Fuel 144 (2015) 71–79

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

# The numerical simulation of biofuels spray

Blaž Vajda [a,*], Luka Lešnik [a], Gorazd Bombek [a], Ignacijo Biluš [a], Zoran Žunič [b], Leopold Škerget [a], Marko Hočevar [c], Brane Širok [c], Breda Kegl [a]

[a] University of Maribor, Faculty for Mechanical Engineering, Engine Research Laboratory, Smetanova ulica 17, SI-2000 Maribor, Slovenia
[b] AVL-AST d.o.o., Trg Leona Štuklja 5, SI-2000 Maribor, Slovenia
[c] University of Ljubljana, Faculty for Mechanical Engineering, Laboratory for Hydraulic Machines, Aškerčeva 6, SI-1000 Ljubljana, Slovenia

## HIGHLIGHTS

- Numerical analysis of biofuels' influence on injected fuel-spray cone's angle and length is being analyzed.
- Pressurized chamber with nitrogen at 40–60 bar is used for experimental measurements of spray development.
- The fuels are experimentally investigated in order to verify the numerical model.
- Empirical expressions were developed for fuel properties and engine-operating conditions.
- Experimental and numerical results confirmed the usability of the numerical model.

## ARTICLE INFO

*Article history:*
Received 18 March 2014
Received in revised form 24 November 2014
Accepted 26 November 2014
Available online 16 December 2014

*Keywords:*
Biofuels
Numerical simulation
Spray shape
Pressure chamber

## ABSTRACT

In this paper, the possibility of replacing mineral diesel fuels with different biofuels is analyzed. The study focuses on a numerical investigation of biofuels' influence on an injected fuel-spray cone's angle and length, which have further influence on the combustion process and the formation of pollutants in internal combustion engines. The influence of different physical and chemical properties of pure mineral diesel fuel, biodiesel fuel and their blends on spray characteristics was investigated with the AVL FIRE simulation program. Several different empirical model parameters, usually the engine-operating regime and biofuel used, must be defined when using numerical models. In this study, the numerical model implemented in AVL FIRE was modified so that all model parameters were determined regarding biofuel properties and engine-operating conditions. Experimental measurements of spray development in a cylindrical chamber pressurized with nitrogen at 40–60 bar were performed for validation of the modified numerical model. Photos of spray development were taken with a high speed camera simultaneously with pressure and needle-lift signals. The comparison of experimental and numerical results confirmed the usability of the numerical model. Numerical results of spray development for different biofuels under different operating regimes and ambient pressure confirm the possible usage of biofuels as a replacement for mineral diesel fuel in diesel engines with the early generation of fuel injection systems.



## 1. Introduction

Global atmospheric pollution has become a serious problem. Competitiveness in the engine industry and rising environmental concerns have increased the research of alternative fuels. It has long been known that biofuels can decrease the pollution from the combustion process in internal combustion engines. Biodiesel is the most frequently used biofuel for decreasing pollution in diesel engines [1–5]. It can be produced from several different raw materials, which influence its physical and chemical properties that are important in the compression ignition engine injection and combustion process. The distribution of fuel droplets and their vaporization in a diesel engine combustion chamber are the dominant factors governing the fuel/air mixture formation, combustion process, engine performance and pollutant formation. The process of spray development and the atomization of biofuels seems to be different in comparison to diesel fuel [6–8].

The influence of different fuel (biofuel) properties on spray characteristics could be investigated experimentally or numerically. Experimental measurements of spray characteristics enable us to see the actual spray development. Numerical analysis (CFD) allows us more detailed investigation into the fuel spray development dynamic and the influence of different fuel properties on

* Corresponding author at: Orešje 124, 2250 Ptuj, Slovenia. Tel.: +386 41 522 145.
*E-mail address:* bvajda@gmail.com (B. Vajda).

http://dx.doi.org/10.1016/j.fuel.2014.11.090
0016-2361/

droplet formation. Numerical simulations are generally faster and less expensive in comparison to experiments.

When numerical simulations are used, fuel injection in internal combustion engines must be considered as a two-phase flow, which could be simulated using the Euler–Euler or Euler–Lagrange approaches. The Euler–Lagrange approach is more suitable for fuel spray simulations because it treats each fuel droplet as an individual particle. In numerical models, several empirical constants are present, regardless of the approach used. These constants need to be defined before the simulation is started. Values of empirical constants depend on injection system characteristics, engine operating regime, and the physical and chemical properties of the fuel used. The determination of constants is based on users' experiences and might be difficult for the cases in which new biofuels are introduced [9–10].

Many studies on spray development have been performed. Agarwal and Chaudhury [11] experimentally investigated the effect of ambient pressure on spray characteristics in a constant volume spray chamber. The fuels used for the research were Karanja KB100 biodiesel produced from feed-stocks such as Jatropha, KB0 diesel fuel, and KB5 and KB20 blends. The results of their investigation showed that spray tip penetration decreases while the cone angle and spray area increase with the increase of ambient pressure. A similar experimental study was also made by Lee et al. in [12]. They investigated the influence of fuel properties on spray tip penetration, mean droplet size, velocity distribution, and injection profiles using a visualization system and a phase Doppler particle analyzer system. The study was made using different mixing ratios of diesel and biodiesel fuel. The results indicate that the mean size of the droplets increases in accordance with the mixing ratio of the biodiesel fuel. The investigation was made using single-cylinder diesel engine with a common-rail injection system. An engine with a common-rail injection system was also used in the study of Grimaldi and Postrioti [13]. They also used conventional mineral diesel fuel, pure bio-derived fuel and blends of them to investigate the influence on spray characteristics, such as penetration length and spray cone angle. The study was made using two different rail pressures, following which spray jets were injected in the chamber with atmospheric pressure. All presented experimental results indicated that the higher viscosity and surface tension of biofuels result in longer spray penetration lengths and narrower spray jets. Higher ambient pressure results in wider spray cone angles and in decreased spray penetration lengths.

Hohman and Renz [14] used an Euler–Lagrange approach for a numerical study of ambient temperature and pressure influence on the vaporization process of unsteady *n*-heptane and binary model D7N3 fuel sprays. They developed an extended droplet vaporization model that accounts for the effects of non-ideal droplet evaporation and gas solubility. The model includes the diffusion of heat and species within fuel droplets. The model has been implemented into the CFD program FLUENT. The results of the numerical simulation were validated using experimental results, which were made in a high-temperature-high-pressure chamber using a phase-Doppler measurement system. The results comparison shows the influence of pressure and temperature on the vaporization rate of fuel droplets.

The effect of the ambient condition on the droplet atomization characteristics of dimethyl ether fuel was studied experimentally and numerically in the work of Suh et al. [15]. They concluded that smaller droplets are distributed at higher ambient pressures. The Sauther mean diameter of fuel droplets increases when the ambient temperature is increased.

Pogorevc et al. [16] numerically investigated the influence of different biofuels properties on spray tip penetration length and spray cone angle at atmospheric pressure. The aim of this study was to numerically analyze the influence of different physical and chemical properties of biofuels on spray characteristics at various engine operating regimes and different pressures. The numerical model based on the Euler–Lagrange approach was modified in order to make it independent of empirical parameters. For verification of a modified numerical model, several measurements of fuel spray development were performed in a specially designed pressure chamber. The focus of the study is on the possibility of replacing the mineral diesel fuels with different biofuels in the tested diesel engine.

This paper discusses the possibility of replacing mineral diesel fuels with different biofuels. The focus of the study is a numerical investigation of an injected fuel-spray cone's angle and length. In addition to injection system measurements, fuel physical properties and injection process characteristics were measured for pure mineral diesel fuel, biodiesel fuel and their blends. The standard numerical model implemented in AVL FIRE was modified in such a way that all model parameters were determined regarding biofuel properties and engine-operating conditions. For validation purposes, the spray was injected into a cylindrical chamber pressurized with nitrogen at 40–60 bar. Spray macro characteristics were taken with a high-speed camera simultaneously with pressure and needle-lift signals. The comparisons of experimental and numerical results were made using AVL FIRE software and confirm the usability of the developed numerical model. The numerical results of spray development for different biofuels under different operating regimes and ambient pressures confirm the possible usage of biofuels as a replacement for mineral diesel fuel in diesel engines with the early generation of fuel injection systems.

## 2. Tested fuels

D2 mineral diesel fuel that contained no additives and conformed to European standard EN 590 and B100 biodiesel fuel produced from rapeseed oil at Biogoriva, Rače, Slovenia that conformed to European standard EN 14214, and the D50B50 blends (blend of 50% diesel fuel and 50% biodiesel fuel) and D85E15 (blend of 85% diesel fuel and 15% ethanol) were used in this study. It is well-known that fuel properties have a perceptible influence on injection and engine characteristics. For this reason, all the fluid properties used should be used as a starting parameters for numerical simulations. In this study, the following fluids were used (Table 1).

## 3. Spray simulations

The spray simulations in this study are based on a statistical method referred to as the discrete droplet method. Droplet parcels are introduced in the flow-domain with initial conditions of position, size, velocity, temperature, and the number of particles in the parcel. The droplets are tracked in the Lagrangian manner through the computational grid used for solving the gas-phase partial differential equations. Full two-way interaction between the gas and liquid phases is taken into account. The basic equation for momentum is [17]:

**Table 1**
Fluid properties.

| Fuel | Density (kg/m$^3$) | Dynamic viscosity at 20 °C (MPa s) | Surface tension at 20 °C (N/mm) |
|---|---|---|---|
| Mineral diesel D2 | 827 | 3.2 | 26.8 |
| Biodiesel B100 | 875 | 6.1 | 28.4 |
| D50B50 | 825 | 4.3 | 27.6 |
| D85E15 | 822 | 2.8 | 25.4 |