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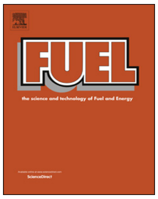

Full Length Article

One-dimensional modeling and simulation of injection processes of bioethanol-biodiesel and bioethanol-diesel fuel blends

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ABSTRACT

This paper presents the development of a complete simulation model for a mechanical in-line injection system feed with diesel, biodiesel, bioethanol fuel blends. The mathematical model is built by using the AVL Boost™ Hydsim software, while the required input data is carefully derived by making use of existing data as well as formulas and numerical procedures described in this work. This setup enables relatively efficient formulation and set-up of the mathematical model as well as consistent and reasonably accurate derivation of input data.

The derived model is used to simulate the injection processes of various bioethanol-biodiesel and bioethanol-diesel fuel blends. The simulation results are compared to experimental data obtained on a Friedman-Maier type 12H100_h test bed at ambient temperature and several operating regimes. The results show that the compared injection pressure and needle lift histories are generally in a good agreement with the experimental ones. Consequently, the simulation model presented is fast and accurate enough to be engaged in various numerical procedures, ranging from investigations of influences of bioethanol addition to injection system optimization.

1. Introduction

It is now widely accepted that the major driver of rising temperatures are anthropogenic greenhouse gas emissions (CO_2, CH_4, N_2O) which are largely related to the burning of fossil fuels [1]. Besides of this, the related pollution, e.g., caused by road transportation, affects adversely human health [2]. Because of these reasons, stringent anti-pollution laws are imposed by the governments, which forces researchers to develop more efficient engines with lower emission levels. In general, this challenge can be addressed in two ways: by improving the engine characteristics and by using biofuels that produce less net greenhouse gases.

As the engines are becoming ever better and more sophisticated, further improvements are increasingly difficult to achieve. In this context, numerical process simulation in combination with systematic numerical optimization procedures are increasingly becoming an absolute necessity. Of course, simulation results can only be as good as the underlying numerical models. So, model accuracy is a very important attribute, which is unfortunately closely related to computational efficiency. At this point, it must be noted that optimization procedures are typically iterative ones and high computational efficiency is needed in order to ensure acceptable optimization times. In this context, it is generally desirable that: (a) the underlying models are at least reasonably accurate, (b) the computation times are acceptable, and (c) the model is developed as quickly as possible by engaging existing numerical simulation software. This paper addresses the development of such a model for a mechanically controlled in-line fuel injection system (FIS) engaged in a diesel engine and fueled by renewable or partially renewable fuel blends.

When it comes to good engine performance, low fuel consumption, and low emissions, the FIS is one of the most important parts because it defines fuel injection characteristics; and fuel injection characteristics are the key to lower engine emissions and lower fuel consumption, while keeping other engine characteristics at an acceptable level. A mechanically controlled FIS is a rather sophisticated mechanical system consisting of deformable solid parts, either fixed or moving, and of a fluid, present in liquid and gaseous form. The understanding and implementation of the physical phenomena involved in its modeling is a rather sophisticated task. Despite of this, previous researches have managed to develop reasonably accurate and computationally efficient models of injection systems for diesel engines fueled by regular diesel fuel [3–5]. Often, these models were later modified to analyze the system behavior when fueled by biofuels [6,7]. Although a model development from scratch may have the advantage of enabling more insight and influence on the behavior of each computational component, other options may also have their benefits. Most of all, it might be of

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benefit to engage as much of existing commercial software as possible. This may shorten the development time considerably although the model development might still prove quite difficult. These difficulties are typically related to proper selection of available model components, adequate description of boundary conditions, and derivation of correct input data and input functions. Once such a model is defined, it is almost unavoidable to test it thoroughly by using experiments.

In this work, the FIS modeling was done by using the AVL Boost™ Hydsim software [8], which allows simulating the injection system of an internal combustion engine. This software is developed for the dynamic analysis of non-stationary hydraulic and hydro-mechanical systems. It is based on the theory of one-dimensional fluid flow and dynamics of multibody systems. Its main application area is the simulation of fuel injection.

Besides of the injection system type, fuel injection characteristics depend significantly on fuel properties [9,10]. This is especially true for mechanically controlled in-line injection systems since the fuel transport way is rather long and its geometry is quite sophisticated. Additionally, the fuel transport itself is plagued by reflected pressure waves and cavitation. Precise determination of fuel properties like viscosity or sound velocity is therefore of very high importance.

In contrast to usual mineral diesel, the properties of various biodiesels and their blends with bioethanol are not so good investigated and documented, although these fuels can be used in internal combustion engines. For example, biodiesel, which is made from vegetable oils, can substitute diesel fuel totally or partially in a compression ignition engine. Meanwhile, bioethanol, which is made from sugar, starch crops and cellulose, makes the same for spark ignition engines. In this work both, diesel and biodiesel fuels, blended with low concentrations of bioethanol are addressed. These blends can be used to run a diesel engine as well, although they come with their own advantages and disadvantages [11–13].

This paper presents the development of a complete simulation model, consisting of the underlying mathematical model and input data. The mathematical model for an in-line injection system is built by using a commercial software and presented in detail with all involved components. Furthermore, the input required for the computation, consisting of simple data and functions, is also carefully prepared and explained. The developed simulation model is validated by experimental data obtained for neat diesel fuel, neat biodiesel made from rapeseed oil, and blends of 15% (v/v) bioethanol in diesel fuel and in biodiesel. The experimental parameters used to validate the simulation model are: needle lift history (h_n) and injection pressure history (p_{II}).

The structure of the paper is as follows. Section 2 presents the involved fuels and their properties. Section 3 describes briefly the experimental data acquisition system. In Section 4 the computational model with all involved components is described. Section 5 describes the preparation of needed input data and involved functions. In Section 6 the numerical results obtained by the proposed model are compared to the experimental one. Finally, the conclusions are summarized in Section 7.

2. Tested fuels and their properties

In the present study, injection characteristics are obtained and analysed for the following fuels: neat mineral diesel fuel without flow improver additives (D100), neat biodiesel from rapeseed oil (B100), a blend of 15% concentration by volume of bioethanol in biodiesel (E15B85) and a blend of 15% concentration by volume of bioethanol in diesel fuel (E15D85). In this paper, bioethanol is considered as an additive; for this reason, the concentration of bioethanol is set in no more than 15% by volume.

According to the manufacturer specifications, the tested bioethanol is produced from fermentation of sugars and satisfies the ISO 9001 specifications. The tested biodiesel is conforming to European standard EN14214; its purity is assured by its ester content being higher than the minimum value prescribed by the biodiesel standard. The tested diesel fuel is conforming to the standard EN590.

Table 1
Test injection system main specifications.

Fuel injection system characteristics	Direct injection system with wall distribution (M system)
Fuel injection pump type	Bosh PES 6A 95D 410 LS 2542
Main components	Plunger-in-barrel assembly, high-pressure (HP) tube, and injector
Pump plunger (diameter × lift)	9.5 mm × 8 mm
High pressure tube (HP tube) (length x diameter)	1024 mm × 1.8 mm
Injection nozzle (number × nozzle hole diameter)	1 × 0.68 mm
Needle opening pressure	175 bar
Maximal needle lift	0.3 mm
Start of delivery (static injection timing)	30 °CA BTC

In order to be able to simulate the injection characteristics, the physical and chemical properties of each fuel must be defined. Some of those properties of D100, B100, bioethanol-biodiesel blends, and bioethanol-diesel fuel blends, were obtained experimentally and published in previous work of the authors: the properties of pure diesel fuel and bioethanol-diesel fuel blends are described in [14], while pure biodiesel and bioethanol-biodiesel blends are addressed in [15]. The sound velocity of all involved fuels (at various pressures) was also determined in previous work; in most detail the results are given in [16,7] and the procedure is briefly presented in Section 3.

3. Experimental data acquisition

In order to validate the simulation model, first of all the experimentally obtained injection characteristics of neat biodiesel and diesel fuel, as well as E15B85, and E15D85 blends are needed. The corresponding tests were performed on a fuel injection system and test bed as specified in Table 1 and Table 2.

All details of the performed tests and the results are shown in a previous study [16]. It is worth, however, to describe briefly how the experiments were actually performed.

Fig. 1 shows the measured injection characteristics (p_I, p_{II}, and h_n histories) for (a) E15D85 at full load (FL) and pump speed of 1100 rpm, and (b) E15B85 at 75% load (75L) at 800 rpm pump speed. The maximum injection pressure is determined as the peak of the pressure p_{II}. Injection duration (time from needle opening to needle closing) and injection timing (start of fuel injection) are determined from needle lift history h_n. It should be noted that p_{II} does not correspond exactly to the actual injection pressure history. This is because p_{II} is not measured in front of the nozzle hole, but at the end of the HP tube, just before the injector inflow. The pressure wave needs some time to travel the distance between these locations and consequently the start of injection does not coincide with the 175 bar pressure (needle opening pressure) of p_{II}. Furthermore, the time of needle closing (h_n becomes zero) does not coincide with the needle closing pressure of p_{II}. In spite of these differences, p_{II} can be regarded as a relative good approximation of the injection pressure and the influence of fuel variation on the injection pressure is well reflected in the variation of the p_{II} history.

In addition to the injection histories, the sound velocity of all tested fuels was also obtained experimentally at various pressures up to 700 bars. These measurements were based on the principle of pressure wave propagation. Essentially, the testing device consists of a specified length of the high-pressure (HP) tube, two piezoelectric-based pressure transducers located at both ends of the tube, and a small plunger-type pump. The pump was used to induce a pressure wave, which was registered by both transducers and simultaneously acquired by an adequate measuring system [16,7]. The obtained results were fitted by a