Butanol-Diesel Blend Spray Combustion Investigation by UV-visible Flame Emission in a Prototype Single Cylinder Compression Ignition Engine

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The present report illustrates the results of an experimental investigation carried out in a prototype optically accessible compression ignition engine fuelled with different blends of commercial diesel and n-butanol. Thermodynamic analysis and exhaust gas measurements were supported by optical investigations performed through a wide optical access to the combustion chamber. UV-visible digital imaging and 2D chemiluminescence were applied to characterize the combustion process in terms of spatial and temporal occurrence of auto-ignition, flame propagation, soot and OH evolution.

Results of the spray combustion for diesel and n-butanol-diesel blends at 20% and 40% volume fraction, exploring a single and double injection strategy (pilot+main) from a common rail multi-jet injection system, are illustrated. Tests were performed setting a pilot+main strategy with a fixed dwell time and different starts of injection. For the diesel case, the whole amount of injected fuel and injection pressure were set at 22 mg/str and 80 MPa corresponding to a medium load regime for an automotive light duty diesel engine. The fuel amount for the butanol-diesel blends was changed to get the same chemical energy of the delivered fuel as the reference diesel case (935J/str). The investigation was carried out at two EGR rates, 0% and 50% , corresponding to a concentration of O_2 at intake of 21 and 17%, respectively.

Taking advantages of the higher resistance to auto ignition of the butanol-diesel blends, the results showed a transition from the conventional to a partial premixed combustion for the BU40 in the single injection case. The combined effect of two-stage injection and EGR increased the ignition delay and the switch to the partial premixed combustion was enhanced. Improvement in NOx-soot trade-off was obtained activating the double injection strategy particularly with the butanol blends.

Optical diagnostics allowed to detect and feature the spatial distributions due to the flame luminosity and OH emission at autoignition and to estimate of the lift-off length. A high concentration of OH radicals was detected for all the test cases without EGR that corresponded to an enhanced oxidation phase and a fast soot reduction. Further, the soot oxidation phase resulted more significant for the higher butanol volume fraction in the blends.

Introduction

Recently, a great interest has been devoted in use of butanol within compression ignition engines as a way to reduce emissions. Butanol, a 4-carbon alcohol, can be produced from biomass (as “bio-butanol”) as well as fossil fuels without difference in the chemical properties. Bio-butanol, obtained from the same feedstock as ethanol including corn, sugar beets, and other biomass feedstock containing cellulose that could not be used as food and would instead go to waste, has more advantages than ethanol, such as higher energy content, lower water adsorption and corrosive properties. Moreover, it has better solubility with diesel allowing to avoid the additive use; its viscosity is similar to diesel fuel and it has a relatively high cetane number compared to ethanol.

The use of butanol within diesel fuel blends is expected to enhance the mixing mechanism due to the longer ignition delay and faster evaporation. Further, the higher latent heat of evaporation can reduce the in-cylinder temperature while the oxygen within the molecule may inhibit soot formation because of leaner mixture regions. On the other hand, blends of diesel/butanol need an accurate control of the air/fuel mixture that plays a fundamental role on combustion efficiency and exhaust emissions within compression ignition engines. As consequence, an appropriate control of injection is crucial for improving engine performance for fully taking advantage of Diesel/Butanol blends considering that differences on viscosity, density and surface tension may produce modifications to the mixture formation process and auto-ignition mechanism

To this aim, the present report illustrates the results obtained by the spray combustion of n -butanol blending in diesel (20% and 40%) characterized within a prototype single cylinder high swirl compression ignition engine, equipped with a common rail multi-jet injection system. Thermodynamic analysis and exhaust pollutant measurements were correlated to UV-visible digital imaging and chemiluminescence in the optically accessible combustion chamber.

Test Conditions and Main Results

The investigation was carried out within a single cylinder 2-stroke compression ignition engine, whose main engine specifications are reported in Table 1. An external high swirl optically accessible combustion bowl (50 mm in diameter and 30 mm in depth), equipped with a high pressure common rail injection system, is connected to the main cylinder through a tangential duct generating a counter clockwise swirl flow that reproduces a fluid dynamic environment similar to a real direct injection diesel engine. The combustion chamber provides two optical accesses: the first one is circular (50 mm diameter) and it is placed in front of the injector, used to collect images; the second one has a rectangular shape (size of 10 x 50 mm), is mounted on a side of the chamber, at 90°with respect to the bowl axis, used for the laser illumination input.

The injection equipment includes a common rail injection system with a solenoid controlled injector located on the opposite side of the circular optical access. The nozzle is a micro-sac 7 hole, 0.136 mm diameter, 148° spray angle nozzle. An external roots blower provided an intake air pressure of 0.107 MPa with a peak pressure within the combustion chamber of 4.3 MPa under motored conditions. The engine was warmed-up by an external heat exchanger system to keep constant the engine thermal regime during the tests.

Tests were carried out comparing the reference commercial diesel fuel to blends of diesel and n-butanol at two different volume fractions, 20% and 40%. Two EGR rates (21 and 17% of O2 at intake) and two injection strategies were tested: a single and a double injection (pilot+main) making a sweep of the start of injection from 14 to 2 CAD BTDC with a step of 3 CAD for the single injection case. The same injection timing was set for the main injection throughout the double strategy and the pilot was advanced 7 CAD before the start of the main: the dwell time between pilot and main was kept at 7 CAD. These conditions and the amount of injected fuel were selected from the ECU data of a commercial 4-stroke light duty diesel engine under investigation to examine the effect of diesel-butanol blends on performance and emissions.

For the diesel case, the whole amount of injected fuel and injection pressure were set at 22 mg/str and 80 MPa, respectively, corresponding to a medium load regime for an automotive light duty diesel engine. The injection interval for the single injection strategy was 867 µs, corresponding to 2.6 CAD, while an interval of 333 µs and 833 µs, corresponding to 1 and 2.5 CAD for pilot and main injection, respectively, was set for the double injection strategy. Engine tests were carried out at constant chemical energy of delivered fuel, therefore the injection duration was set to achieve, for all the investigated blends, the same energy content as the reference diesel (935 J/str).
The spray combustion process was recorded through the quartz window using an intensified CCD camera (PiMAX 3) with a 78 mm focal length lens (Nikkor). The camera was featured by a 1024x1024 pixels sensor with 13x13 µm pixel size, 16-bit pixel digitization and 1MHz sustained repetition. The ICCD was employed in full-chip configuration. The set-up allowed a resolution of 83 µm per pixel. In addition to the broadband acquisition that exploits the high quantum efficiency of the ICCD in the spectral range 250-700 nm, two 50x50mm band-pass filters (Asahi Spectra Inc.) were used to selectively record flame emissions at 310 nm (OH) and 690 nm (Soot).

The main outcomes may be summarized as in the following:

- ✓ The combined effect of n-butanol and EGR delayed the autoignition resulting in reduction of local fuel-air equivalence ratio and combustion temperature with a decrease in NOx emission. The oxygen content within the butanol molecule enhanced the soot oxidation and limited the smoke emission at the exhaust compared to the reference diesel. This result was also highlighted by the UV-visible flame emission with a lower emission intensity given by the butanol blends compared to the reference diesel fuel.
- ✓ The higher resistance to auto ignition of the butanol-diesel blends accomplished a transition from the conventional to a partially premixed combustion for the butanol blend at higher volume fraction (BU40) in the single injection case with a reduction in the exhaust soot emission. Further, it is noteworthy that this result was highlighted by the higher OH radicals detected by the flame emission measurements meaningful of an enhanced oxidation phase.
- ✓ The double injection strategy reduced the NOx but caused an increase in the exhaust soot emission because of the lower combustion temperature which reduced the soot oxidation rate as demonstrated by the temporal distribution of soot luminous signal and drop in OH concentration .
- ✓ The lift-off length that is an indicator of the percentage of stoichiometric air entrained up to the lift-off length for the spray jet flame was evaluated from UV-visible, OH and soot emissions. For each fuel injection strategy it denoted increasing values for higher n-butanol volume fraction and with the EGR activation.