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Combustion process investigation in a high speed diesel engine fuelled with n-butanol diesel blend by conventional methods and optical diagnostics

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ABSTRACT

The use of alternative fuels, as biodiesel and ethanol, for light duty CI engines to approach the target of ultra low NO_x and PM emissions without fuel economy penalty has been widely investigated. Recently, it is growing the interest in the butanol as a viable alternative either single or blended with conventional based fuels both to cut the demand for fossil fuel and to reduce emissions of particulate matter without significantly increasing in NO_x.

In this paper, butanol effects on combustion process were investigated through conventional methods and optical diagnostics. First, blends of 80% diesel and 20% n-butanol (BU20) were used in a four cylinder, turbocharged, water cooled, DI diesel engine, equipped with a common rail injection system. Management of timing and injection pressure was carried out to achieve conditions in which the almost total amount of fuel was delivered before auto-ignition. BU20 allowed to attain almost smokeless emissions at lower injection pressure (100 MPa) than diesel fuel (120 MPa). Smokeless conditions were achieved with a slight increase in NO_x emissions (around 20%) and a minor penalty for the specific fuel consumption.

Afterward, the blends effects on the combustion process were studied in the combustion chamber of a single cylinder compression ignition engine equipped with the same common rail multi-jets injection system. Spray combustion and pollutant formation were investigated by UV–visible digital imaging and natural emission spectroscopy. UV–visible emission spectroscopy was used for the detection of the chemical markers of combustion process. Chemiluminescence signals, due to OH, HCO and CO_2 emission bands were detected. OH emission was correlated to NO_x measured at the exhaust. The soot spectral feature in the visible wavelength range was related to the engine out soot emissions.

1. Introduction

The use of alternative fuels, as biodiesel and ethanol, for light duty engines to approach the target of ultra low NO_x and PM emissions without fuel economy penalty was widely investigated [1–4]. Growing attention is being converged on renewable fuels to reduce petroleum based fuel consumption. Biodiesel can be considered the primary alternative to diesel fuel due to its properties close to diesel fuel and its miscibility with diesel in any percentage. Although a dominant role in diesel alternative is played by biodiesel produced from animal fats, algae or non-food crop plants, bio-alcohols have become the most interesting solution to replace fossil fuels due to a variety of locally available feedstock [5–7]. Recently it is growing the interest in the butanol as a viable alternative either single or blended with conventional based fuels both to reduce the demand for fossil fuel and to reduce emissions of particulate matter without significantly increasing NO_x or significantly lowering the cetane number [8–12]. If compared with other alcohols, butanol has higher energy content, lower water adsorption and corrosive properties, is less volatile, has better solubility with diesel allowing to avoid the additive use, viscosity similar to diesel fuel and the it has the ability to be used in conventional internal combustion engines without the need for modification. Like ethanol, butanol can be produced both by petrochemical and fermentative processes [13–15].

Scientific literature reports several experimental investigations to evaluate the effects of butanol–diesel blends on the performance, exhaust emissions, and combustion behaviour for different engine operating conditions including the transient conditions [8–11,16]. Previous works demonstrated that the longer ignition delay of BU20, at reduced intake oxygen concentration, with respect to diesel fuel, leads to a better mixing rate before start of combustion

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and an improvement in NO_x and smoke emissions [11]. This result allowed operating at earlier start of injections and lower injection pressures still achieving partial premixed low temperature combustion in which almost the total amount of fuel is injected before the start of combustion. Moreover, the higher volatility of blends increased the dispersion of fuel vapour within the combustion chamber. The joint action of a longer ignition delay and a better fuel volatility brought to almost smokeless combustion at moderate injection pressure (100 MPa) and intake oxygen concentrations (19.5–19.0%). Smokeless combustion was achieved using butanol blends with a small penalty (around 20%) in NO_x emissions. Instead this combustion mode cannot be attained using commercial diesel fuel.

In this paper, butanol effects on spray combustion process were performed through conventional methods and optical diagnostics. Blends of diesel and n-butanol were used to supply a common rail DI diesel engine running at different operating conditions. Exploration management of timing and injection pressure were carried out to achieve conditions in which the almost total amount of fuel was delivered before ignition. This experimental activity was performed on a four cylinder, turbocharged, water cooled, DI diesel engine, equipped with a common rail injection system. Successively, the blends and their effects on combustion process were investigated in the combustion chamber of a single cylinder compression ignition engine equipped with the same common rail multi-jets injection system. Spray combustion and pollutant formation were followed through UV–visible digital imaging and natural emission spectroscopy.

2. Experimental apparatus

The investigation was accomplished in two steps, first, the effect of diesel/n-butanol blend on combustion and engine out emissions was investigated in a four cylinder, turbocharged, water cooled, DI diesel engine, equipped with a common rail injection system. After that, the combustion behaviour of the blend was explored in an optically accessible combustion chamber of a single cylinder compression ignition engine equipped with the same injection system. The aim was to investigate the chemical and physical phenomena occurring in the combustion chamber in order to better understand the results obtained for the real engine in terms of performance and emissions.

2.1. Real engine set up and test conditions

The experimental activity was carried out on a turbocharged, water cooled, DI diesel engine, equipped with a common rail injection system. The injection system included a solenoid controlled injector with a micro-sac 7 hole, 0.141 mm diameter, 148° spray angle able to inject the fuel up to 160 MPa. The main engine parameters, such as injection pressure and interval, timing and load, were controlled by the ECU via the INCA SW. The main engine characteristics are reported in Table 1. The engine equipment included a super cooled exhaust gas recirculation (EGR) system controlled by an external driver, a piezo-quartz pressure transducer to detect the in-cylinder pressure signal and a current probe to acquire the energizing current to the injectors. A torque sensor, installed on the rotor asynchronous motor, connected to the thermal engine, allowed the acquisition of the torque signal. Intake and exhaust O_2 concentration were checked by two O_2 sensors.

Table 1
Engine specifications.

4 cylinder, 4 valve, DI diesel engine	
Bore	82 mm
Stroke	90.4 mm
Connecting rod	145 mm
Displacement	1910 cm^3
Compression ratio	17.5:1

2.2. Test fuels and conditions

Engine tests were carried out for two different fuels. The baseline fuel was the European low sulphur (max 10 ppm) commercial diesel with a cetane number of 52. The comparison fuel was blended by 80% of the baseline diesel and 20% n-butanol by volume, denoted in the following as BU20. Engine tests were carried out exploring the effect of injection pressure, start of injection and O_2 concentration at the intake on the ignition delay, which is taken as a critical parameter to evaluate the mixture premixing level. Engine tests were carried out at the engine speed of 2500 rpm and 0.8 MPa BMEP that is one of the operating points of the reference multi-cylinder engine New European Driving Cycle (NEDC) and was chosen owing to its important contribution to the total engine out emissions for automotive applications. Tests were performed setting the injection interval to keep constant the BMEP for any blend at EGR = 0%. The start of injection, the injection pressure and the O_2 concentration at the intake were explored till the limit imposed by combustion instability, fixed considering the COV of IMEP at 3%. NO_x emissions were measured by the AVL Di Gas 4000 analyzer while the AVL 415 Smoke Meter (0.1% value resolution) was used for smoke emissions.

2.3. Optical engine set up and test conditions

Engine test bench includes an optically accessible single cylinder 2-stroke Diesel engine having 150 mm bore, 170 mm stroke, equipped with a swirled combustion chamber and a common rail high pressure injection system. Fig. 1 shows the optically accessible combustion bowl of the engine (left side), the main engine specifications are reported in Table 2. The engine has been equipped with a cylindrical shaped combustion chamber, having 50 mm in diameter and 30 mm in depth, suitable to stabilize swirl conditions during the compression stroke to reproduce the fluid dynamic environment similar to those within a real direct injection diesel engine. The main cylinder, connected to the optically accessible combustion chamber through a tangential duct, allows to supply air flow to the chamber as the piston moves upward to TDC. Hence, the air flow, coming from the engine cylinder, is forced within the combustion chamber. In this way, a counter clockwise swirl flow, with the rotation axis about coincident to the symmetry axis of the chamber, is generated. The injector is mounted within this swirled chamber with its axis coincident to the chamber axis. The fuel, injected by the nozzle, is mixed up through a typical interaction with the swirling air flow. The combustion process starts and mainly proceeds in the chamber. As soon as the piston moves downward, the flow reverse its motion and the hot gases flow through the tangential duct to the cylinder and finally to the exhaust ports. The combustion chamber also provides a circular optical access (50 mm diameter) on one side of it, used to collect images, and a rectangular one (size of 10×50 mm^2) at 90°, shaped on the cylindrical surface of the chamber. The injector has been located on the opposite side of the circular optical access with the axis coincident to that of the combustion chamber. The injection system is the same equipped on the 4 cylinder engine. An external roots blower provides an intake air pressure of 0.107 MPa with a peak pressure within the combustion chamber of 4.9 MPa, under motored conditions.