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The influence of biodiesel fuel on injection characteristics, diesel engine performance, and emission formation

Luka Lešnik [a], Blaž Vajda [a], Zoran Žunič [b], Leopold Škerget [a], Breda Kegl [a,*]

[a] University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, SI-2000 Maribor, Slovenia
[b] AVL AST d.o.o., Trg Leona Štuklja 5, SI-2000 Maribor, Slovenia

HIGHLIGHTS

- MCC combustion model is suitable for simulation in M injection system.
- Injection, fuel spray and combustion models give good agreement with experiment.
- Biodiesel properties increase NO_x emission up to 15% relative to diesel.
- Biodiesel properties reduce CO emissions up to 75% relative to diesel.

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ABSTRACT

The presented work focuses on numerical and experimental analyses of biodiesel fuel's influence on the injection characteristics of a mechanically-controlled injection system, and on the operating conditions of a heavy-duty diesel engine. Addressed are mineral diesel fuel and neat biodiesel fuel made from rapeseed oil. The influence of biodiesel on mechanically controlled injection system characteristics was tested experimentally on an injection system test-bed. The injection test-bed was equipped with a glass injection chamber in order to observe the development of the fuel-spray by using a high-speed camera. The results of the experimental measurements were compared to the numerical results obtained by using our own mathematical simulation program. This program has been used to analyze the influences of different fuel properties on the injection system's characteristics. The photos taken with a high-speed camera were compared to the simulation results obtained by using the AVL FIRE 3D CFD simulation program. This software was used to simulate the fuel-spray development during different stages of the injection process. Furthermore, the influence of biodiesel fuel on the engine operating condition of a heavy-duty diesel engine and its' emission formation was tested experimentally on an engine test-bed, and numerically by using the AVL BOOST software. It was found out that the tested biodiesel could be used as an alternative fuel for heavy-duty diesel engines.

1. Introduction

Decreases in fossil-fuel resources and global atmospheric pollution are becoming major problems throughout the World. Biofuels can provide a good alternative to fossil-fuels and they can reduce harmful emissions like carbon monoxide (CO), carbon dioxide (CO_2), unburned hydro carbon (HC) emissions, and soot. In diesel engines, biodiesel can potentially be used instead of mineral diesel fuel. Biodiesel can be made from different raw materials like canola oil, rapeseed oil, animal tallow, algae, and others. The raw material used influence the biodiesel properties that may be more or less similar to the one of mineral diesel. Biodiesel fuels typically consist of lower alkyl fatty acid, esters of short-chain alcohols, and methanol. Demirbas [1] and Torres et al. [2] investigated the differences in the physical and chemical properties of ethanol–biodiesel fuel-blends and their influence on injection and engine characteristics. The experimentally tested properties were density, viscosity, cold filter plugging, cloud-point, flash-point, and so on. Torres et al. [3] also tested how ethanol addition to mineral diesel fuel influences the operating characteristics of injection systems. Fengkun et al. [4] have tested how different oxygenic fuel additives can contribute to the improvement of diesel and petrol fuel combustion. For this purpose, they experimentally-measured the surface tensions of different diesel and petrol mixtures containing ethanol and other additives. From their results for surface tension, they assessed how the different concentrations of additives influence fuel atomization and combustion. Cecil et al. [5] presented a method for

* Corresponding authors. Tel.: +386 22207732.
E-mail address: breda.kegl@um.si (B. Kegl).

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predicting the of biodiesel fuels from their fatty acid compositions. From their results, they assessed how surface tension influences fuel atomization.

Investigations of biodiesel's influence in diesel engines can be divided into three major parts. The influence of biodiesel's fuel properties on the injection system's characteristics, influence on spray formation, and its influence on diesel engine performance and emissions formation [6–16]. Mechanically-controlled and electronically-controlled injection systems have to be considered separately. Kegl and Hribernik [7], and Torres et al. [6], investigated the influence of biodiesel properties on various mechanically-controlled injection systems' operating characteristics, like fueling, mean injection rate, mean injection pressure, injection timing, etc. Thumheer [11] tested different fuel injection strategies in heavy-duty diesel engines equipped with common rail injection systems and their influence on engine performance and emission formation. Hulwan and Joshi [17], and Park et al. [18] also tested how different ethanol, diesel and biodiesel fuel mixtures influence engine operating conditions and emission formation. In [19] an optimization model was developed in order to establish the optimal blend of diesel, ethanol, and biodiesel fuel with the aim to lower the production costs and meet market demands. Kannan et al. [20] investigated how ferric chlorides, used as additives to waste cooking and palm oil based biodiesel, influence the emission formation and engine thermal efficiency. Most researchers agree that the use of biodiesel as a replacement for mineral diesel can contribute to a reduction of HC, CO, CO_2, and soot emissions. The same pattern of emission reduction was also observed with the use of ethanol, diesel, and biodiesel fuel mixtures in [18], where the author also observed a slight decrease in NO_x emissions. Apart from emissions, biodiesel fuels typically cause a reduction in engine power and torque due to their lower calorific values and lead to increased fuel consumption in engines with mechanically controlled injection systems. So far, most investigations are done by using experimental testing combined with numerical simulation. On the other hand, some alternative approaches have also been adopted. For example, Ismail et al. [21] used artificial neural network modeling for nine different engine response parameters. Pandian et al. [22] and Wu and Wu [23] used a response surface method and the Taguchi method, respectively, for the determination of different engine and/or injection system parameters when using biodiesel fuels.

Several different computation fluid dynamic (CFD) simulation programs can be used when simulating diesel spray development. Mostly the Euler–Lagrange approach is adopted, which treats each fuel droplet as an individual particle. Volmajer and Kegl [24] used the FIRE 3D CFD program for simulating the diesel spray by using various injector nozzles. Lucchini et al. [25] used the OpenFOAM simulation software to simulate the fuel spray development. In order to reduce the mesh dependency, they implemented an adaptive mesh refinement technique. Based on experimental results, specific sub-models for spray breakup were developed, tested, and verified. Dynamic (adaptive) mesh refinement technique for improving spray simulation was also employed by Kolakaluri et al. [26], where it was implemented within the KIVA-4 CFD program. CFD simulation by using the FLUENT software can also be used for analyzing emission formation within the combustion chamber [27], where several different biodiesel were tested and their effect on thermal and prompt NO emissions, and on soot formation was evaluated.

In this paper the influence of biodiesel from rapeseed oil on injection and combustion characteristics of a bus diesel engine with mechanically controlled M injection system is considered at various engine operating regimes. For this purpose, some important engine characteristics were determined by experiment and by numerical simulation. At first, the injection pressure, the needle lift, and the injected fuel per cycle were determined experimentally on a fuel injection system test bed and numerically by using our own mathematical model. Furthermore, to the test bed a glass chamber was added, into which fuel spray was injected in order to record spray development using a high speed camera. Simulations of the spray development were also performed using the AVL FIRE CFD simulation program, and the Euler–Lagrange approach. Finally, the influence of biodiesel on engine torque, power, exhaust gas temperature, NO_x and CO emissions was tested numerically using the AVL BOOST simulation program, and experimentally on the engine test bed under full load, and various engine speeds. The attention is focused on the possibility to replace mineral diesel fuel by pure rapeseed biodiesel in the tested diesel engine.

2. Tested fuels

Mineral diesel fuel D2 that contained no additives and conformed to European standard EN 590, and biodiesel fuel B100 produced from rapeseed oil at Biogoriva, Rače, Slovenia, that conformed to European standard EN 14214, were used during the presented study. It is well-known that fuel properties have a noticeable influence on injection and engine characteristics. For that reason, some of the more important properties of mineral diesel and biodiesel fuel were measured experimentally by using different test methods that correspond to European or other standards. Fuel density was measured at 15 °C by using a method that conformed to European standard EN ISO 12185, kinematic viscosity was measured at 40 °C by using a test method that conformed to European standard EN ISO 3104, and fuel composition was measured by using the test method ASTM D 5291. The sound velocity in fuels was measured at different pressures up to 700 bar and is presented in Fig. 1. Measures were based on the monitoring of pressure wave propagation along a specified length in a high pressure tube with two piezoelectric pressure transducers that were located at the opposite sides of high pressure tube. A small pump with a plunger was used to induce system pressure and pressure waves that were monitored using piezoelectric transducers. Some of the used fuel properties are presented in Fig. 1 and Table 1.

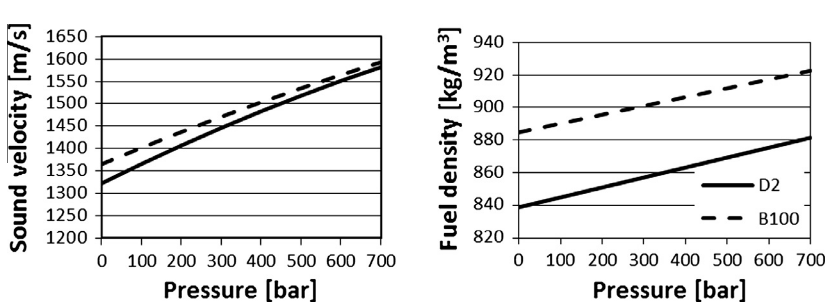

Fig. 1. Fuel properties.