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Optical investigations in a CI engine fueled with water in diesel emulsion produced through microchannels

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ABSTRACT

The paper reports the results of an experimental investigation carried out on a prototype optically accessible compression ignition engine fueled with water in diesel emulsion (WiDE) and Diesel only. The effect of WiDE on combustion process evolution and exhaust emissions was investigated through standard engine benchmark and optical diagnostics. 2D chemiluminescent emission measurements centered at 690 nm were carried out during the whole combustion process to discriminate the soot emission from other excited chemical species. The emulsion was produced through a prototype designed microchannels emulsifier that can also work inline. The water concentration was 9.1%v with a small amount (0.2%v) of nonionic surfactant (SPAN80) used to stabilize the emulsion. Tests were performed comparing combustion and exhaust emissions of the reference commercial diesel fuel to the WiDE. For any investigated fuel and operating point, engine tests were carried out changing the injection interval to achieve the same chemical energy as the reference diesel (935 J/str). Compared to Diesel, the WiDE induced an increase in ignition time, enhancing the air/fuel mixing with a simultaneous reduction in both PM and NOx. The digital imaging and 2D chemiluminescence techniques highlighted a reduction in soot formation without significant changes on the soot oxidation rate. The results suggest the use of WiDE as a reliable method to improve NOx-soot trade-off of CI engines.

1. Introduction

The continuous demand for a drastic reduction in CO_2 emission makes the Diesel engine still attractive due to its high fuel efficiency and specific power output. On the other hand, the high Nitrogen Oxides (NOx) and Particulate Matter (PM) production represents a limit and imposes to find reliable solutions to meet worldwide exhaust emissions regulation [1–5].

A widespread option is the use of exhaust gas recirculation (EGR) and combined selective catalyst reduction (SCR)-diesel particulate filter (DPF) after treatment device: the first one lowers the in-cylinder temperature peak, reducing NOx formation while smoke increases due to the lower oxygen content; the latter allows a strong reduction in all harmful emissions [6,7]. Both systems provide a penalty on fuel efficiency. An alternative solution is replacing diesel with fuels featured by a lower cetane number to enhance the air-fuel mixing with the control of combustion phasing through proper injection strategies. A larger induction time locally increases the air-to-fuel ratio (AFR) in the regions close to autoignition nuclei, reducing the local temperature peak with a simultaneous reduction of NOx and PM levels, without compromising the thermal efficiency [8,9].

Gasoline-diesel blend was demonstrated to increase the ignition delay and improve fuel volatility, reducing soot emissions. Controversial results were found concerning the effect on NOx emissions. Depending on the engine operative conditions, if the amount of fuel burned during the premixed phase is able to change the combustion mechanism, both PM and NOx are simultaneously reduced, otherwise the increase in ignition delay may promote the in-cylinder pressure peak raise with a consequent increase in combustion temperature and NOx emission [10–13].

Compared to gasoline/diesel, alcoholic fuels/diesel blends provide similar advantages regarding the high volatility and resistance to autoignition [14,15]. An additional advantage of alcohol based fuel is the oxygen content within the molecule that enhances the soot oxidation limiting the smoke emission at the exhaust [16,17].

Recently, great attention has been paid in using water to lower air-fuel charge temperature with benefits for NOx and PM emissions. Water can be introduced in the engine by a separate injection system, through the intake manifold or directly in the combustion chamber, or by mean of fuel as Water in Diesel Emulsion (WiDE) [18–20]. Water injection

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Nomenclature

AFR	air-to-fuel ratio
ATDC	after TDC
BTDC	before the TDC
BTE	brake thermal efficiency
CAD	crank angle degree
CCD	charge-coupled device
DPF	diesel particulate filter
EGR	exhaust gas recirculation
ID	ignition delay
FEP	fluorinated ethylene propylene
NOx	nitrogen oxides
PM	particulate matter
SCR	selective catalyst reduction
SOC	start of combustion
SOI	start of injection
TDC	top dead centre
TTL	transistor-transistor logic
UHC	unburned hydrocarbons
WI	water injection
WiDE	water in diesel emulsion

(WI) allows a simultaneous reduction in NOx and PM emission: NOx emission decreases due to in-cylinder temperature lowering and charge dilution; the larger induction time promotes a better air-fuel mixing, reducing the smoke. Compared to the emulsion, water injection allows changing the water-diesel ratio depending on the engine operative conditions. On the other hand, the complex engine design due to the introduction of a secondary injection system makes this solution expensive and unfeasible. Moreover, a double injection system could lead to local too high water concentration region and impingement against the cylinder wall with risk of water dilution in the oil.

First use of WiDE dates back to the 70′s. In the 1978 Cook and Law [21] studied the effect of water-emulsification on the PM emission of a single cylinder Diesel engine. In the same year Murayama et al. [22] tested the performance and the emission a DI engine fueled with water-fuel emulsion. They found a reduction in NOx, smoke and fuel consumption over diesel fuel and water fumigation. WiDE was found to improve brake power, torque and thermal efficiency (BTHE), compared to net Diesel at medium-high load in a wide range of engine speeds [23–26]. Compared to WI [19,20], WiDE provides larger reduction in PM-NOx emission, with further benefits on engine performance. While WI induces a lowering of fuel efficiency and of BTHE due to the reduction in the charge temperature, WiDE provides a more efficient combustion even over net diesel fuel. The reason for this improvement should be ascribed to the micro-explosion phenomenon [23,24,27]. Due to the difference in the evaporation rates of diesel and water, the water droplets reach their boiling point faster, destroying the diesel shell, promoting a secondary breakup [28]. The consequent increase in diesel surface to volume ratio results in a higher burning efficiency. The atomization efficiency of droplets micro-explosion depends on engine operative conditions [25] as well as on the emulsion structure [28]. The size distribution of the dispersed water droplets affects the BTE [29], NOx emissions, smoke and unburned Hydrocarbons (UHC) [30]. Related to these findings, the emulsion stability results to be a serious drawback: even though several techniques allow managing the size distribution and homogeneity of emulsions [24], their properties can change quickly after the storage or during the engine run [31]. On the other hand, the use of large amounts of surfactants to enhance the stability can favor the raise of sludge and cause the wear of the engine components. With this aim, emulsifier technology, capable to produce the fuel emulsion on board, right before the injection, can overcome stability issues without the use of additives [32,33].

This paper discusses the results concerning the spray combustion of WiDE (9.1%v water concentration), produced through an especially designed microchannels emulsifier [34], within a prototype single cylinder high swirl compression ignition engine, equipped with a common rail injection system.

Thermodynamic analysis and exhaust pollutant measurements were performed simultaneously to combustion digital imaging in the optically accessible combustion chamber. Considering the lack of scientific literature on the effect of WiDE on combustion, the 2D chemiluminescence was detected through flame emission filtering at 690 nm to follow the soot evolution.

2. Experimental set-up and procedure

2.1. Microchannels emulsification

The emulsion was produced through an especially designed microchannels emulsifier [34]. A sketch of the experimental set-up is shown in Fig. 1. A double piston displacement pump (ARMEN-APF-100-251)

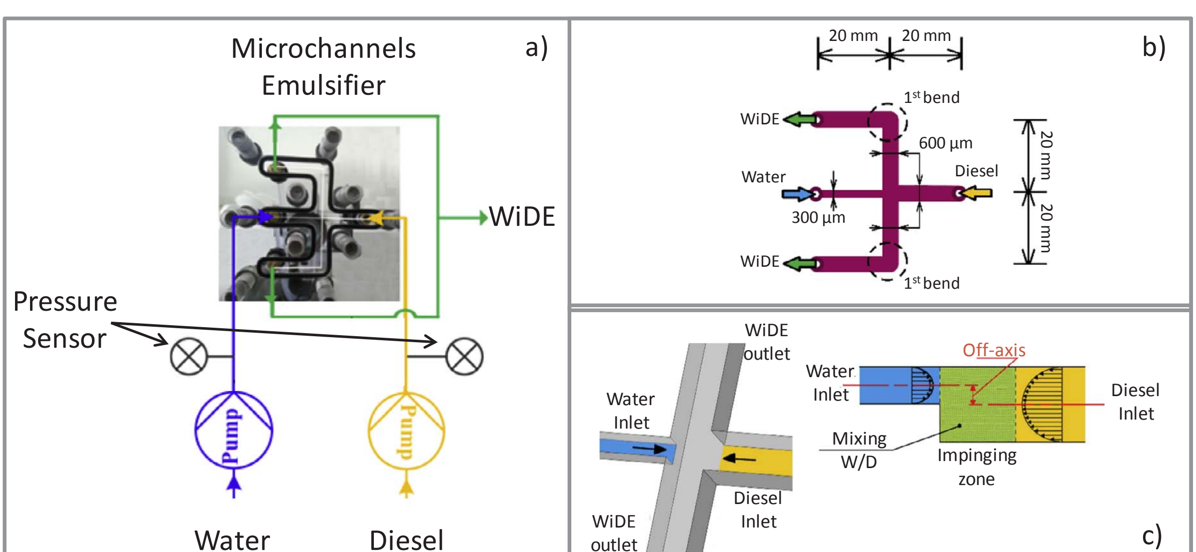

Fig. 1. (a) Emulsification set-up, (b) Schematic of microchannels emulsifier (c) sketch of Water/Diesel impinging zone.