LIQUID FUEL TEMPERATURE, PRESSURE AND INJECTION RATE INFLUENCE ON INJECTOR NOZZLE REYNOLDS NUMBER AND CONTRACTION COEFFICIENT

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Abstract: *The influences of liquid fuel temperature, pressure and injection rate on fuel contraction coefficient and Reynolds number during a fuel injection were investigated in this paper. Nozzle geometry parameters remained constant during the whole numerical analysis. Calculations were performed with a standard diesel fuel D2. Increase in liquid fuel temperature cause increase in fuel contraction coefficient. Fuel temperature increase resulted in a slight increase in contraction coefficient at low fuel pressures, while at high fuel pressures increase in fuel temperature causes significant increase in fuel contraction coefficient. Increase of fuel pressure resulted in a decrease in liquid fuel contraction coefficient, for every fuel injection rate and for every fuel temperature. Reynolds number increases with an increase in fuel temperature and also with an increase in fuel injection rate. The main goal of presented analysis is to be usable not only for one fuel injector and its nozzles, but for a large number of the fuel injectors and for many liquid fuels.*

KEYWORDS: *LIQUID FUEL, FUEL INJECTOR NOZZLE, CONTRACTION COEFFICIENT, REYNOLDS NUMBER*

1. Introduction

In internal combustion engine fuel temperature, pressure and injection rate as well as the injector nozzle geometry strongly affect the fuel atomization process. A liquid fuel atomization process has a strong influence on the engine combustion process and on exhaust emissions. However, due to the small length and time scales during the fuel injection process, it is still a challenge to capture and explain the physics and influences behind those processes.

Internal nozzle flow influence on spray atomization along with fuel properties and injection rates was investigated by several authors in the past [1], [2]. Newer investigations about this topic is presented by Madero and Axelbaum [3] which was investigated fuel spray breakup and structure of spray flames for low-volatility wet fuels. Greenberg [4] investigated the impact of the initial droplet size distribution on the behavior of an edge flame. Nozzle configuration effects on internal flow and primary spray breakup for flash boiling fuel sprays was analyzed by Wu et al. [5] while Abianeh et al. [6] investigated the nozzle flow influence and characteristics on multi-component fuel spray evaporation process. Experimental study on fuel spray characteristics under atmospheric and pressurized cross-flow conditions presented Guo et al. [7].

The impact of the injector nozzle geometry and fuel properties on fuel injection, fuel atomization and evaporation processes must be involved in any detail internal combustion engine simulation, as the one presented in [8] for a high speed direct injection turbocharged diesel engine. The same impact is inevitable in simulations of large marine two-stroke slow speed diesel engines [9].

2. Liquid fuel contraction coefficient

Liquid fuel contraction is liquid stream constriction which occurs because the fluid streamlines cannot abruptly change direction. For the fuel injector nozzle, the fluid streamlines are unable to closely follow the sharp angle in the nozzle wall. Maximum contraction is the place in a liquid fuel stream where the diameter of the stream is the lowest. The maximum contraction takes place slightly downstream of the fuel injector nozzle, Fig. 1.

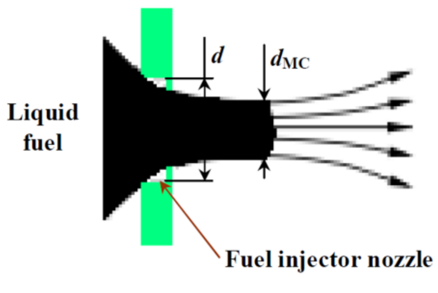

Fig. 1. *Liquid fuel contraction coefficient definition for fuel injector nozzle*

According to Fig. 1, the liquid fuel contraction coefficient for the fuel injector nozzle is defined as a ratio of liquid fuel stream diameter at maximum contraction point and the nozzle diameter:

$$C_d = \frac{d_{MC}}{d} \tag{1}$$

where: C_d = liquid fuel contraction coefficient, d_{MC} = liquid fuel stream diameter at maximum contraction point, d = nozzle diameter.

Liquid fuel contraction coefficient value is always lower than 1 and depends on the fuel stream parameters (pressure, temperature and injection rate) as well as on nozzle geometry.

3. Injector nozzle geometry parameters

The main goal of presented mathematical model in this analysis is to be usable not only for one fuel injector and its nozzles, but for a large number of the fuel injectors and for many liquid fuels. As analysis baseline is used fuel injector DLLA 775 from [10].

Three fuel injector nozzle geometry parameters which influenced liquid fuel contraction and Reynolds number are nozzle diameter (d), nozzle length (l) and nozzle inlet radius (r). The nozzle inlet radius value is usually shown as a ratio of nozzle diameter (r/d), what was also adopted in presented analysis.

In analysis were selected nozzle geometry parameters similar to ones for fuel injector DLLA 775 [10], which are the most used in practice. Selected nozzle geometry parameters remain unchanged throughout the analysis.

The variables which strongly influenced fuel contraction coefficient and Reynolds number are fuel pressure, fuel temperature and fuel injection rate. Those variables were varied.

4. Liquid diesel fuel used in the analysis

In analysis was used diesel fuel D2, which main characteristics and specifications are presented in Table 1. Although the analysis is made with diesel fuel D2, the mathematical description of the liquid fuel contraction coefficient and the Reynolds number allows the usage of any standard or alternative liquid fuel.

Table 1. *Main specifications of diesel fuel D2 [11]*

Liquid diesel fuel D2 property	**Value**
Sulfur content	0.3 percentage of mass
Molecular mass	198 kg/kmol
Density at 15.5 °C	0.842 g/cm^3
Kinematic viscosity at 38 °C	$2.84 \cdot 10^{-6}$ m^2/s
Critical pressure	20.9 bar
Critical temperature	453 °C
Boiling point	266 °C
Flash point	75 °C
Aniline point	71.7 °C

5. Liquid diesel fuel D2 thermodynamics properties necessary for analysis

5.1. Density of liquid diesel fuel D2

Liquid diesel fuel D2 density dependence on the fuel pressure and temperature is given by the following equation [11]:

$$\rho = \rho_0 \cdot \left(1 + \frac{p}{E} - \frac{\Delta t}{A}\right) \tag{2}$$

where: ρ = liquid fuel current density (g/cm^3), ρ_0 = 0.845 g/cm^3 (liquid fuel density on the environmental pressure = 1 bar and temperature = 25 °C), p = liquid fuel current pressure (Pa), $E = 19.6 \cdot 10^8$ Pa (liquid fuel elasticity module), Δt = liquid fuel temperature above the environment temperature, A = 1350 °C (reciprocal value of the liquid fuel thermal expansion coefficient).

5.2. Dynamic viscosity of liquid diesel fuel D2

Liquid diesel fuel D2 dynamic viscosity change can be calculated by a second degree polynomial [11]:

$$\mu = A(t) + B_1(t) \cdot p + B_2(t) \cdot p^2 \tag{3}$$

$$\begin{aligned} A(t) &= 5.92723 \cdot 10^{-5} + 0.0030803 \cdot \exp\left(-\frac{t - 17.45789}{13.98351}\right) + \\ &+ 0.0036761 \cdot \exp\left(-\frac{t - 17.45789}{77.77}\right) \end{aligned} \tag{4}$$

$$\begin{aligned} B_1(t) &= 8.02964 \cdot 10^{-6} - 1.17256 \cdot 10^{-7} \cdot t + 3.82129 \cdot 10^{-10} \cdot t^2 + \\ &+ 1.30035 \cdot 10^{-12} \cdot t^3 \end{aligned} \tag{5}$$

$$\begin{aligned} B_2(t) &= 2.21756 \cdot 10^{-8} \cdot \exp\left(-\frac{t - 20}{9.126829}\right) + \\ &+ 5.85318 \cdot 10^{-9} \cdot \exp\left(-\frac{t - 20}{51.453}\right) \end{aligned} \tag{6}$$

where: p = liquid fuel current pressure (bar), t = liquid fuel current temperature (°C), μ = liquid fuel current dynamic viscosity (kg/m·s).

6. Liquid fuel Reynolds number and contraction coefficient

The Reynolds number for the fuel injector nozzle is defined by the expression:

$$\mathrm{Re} = \frac{\rho \cdot v_i \cdot d \cdot 10^{-3}}{\mu} \tag{7}$$

where: ρ = liquid fuel density (kg/m^3), v_i = liquid fuel injection rate (m/s), d = nozzle diameter (mm), μ = liquid fuel dynamic viscosity (kg/m·s).

Reynolds number coefficient f used in the contraction coefficient equation was calculated by the equation:

$$f = \mathrm{Max}\left(0.316 \cdot \mathrm{Re}^{-0.25}, \frac{64}{\mathrm{Re}}\right) \tag{8}$$

Contraction loss coefficient K_{in} is a function of nozzle inlet radius r and nozzle diameter d ratio. According to [12] contraction loss coefficient K_{in} can be defined by the following polynomial:

$$\begin{aligned} K_{in} &= 162.52076 \cdot (r/d)^4 - 143.12017 \cdot (r/d)^3 + \\ &+ 47.86559 \cdot (r/d)^2 - 7.50909 \cdot (r/d) + 0.51243 \end{aligned} \tag{9}$$

where: K_{in} = contraction loss coefficient (-), r = nozzle inlet radius (mm), d = nozzle diameter (mm).

Flow in the fuel injector nozzle is turbulent with the possibility of cavitation occurrence. Taking into account the turbulent flow in the fuel injector nozzle without the occurrence of cavitation [12], the liquid fuel contraction coefficient can be defined as:

$$C_d = \frac{1}{\sqrt{K_{in} + f \cdot \frac{l}{d} + 1}} \tag{10}$$

where: C_d = liquid fuel contraction coefficient (-), K_{in} = contraction loss coefficient (-), f = Reynolds number coefficient (-), l = nozzle length (mm), d = nozzle diameter (mm).

7. Mathematical model results and discussion

Change in liquid fuel contraction coefficient for different fuel injection rates and temperatures, at fuel pressure of 800 bars, was presented in Fig. 2. This figure, as all the other figures through this paper, was obtained by using nozzle geometry and fuel characteristics presented in boldface legend in the figure.

From Fig. 2 can be seen that contraction coefficient increases with the increase in fuel temperature. During the injection rate increase, at any fuel temperature, increase in contraction coefficient is significant for low injection rates (from 10 m/s to 100 m/s). Further increase in the fuel injection rate (above 100 m/s) causes low, almost negligible increase in contraction coefficient, for any fuel temperature.

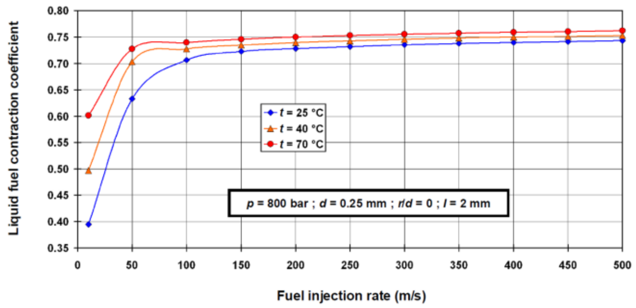

Fig. 2. *Change in liquid fuel contraction coefficient for different fuel injection rates and temperatures (p = 800 bars)*

For the same fuel injector nozzle operating parameters and fuel pressure as in Fig. 2, change in Reynolds number which is calculated according to equation (7) is presented in Fig. 3.

For any fuel injection rate, Reynolds number increases with an increase in fuel temperature. Increase in fuel injection rate also increases Reynolds number, for every fuel temperature. During the increase in injection rate, the increase in Reynolds number is as higher as the fuel temperature increase, so the highest Reynolds numbers were obtained for the highest observed fuel temperature and injection rate. Dispersion of Reynolds numbers for a various fuel temperatures became as higher as fuel injection rate increases.

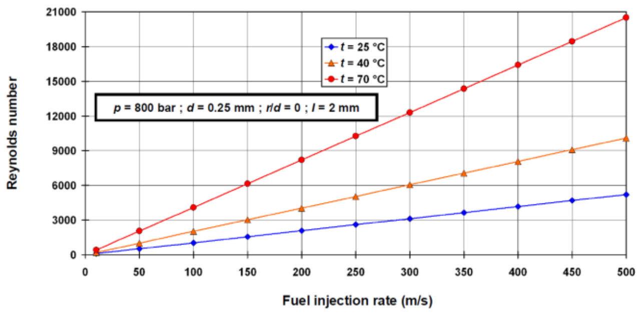

Fig. 3. *Change in Reynolds number for different fuel injection rates and temperatures (p = 800 bars)*

Change in liquid fuel contraction coefficient for different fuel injection rates and temperatures, for the same fuel injector nozzle operating parameters as in Fig. 2, but with increased fuel pressure (from 800 bars to 2000 bar) is presented in Fig. 4.

For any fuel pressure is valid a fact that the increase in fuel temperature causes an increase in contraction coefficient, for any fuel injection rate. Increase in fuel injection rate causes a different change of contraction coefficient for low fuel pressures (Fig. 2) in comparison with high fuel pressures (Fig. 4).

At high fuel pressures, increases in the fuel injection rate (from 10 m/s to 500 m/s) causes a continuous and significant increase in contraction coefficient, when the fuel is on environmental temperature (25 °C). For higher fuel temperatures, an increase in contraction coefficient during the increase in injection rate is significant only for lower injection rates (from 10 m/s to 250 m/s).

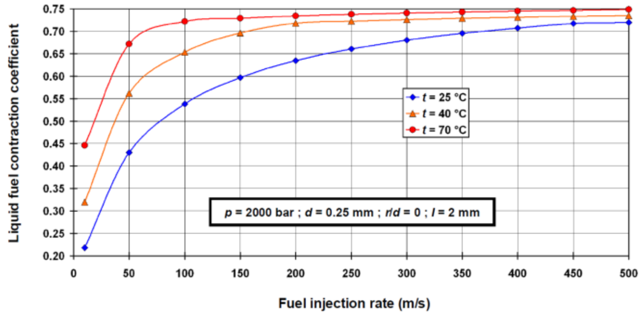

Fig. 4. *Change in liquid fuel contraction coefficient for different fuel injection rates and temperatures (p = 2000 bar)*

Change in Reynolds number for different fuel injection rates and temperatures at fuel pressure of 2000 bar is presented in Fig. 5. When compared Fig. 5 (fuel pressure 2000 bar) and Fig. 3 (fuel pressure 800 bar) it can be concluded that a change in Reynolds number during the change in the fuel injection rate and fuel temperature has the same trend for every fuel pressure.

The only significant influence of fuel pressure on Reynolds number can be seen in the Reynolds number value. Increase in fuel pressure causes decrease in Reynolds number, for the same fuel injector nozzle operating parameters. At fuel pressure of 2000 bar, Fig. 5, maximum Reynolds number does not exceed Re = 7500, while at fuel pressure of 800 bars, Fig. 3, maximum Reynolds number reaches almost Re = 21000. Again, for both fuel pressures, the maximum Reynolds number was obtained at the highest fuel temperature and at the highest injection rate.

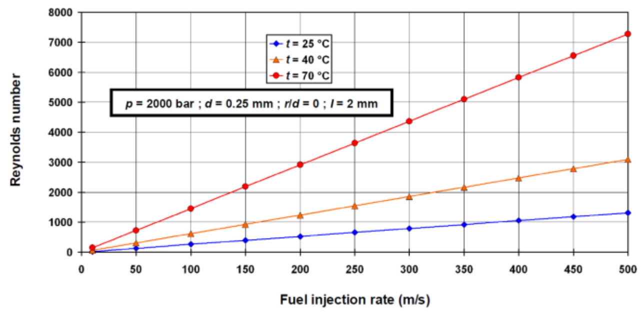

Fig. 5. *Change in Reynolds number for different fuel injection rates and temperatures (p = 2000 bar)*

Change in liquid fuel contraction coefficient for different fuel pressures and injection rates at a fuel temperature of 25 °C, is presented in Fig. 6.

Increase in fuel pressure resulted with a decrease in liquid fuel contraction coefficient, for every fuel injection rate, but the decrease trends are not the same at each injection rate. For the lowest observed injection rate (100 m/s) decrease in contraction coefficient, during the increase in fuel pressure is the sharpest. Increase in fuel injection rate causes that decrease in contraction coefficient, during the fuel pressure increase, becomes less and less sharp. For low fuel pressures, dispersion of contraction coefficients for every observed injection rate is low, while it becomes bigger and bigger as fuel pressure increases.

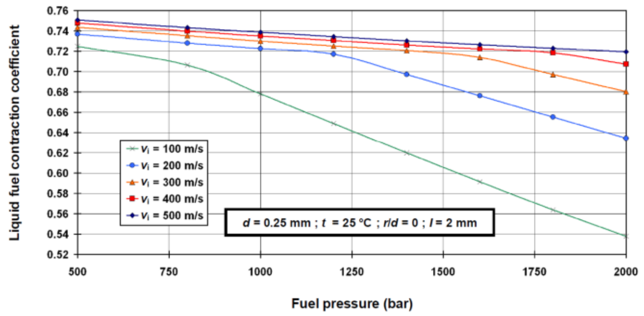

Fig. 6. *Change in liquid fuel contraction coefficient for different fuel pressures and injection rates (t = 25 °C)*

Change in liquid fuel contraction coefficient for different fuel pressures and injection rates, for the same fuel injector nozzle operating parameters, but for increased fuel temperatures was presented in Fig. 7 for fuel temperature of 40 °C and in Fig. 8 for fuel temperature of 70 °C.

As in Fig. 6, increase of fuel pressure resulted in a decrease in liquid fuel contraction coefficient, for every fuel injection rate, and the decrease is the highest for the lowest observed fuel injection rate (100 m/s).

When compared Fig. 6 and Fig. 7, it can be noted that the increase in fuel temperature from 25 °C to 40 °C resulted in a slight increase in contraction coefficient at low fuel pressures, while at high fuel pressures increase in fuel temperature causes significant increase in fuel contraction coefficient, for any injection rate. This conclusion and comparison with lower fuel temperature is also valid when fuel temperature is the highest observed (70 °C, Fig. 8).

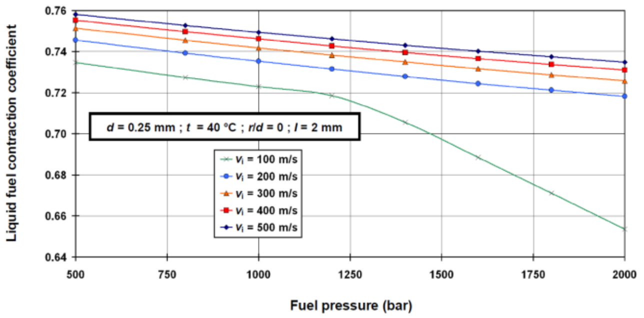

Fig. 7. *Change in liquid fuel contraction coefficient for different fuel pressures and injection rates (t = 40 °C)*

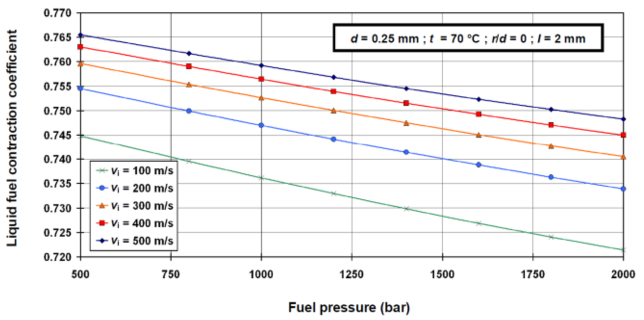

Fig. 8. *Change in liquid fuel contraction coefficient for different fuel pressures and injection rates (t = 70 °C)*

Change in Reynolds number for different fuel pressures and injection rates is presented in Fig. 9 and Fig. 10. Injector nozzle geometry parameters remains the same in all figures, while the fuel temperature was varied and amounts 25 °C - Fig. 9 and 70 °C - Fig. 10.

The most of the conclusions for Reynolds number change are the same at each fuel temperature. Increase in fuel pressure causes decrease in Reynolds number for every fuel temperature and injection rate. The decrease in Reynolds number during the fuel pressure increase is the highest for the highest fuel injection rates, at any fuel temperature. Dispersion of Reynolds numbers for different fuel injection rates are the highest at the lowest fuel pressures while the same dispersion is the lowest for the highest observed fuel pressures, what is a valid conclusion for every fuel temperature.

Change in fuel temperature influences only the Reynolds number value. For every fuel temperature, the highest Reynolds numbers were obtained at the lowest fuel pressure and at the highest fuel injection rate. Increase in fuel temperature resulted in an increase in Reynolds number.

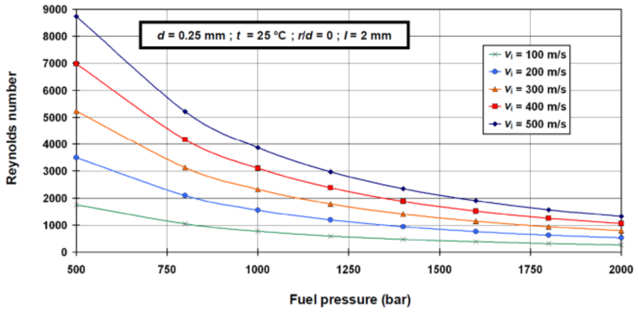

Fig. 9. *Change in Reynolds number for different fuel pressures and injection rates (t = 25 °C)*

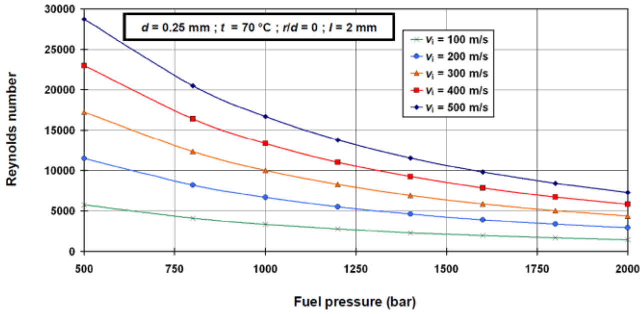

Fig. 10. *Change in Reynolds number for different fuel pressures and injection rates (t = 70 °C)*

8. Conclusion

In this paper were investigated influences of liquid fuel temperature, pressure and injection rate on fuel contraction coefficient and Reynolds number during fuel injection. Nozzle geometry parameters remained constant during the whole numerical analysis. As expected, fuel temperature, pressure and injection rate are very influential parameters which can significantly change the fuel contraction coefficient and Reynolds number. Calculations were performed with a standard diesel fuel D2.

Increase in liquid fuel temperature cause increase in fuel contraction coefficient. Fuel temperature increase resulted in a slight increase in contraction coefficient at low fuel pressures, while at high fuel pressures increase in fuel temperature causes significant increase in fuel contraction coefficient. To obtain contraction coefficient as high as possible, for low fuel pressures is advisable to increase the fuel injection rate, but not much higher than 100 m/s. At high fuel pressures, increases in the fuel injection rate causes a continuous and significant increase in contraction coefficient when the fuel is on environmental temperature (25 °C), while for higher fuel temperatures increase in contraction coefficient during the increase in injection rate is significant only for lower injection rates. Increase of fuel pressure resulted in a decrease in liquid fuel contraction coefficient, for every fuel injection rate and for every fuel temperature.

Reynolds number increases with an increase in fuel temperature and also with an increase in fuel injection rate. During the increase in injection rate, the increase in Reynolds number is as high as the fuel temperature increase, so the highest Reynolds numbers were obtained for the highest observed fuel temperature and injection rate. Change in Reynolds number during the change in the fuel injection rate and fuel temperature has the same trend for every fuel pressure. For every fuel temperature, the highest Reynolds numbers were obtained at the lowest fuel pressure and at the highest fuel injection rate. Increase in fuel pressure causes decrease in Reynolds number for every fuel temperature and injection rate.

The main goal of presented analysis is to be usable not only for one fuel injector and its nozzles, but for a large number of the fuel injectors and for many liquid fuels. Future research will be based on investigations of the same fuel and fuel injector operating parameters for alternative fuels and its comparison with presented ones for a standard diesel fuel.

9. Acknowledgment

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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.

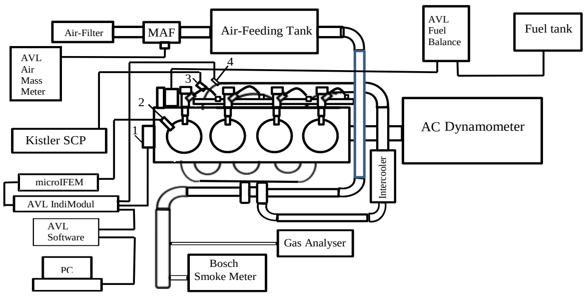

Fig. 1. *Schematic arrangement of the engine test stand: (1) AVL crank-angle encoder; (2) piezoelectric in-cylinder pressure transducer; (3) fuel high-pressure line transducer mounted in front of the injector; (4) air boost pressure sensor mounted in the intake manifold.*

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