second phase of the activity focused on exhaust emissions by means of a Cambustion DMS 500 fast particle spectrometer. Results highlighted nearly smokeless combustion for pure oxygenated fuels and a non-linear soot emission reduction with increasing O_2 content in the blend.

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1. Introduction

To reduce pollutants several methodologies and measures have been adopted by legislators, academia and industry [1]. Research laboratories and manufacturers pursue among others the use of fuel blends with a variety of physical and chemical properties. With particular reference to soot emissions reduction from diesel engines, oxygenated fuels are currently being investigated as being promising alternative fuels to commercial diesel. Oxygenated fuels may be produced from renewable sources such as vegetable oils or animal fats in the case of biodiesel fuels, from alcohols like ethanol

and n-butanol or from methanol with a gas-to-liquid technology or from several feed stocks, including waste biomasses, natural gas and coal. Many studies have been focused on the effect of oxygen content in alternative fuels from the first two categories, biodiesel and alcohols. Valentino and Iannuzzi [2] investigated the effect of different oxygenated fuels on emissions and performance of a light duty diesel engine stating that oxygen availability within fuel molecule is a key factor to reduce soot emissions. Previous studies on the use of oxygenated fuels have shown a reduction of particulate matter [3–18] and recommend the use of oxygenates to suppress the C–C bonds and therefore the soot precursor species [3]. However, some of them, e.g. dimethyl ether (DME), require modifications to the engine infrastructure because of their properties (e.g. vapor pressure and ability to produce methane). DME has been studied in several research centres [19–26] and if on one hand allows an almost smokeless combustion, on the other hand requires significant modifications to the fuel injection system in diesel engines because of its low viscosity, low lubricating capability and being in a gaseous state under atmospheric conditions. Therefore, oxygenates with higher viscosity and boiling point are

Abbreviations: 2D2CP, two dimensional two color pyrometry; DMM or OME1, dimethoxymethane; Luminosity, unit: count of all pixel; OME2-5%, 5% OME2 in diesel blend; OME2-30%, 30% OME2 in diesel blend; OME2-50%, 50% OME2 in diesel blend; POMDME, poly(oxyethylene) dimethyl ether; PM, particulate matter; RoHR, rate of heat release; kL , normalized absorption coefficient k times flame thickness L [–]; SOC, start of main combustion; SOI, start of injection.

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definitely more attractive. Poly (oxymethylene) dimethyl ethers (POMDME or OME in abbreviated form) are characterized by a $\text{CH}_3\text{-O-(CH}_2\text{-O)}_n\text{-CH}_3$ general structure, with a mass fraction of oxygen within the molecule up to almost 50%. These fuels can be obtained from methanol in a process chain described in detail by Burger et al. [27–29]. The first fuel of the POMDME family, with $n = 1$, is dimethoxymethane (DMM) which has been investigated both blended with commercial diesel and pure, still though with some fuel system modifications. DMM is still more volatile than diesel, having its boiling point at 42 °C and therefore problems related to vapor lock may occur. Sirman et al. [4] investigated a 15% DMM in diesel blend in a direct injection diesel engine and found great benefits in exhaust emission reduction. However they state that it is not possible to substitute this fuel into existing engines without modifications to fuel system. Kenney et al. [5] investigated the same blend in several speed/load conditions and found a PM reduction at any investigated operative point while no significant reduction in NOx emissions. Ogawa et al. [6] achieved ultra-low emission and efficient diesel combustion with pure DMM and a combination of high EGR and a three-way catalyst. Härtl et al. [30] tested a pure OME1-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. However they found a growing output of methane near stoichiometric conditions. Because of the low cetane number (CN), high volatility and weak viscosity and lubricity of OME1 the authors considered higher OMEs ($n = 3, 4, 5$) more suitable for application in a diesel engine as neat substance [30].

Burger et al. [27] state 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. Further long chains, instead, could lead to precipitation at low temperatures having as a consequence a clog in filters or other parts of the fuel system.

Just few papers have been published regarding the use of pure or blended POMDME fuels [31–35]. Pellegrini et al. state that, comparing a 7.5% POMDME in diesel blend with commercial diesel, at fixed NOx emission level, a significant reduction of PM is achieved but higher PAH emissions were found, because of the higher EGR rate and lower exhaust gas temperature that 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 [34].

The aim of the present work is to investigate several oxygenated fuel blends containing OME and characterized by different oxygen percentages and physical properties. The comparison is conducted by investigating the combustion and soot formation and oxidation processes in a constant volume cylindrical cell (instead of an engine) in order to apply optical diagnostics, with particular reference to the two dimensional two color pyrometry (2D2CP). The understanding of how both soot formation and oxidation processes are affected by the fuel oxygen content is the key factor for having conducted the present investigation. The authors aim has been to study whether the reduction of soot mass at the exhaust may be referred to a reduction of soot formation (because of a reduction of the locally rich regions), an enhancement of soot oxidation (because of oxygen being available directly in the fuel molecule) or a contribution of both processes. In addition the relation between temperature variation and different oxygen content with regard to these processes has been investigated. Moreover exhaust soot emissions are investigated through a fast particle spectrometer.

The experimental apparatus and results are described in detail in the following.

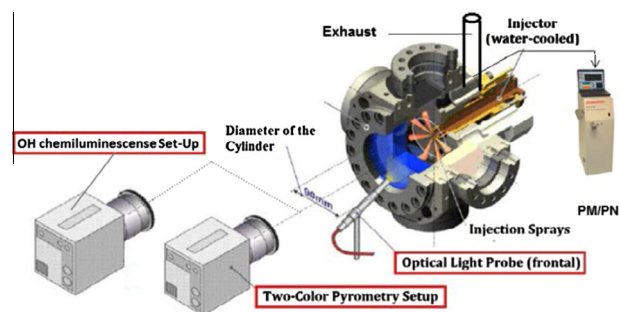


Fig. 1. Sketch of experimental setup.

2. Experimental apparatus

2.1. Cell set-up

The air path of the cylindrical constant volume chamber (CCVC) contains an autoclave, a connecting inlet tube, the chamber itself (Fig. 1) and an exhaust tube. The first three parts are equipped with pressure and temperature sensors as well as heating elements. In the chamber, a temperature in the order of 800 K can be reached. In order to emulate engine-like ignition temperatures, a pilot injection can be applied. An external compressor is used to achieve suitable in-cell pressures before combustion. The compressor is connected to the autoclave via a pressure control valve to reduce the pressure to its set point value. The autoclave has a considerably larger volume compared to the cell body. This pressure reservoir feeds the cell via the connecting inlet tube as soon as a cycle is initiated. The fuel pressure is generated by a pneumatic high pressure pump, which is able to reach fuel pressures up to 1600 bar. A Bosch piezo injector (8 holes, 0.108 mm nozzle diameter) from a passenger car was used for the experimental activity. In order to have optical access to the complete combustion volume, the originally cubic-formed vessel has been retrofitted with steel cylindrical walls, concentric to the axis of the injector. Due to the insertion of the cylinder, the optical access is limited to the front window. Nevertheless, this ensures all regions in the combustion chamber are visible through the front window. The exhaust valve releases the pressure at around 55 bar. The resulting pressure wave is used to flush a volume connected to the exhaust tube and to a non-returning valve on the other side. Part of the exhaust volume is sampled and analyzed using a Cambustion DMS 500 fast particle spectrometer.

2.2. Optical instrumentation

The optical setup (sketch in Fig. 2) comprises two cycle resolved CCD cameras, a LaVision HSS6 for two dimensional two color pyrometry and a LaVision HSS5, connected to an IRO image intensifier, for OH-chemiluminescence acquisition. The OH camera is not set in front of the cell window (because of the 2D2CP camera being there) and thus the light coming from the cell, filtered at 309 nm, reaches the camera through a system of mirrors that permit to acquire only a part of the whole area. In addition a second system of lens and mirrors is used, for the 2D2CP system, to split the light into two beams and filter it at two different wavelengths, as reported from Barro et al. in [36]. The emitted light from the cell window enters the system through a zoom lens with a variable focal length of $f = 18\text{--}125$ mm. The diverging light beam is defocused (infinite focal length) with the $f = 127$ mm lens and progresses to the first dichroic beam splitter (cold mirror). Wavelengths below 700 nm are rejected and wavelengths above 700 nm transmitted. Afterward the rejected beam passes through

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