THE EFFECT OF N-BUTANOL ADDITIONS TO DIESEL FUEL ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS

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Abstract: *The article deals with the effects of butanol-diesel fuel blends on performance and exhaust emissions of a turbocharged, CRDI 1154HP (85 kW) diesel engine. Load characteristics were taken when running with normal diesel fuel and n-butanol-diesel fuel blends DB1, DB2, DB3, and DB4 possessing 1wt%, 2wt%, 3wt%, and 4wt% of fuel-oxygen at speeds of 1800 and 2500 rpm. The auto-ignition delay increased by 15.5%, burn angle MBF 50 and the combustion ended 7.6% and 6.5% earlier in the cycle, bsfc and engine efficiency were 2.8% and 1.9% higher when using fuel blend DB4 than the respective values of 17.4^0, 20.9^0 and 61.2^0 CADs, 234.4 g/kWh and 0.361 a fully loaded (100%) straight diesel develops at speed of 2500 rpm. The NO_x, CO, THC emissions, and smoke decreased by 5.1%, 29.5%, 3.7 times, and 48.1% against the respective values of 1020 ppm, 563 ppm, 260 ppm, and 12.9% a straight diesel develops under these test conditions.*

Keywords: DIESEL ENGINE, N-BUTANOL-DIESEL FUEL BLENDS, AUTO-IGNITION, ENGINE EFFICIENCY, EMISSIONS

1. Introduction

The environmental air pollution problems were identified in the first Clean Air Act enacted by Congress of the United States on July 14, 1955 [1]. To reduce air pollution the effects of ethanol, petrol, and rapeseed oil [2], ethanol-diesel-biodiesel [3], and oxygenated diesel-HRD fuel blends [4,5] on DI engine performance and exhaust emissions were investigated. The other researchers investigated the effects of various vegetable oils [6], or biodiesel [7] and their blends with ethanol, n-butanol or DME [8] because *n*-butanol is more preferable as oxygenator source than ethanol due to advantageous properties such as better density, viscosity and thus lubricity, higher hydrogen content, net heating value and the cetane number that may positively affect performance and engine-out emissions.

The purpose of the research was to study the effects of diesel-n-butanol fuel blends on the auto-ignition delay, combustion history, maximum heat release rate, burn angles MBF 50, MBF 90 representing the end of combustion, brake specific fuel consumption, brake thermal efficiency, exhaust smoke, and NO_x, CO, THC emissions of a turbocharged CRDI diesel engine running at various loads (bmep) and speeds of 1800 and 2500 rpm.

2. Experimental set up and research methodology

A turbocharged, CRDI diesel engine FIAT 1.9 JTD 8V 115 HP (85 kW) with a displacement volume of 1.91 dm^3 and compression ratio of 18:1 was used for the experimental tests. The uncooled air entered the capacity chamber and the cylinder at a controllable boost pressure of 0.160 MPa and the temperature of 85 ^{0}C. The EGR system was switched off to eliminate the potential side effects on the engine performance. The electronic control unit EDC-15C7 CR governed the timing and the duration of the fuel injection. The test setup consisted of a diesel engine, an engine test bed, the AVL indicating system, the air and the fuel mass flow measuring equipment, a gas analyzer, and a smoke meter as shown in Fig. 1.

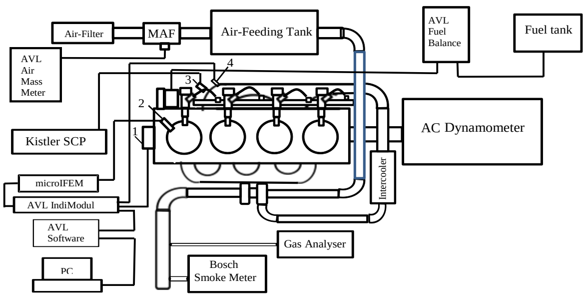

Fig. 1. *Schematic arrangement of the engine test stand: (1) AVL crank-angle encoder; (2) piezoelectric in-cylinder pressure transducer; (3) fuel high-pressure line transducer mounted in front of the injector; (4) air boost pressure sensor mounted in the intake manifold.*

Load characteristics with a diesel fuel (DF) EN 590 (class 1) as a 'baseline' fuel and its 95.375/4.625 wt% (DB1), 90.749/9.251 wt% (DB2), 86.124/13.876 wt% (DB3) and 81.499/18.501 wt% (DB4) blends with n-butanol (B) were taken at speeds of 1800 and 2500 rpm. The combustion phenomena, heat release rate, engine performance, smoke, and emissions revealed when using fuel blends DB1, DB2, DB3 and DB4 involving 1 wt%, 2 wt%, 3 wt%, and 4 wt% of butanol-oxygen were compared with the respective values the reference diesel fuel develops under these test conditions.

A high-speed indicating system with AVL angle encoder 365C and pressure transducer GU24D coupled to the microIFEM piezoelectric amplifier and signal acquisition platform IndiModul 622, was introduced for the recording, acquisition, and processing of crank-angle-pressure signals in the first cylinder. The data post-processing software AVL CONCERTO^{TM} advanced version 4.5 was used to enhance the productivity and measurement accuracy of the test results. The net heat release rate was calculated by using the AVL BOOST program, summarized over 100 engine cycles in-cylinder pressure-data, instantaneous cylinder volume, and their first order derivatives with respect to crank angle.

The engine torque was measured by using an electrical dynamometer KS-56-4 with a definition rate of ±1 Nm, and the speed with crank angle encoder 365C. A real-time air-mass flow into the cylinders was measured with the AVL air-mass flow meter and fuel mass consumption for every load-speed setting point was recorded with the AVL dynamic fuel balance 733S flex-fuel system.

The start of injection (SOI) was recorded by using the Kistler piezoelectric pressure sensor ASMB 470004-1 mounted on a high-pressure tube in front of the injector. The pressure sensor was coupled to the Kistler 2-channel charge amplifier-module 4665 mounted on the signals conditioning platform-compact 2854A to record high-pressure history at the injector with an accuracy of ±0.5% in the pressure variation range of 0–200 MPa.

The auto-ignition delay was determined as a period in CADs between the start of injection (SOI) and the start of combustion (SOC) with an accuracy of ± 0.1^0. As the start of injection was taken crank angle, at which the fuel pressure in a high-pressure tube drops temporary down due to the opening of the nozzle-needle-valve of the injector. As the start of combustion was taken crank angle, at which the total heat release-rate crosses the zero line and changes its value from the minus side to the plus side.

3. Analysis of properties of the tested fuel blends

Conventional automotive diesel fuel was produced at the oil refinery "Orlen Lietuva" and satisfied the requirements of standard EN-590:2009+A1. The n-butanol (CH3CH2CH2CH2OH) was produced at Ltd. „Sigma-Aldrich", Germany (Seelze) and satisfied the requirements of standard 1.00988.6025 1-Butanol EMPROVE® ESSENTIAL NF. Molecular weight of diesel fuel is about 180 [3] and that of 74 belongs to n-butanol [8]. Kinematic viscosity

Burn angle MBF 90, which represents the end of combustion, was 1.4-3.4%, 3.7-30.2%, 2.1-26.7% and 0.0-1.5%, 2.0-2.1%, 1.0-6.5% lower when running with blends DB1-DB4 than those values of 50.1^0, 54.3^0, 58.0^0 and 53.1^0, 56.1^0, 61.2^0 CADs the combustion of diesel fuel ends up for the respective loads at speeds of 1800 and 2500 rpm. The role of butanol-oxygen on the end of combustion is less significant when running at a higher speed because of higher turbulence intensity, swirl, and temperature inside the cylinder.

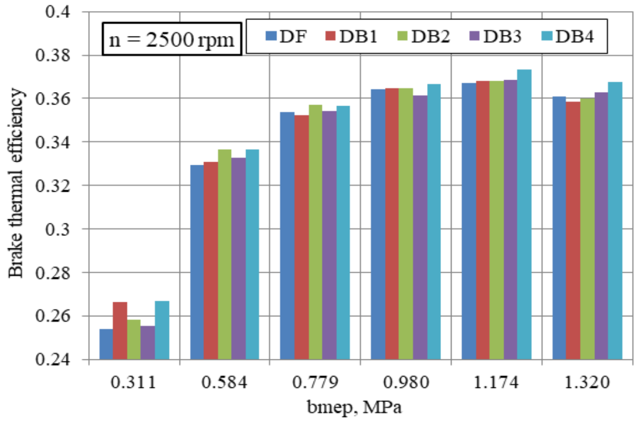

Fig. 4. *The brake thermal efficiency as a function of engine load (bmep) when running with diesel-n-butanol fuel blends at speed of 2500 rpm.*

The engine thermal efficiency increased with increasing load and reached the highest value of 0.373 (1.6%) when using the most oxygenated fuel blend than that of 0.367 a fully loaded (1.174 MPa) straight diesel develops at speed of 2500 rpm (Fig. 4). The bigger is a lack of air-born oxygen inside the cylinder, the greater the need for the fuel-bound oxygen to burn the fuel completely and ensure engine efficiency. The results show that there does not exist a fuel blend, which could ensure the best possible engine efficiency within wide range of engine loads and speeds. Lapuerta et al. also did not observe any decrease in engine efficiency because the fuel consumption increased proportionally to its lower heating value when diesel-n-butanol fuel blends up to 20vol% were used in a Euro 6 engine following the New European Driving Cycle [10].

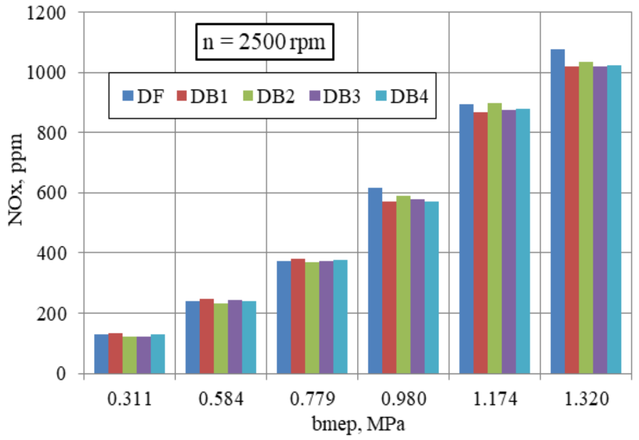

Fig. 5. *The nitrogen oxide emissions (NO_x) as a function of engine load (bmep) when using diesel-n-butanol fuel blends at speed of 2500 rpm.*

The NO_x production depends on the ignition delay time and the amount of the fuel premixed for rapid combustion, maximum heat release rate, combustion duration, pressure inside the cylinder, and adiabatic flame temperature [11]. Therefore, the NO_x emissions from combustion of fuel blend DB1 (1.0 wt%) increased only by 3.9%, 3.8% and 2.1% when running at light loads of bmep = 0.311, 0.583 and 0.778 MPa against, 128. 240 and 374 ppm, a straight diesel produces at speed of 2500 rpm. Whereas the biggest NO_x emissions of 618, 892 and 1075 ppm emerged namely from combustion of oxygen-free diesel fuel when running under higher loads of bmep = 0.979, 1.174 and 1.320 MPa at the latter speed (Fig. 5). The combustion of fuel blend DB2 generated NO_x emissions similar as a straight diesel produces, but slightly more, 588, 897 and 1036 ppm, than the respective diesel-n-butanol fuel blends DB1, DB3 and DB4 produce for these test conditions. Thus, the increased fuel-bound oxygen mass content is important, but equally important is air-to fuel equivalence ratio ‘lambda’ (load), the temperature inside the cylinder and the residence time in a high temperature on which the NO_x production mainly depends [12].

The production of CO emissions depends on engine load, speed, and the availability of the air-born and the fuel-bound oxygen in the cylinder. When running with diesel-n-butanol fuel blends, an extra fuel-bound oxygen comes with an essential help to burn the fuel completely and reduce pollutant emissions, if in the combustion chamber is a lack of air-born oxygen. Because time needed for the oxidation reactions is limited at the high speed of 2500 rpm, CO emissions decreased from 300 ppm to 235, 175, 120 ppm with engine load increased from bmep = 0.311 MPa to 0584, 0.779, 0.980 MPa to increase ones again to 145 and 560 ppm for the higher bmep = 1.174 and 1.320 MPa when running a straight diesel at speed of 2500 rpm (Fig. 6).

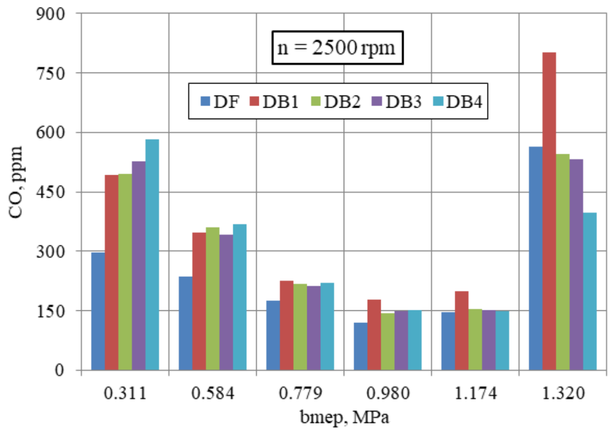

Fig. 6. *The carbon monoxide emissions (CO) as a function of engine load (bmep) when using diesel-n-butanol fuel blends at speed of 2500 rpm.*

These emissions are always higher when running at light loads because of the low temperature inside the cylinder whereas the following CO emissions increase with engine load caused the lack of air-born oxygen needed to convert all carbon in the fuel to CO_2 and all hydrogen to H_2O. For these reasons, the CO production increased with increasing fuel-oxygen mass content because n-butanol added to diesel fuel reduced net heating value of the fuel and thus temperature inside the cylinder at low-load operation. Whereas the CO production progressively decreased from the highest value of 800 ppm (DB1) to 545 (DB2), 530 (DB3) and 395 ppm (DB4) with adding of n-butanol to diesel fuel when running under the highest load of bmep = 1.320 MPa at speed of 2500 rpm.

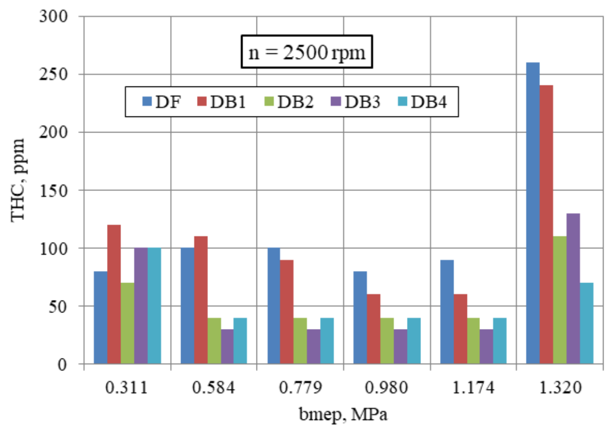

Fig. 7. *The total unburned hydrocarbons (THC) as a function of engine load (bmep) when using diesel-n-butanol fuel blends at speeds of 2500 rpm.*

The THC emissions increased by 50.0% and 10.0% against the respective values a straight diesel produces for light loads of bmep = 0.311 and 0.583 MPa when running with a slightly (1.0 wt%) oxygenated fuel blend DB1 at speed of 2500 rpm. The emissions decreased for a higher load of bmep = 1.174 MPa. Actually, the production of THC emissions became 7.7% then 2.4, 2,0 and 3.7 times lower when using the respective fuel blends DB1, DB2, DB3 and DB4 than that value of 260 ppm a fully loaded, bmep = 1.320 MPa, straight diesel produces at speed of 2500 rpm (Fig. 7).

The higher brake thermal efficiency (Fig. 4), lower CO (Fig. 6) and THC (Fig. 7) emissions were accompanied by 25.6%, 26.4% and 48.1% less exhaust smoke generated from combustion of fuel blends DB2, DB3 and DB4 than that, 12.9%, a straight diesel produces at speed of 2500 rpm. Apart of fuel-bound oxygen, to lower smoke contributed lower density, viscosity, C/H atoms ratio, absence of aromatics in n-butanol composition, and stoichiometric air-fuel ratio of fuel blends that reduced the need for air-born oxygen on which transparency of the exhaust mainly depends.

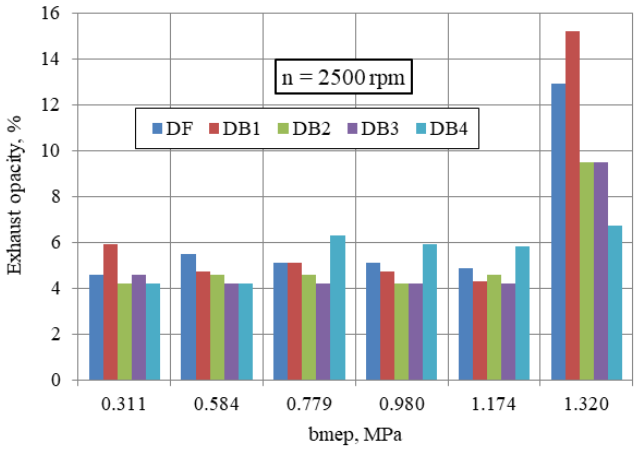

Fig. 8. *The exhaust smoke as a function of engine load (bmep) when running an engine with various diesel-n-butanol fuel blends at speed of 2500 rpm.*

Summary and conclusions

The auto-ignition delay period of a pilot diesel-n-butanol fuel blends DB1-DB4 portions increased by 3.9-13.8% and 2.3-15.5% against, 15.2^0 and 17.4^0 CADs, the normal diesel fuel auto-ignites when running a fully loaded (100%) turbocharged CRDI diesel engine at the respective speeds of 1800 and 2500 rpm.

Burn angle MBF 50 occurred 0.0-6.5% and 4.7-7.6% earlier in the cycle when running a fully loaded engine with oxygenated fuel blends DB1-DB4 than that 17.7^0 and 20.9^0 CADs the 50% mass-portion of a diesel fuel gets burned at speeds of 1800 and 2500 rpm. While the effect of diesel-n-butanol fuel blends on the end of combustion was minor for all loads tested at speed of 2500 rpm.

Brake specific fuel consumption increased to 230.0 (0.9%), 232.3 (1.9%), 234.5 (2.9%), and 234.4 g/kWh (2.8%) for the respective fuel blends DB1, DB2, DB3 and DB4 against that value of 228.0 g/kWh of a straight diesel running at bmep = 1.174 MPa and speed of 2500 rpm.

The brake thermal efficiency increased to 0.383 for diesel-n-butanol fuel blend DB3 (3.0 wt%) and 0.377 for a straight diesel when running at bmep = 1.174 MPa and the low speed of 1800 rpm. The highest engine efficiency of 0.373 (1.6%) suggested the most oxygenated blend DB4 (4.0 wt%) compared with that of 0.367 a straight diesel develops for bmep = 1.174 MPa at speed of 2500 rpm.

The production of total NO_x emissions decreased to the lowest values of 955 ppm (1.5%) and 1020 (5.1%) ppm when running at bmep = 1.590 MPa and 1.320 MPa, with the most oxygenated fuel blend DB 4 (4.0 wt%) at speeds of 1800 and 2500 rpm. Whereas CO emissions decreased by 2.7%, 5.4% and 29.5% when running with fuel blends DB2, DB3 and DB4 against that, 560 ppm, a straight diesel produces for 1.320 MPa load at speed of 2500 rpm.

THC emissions decreased 2.4, 2,0 and 3.7 times, when running with fuel blends DB2, DB3 and DB 4 against that value of 260 ppm a fully loaded, bmep = 1.320 MPa, straight diesel produces at high speed of 2500 rpm. Transparency of the exhaust was also 25.6%, 26.4% and 48.1% better when using the respective blends than that, 12.9%, a straight diesel produces for considered test conditions.

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