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Numerical Analysis of the Fuel–Air Mixture Formation Process in a Dual-Fuel Engine Cylinder

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Mathematical modeling of the working cycle of a piston engine is a highly complex process, as it involves thermodynamic and gas-dynamic phenomena occurring within a variable-volume cylinder, taking into account combustion chemistry and charge exchange processes. The co-combustion of fuels with different reactivity is a process that occurs, among others, in a dual-fuel compression ignition piston engine. Such a combustion system is determined by numerous physical and chemical factors. In this system, there is port fuel injection of a low-reactivity fuel (C_2H_5OH) and direct injection into the combustion chamber of a high-reactivity fuel, such as diesel. In the first phase, the quality of the prepared combustible mixture in both cases is determined by physical phenomena, such as the range and shape of the fuel spray, atomization, evaporation of fuel droplets, and the mixing process with air, supported by flow phenomena. Port fuel injection and direct injection differ physically because they occur under different gas-dynamic and thermal conditions. Once a combustible mixture is obtained, its ignition is controlled by combustion kinetics. The kinetics of chemical phenomena are described by combustion models that account for high-temperature oxidation processes. This paper presents the results of computational fluid dynamic simulation studies of a dual-fuel piston engine with two independent injection systems. The simulation analysis focused on the effect of the type of ethanol injector on the distribution and evaporation of the fuel during the cylinder filling stroke. The analysis included the rate of heat release and emissions of toxic exhaust components. The model's sensitivity to changes in fuel ratios and combustion process control was confirmed by experimental results for selected engine operating points.

topics: dual fuel engine, port fuel injection (PFI), diesel engine, ethanol

1. Introduction

In the era of the energy crisis and intensified efforts to reduce the negative impact of the economy on the natural environment, alternative energy sources to fossil fuels are being sought [1]. Until now, petroleum-derived fuels have been the primary fuel for powering piston engines. The combustion of these fuels has significantly contributed to the deterioration of the Earth's climate; hence, there is a search for fuels that are characterized by low greenhouse gas emissions. Such fuels should contain as few carbon atoms as possible in their molecular structure [2]. Typically, the properties of these fuels do not allow them to power an engine independently. The solution to this problem is a dual-fuel engine, in which fuels with different properties can be co-combusted. In such an engine, diesel fuel is used only as an ignition initiator. This combustion system can achieve high engine efficiency and reduce exhaust emissions [3]. The restrictions on GHG (greenhouse gases) emissions outlined in Fit for 55 compel users to utilize renewable energy sources [4]. For piston engines, alternative fuels can include rapeseed oil esters (RME/FAME), alcohols, or biogases [5]. An interesting fuel for powering a compression ignition engine is ethanol, which requires a dose of a more reactive fuel to initiate combustion. The issue of using ethanol to power a piston engine has been known for many years. Experimental studies have been conducted on the use of ethanol in mixtures with diesel fuel or biodiesels [6–8].

Commonly available engine fuels are mixtures of diesel, biodiesel, or gasoline and alcohols, hence the interest in the impact of alcohol additives burned in the engine on its performance and emissions. It has been shown that the addition of alcohol, which contains oxygen in its molecular structure, significantly reduces soot emissions from compression ignition engines [9]. Burning alcohols in mixtures with diesel or biodiesel is the simplest way to replace traditional fuels with alternative fuels. This technology does not require significant modifications to the engine's fuel system, however, the limitation is the fixed proportion of the two fuels, which cannot be changed during engine operation [10, 11]. Another technology for co-combusting fuels is the dual-fuel engine. The concept of such an engine is based on combining two fueling systems, i.e., port fuel injection (PFI) of the alternative fuel into the engine's intake manifold and direct injection of conventional fuel into the combustion chamber [11, 12].

Simulation studies using advanced tools provide valuable information at a relatively low cost. Many researchers use these tools in their studies of piston engines. Due to its specific cyclical operation, the piston engine is a very challenging subject for modeling. It involves multiphase flows with combustion in a variable geometry of the working space.

Jaworski et al. [13] conducted an experimental validation of the 3-zones extended coherent flame model (ECFM-3Z) combustion model in the FIRE software using a rapid compression machine (RCM). The authors confirmed the usefulness of this model for simulating the combustion process in a compression ignition engine. Tutak et al. [14, 15] used computational fluid dynamic (CFD) modeling to analyze the performance of a compression ignition engine and a dual-fuel compression ignition engine. They found that appropriate model calibration allows for obtaining useful results, not only qualitative but also quantitative. It is possible to achieve reliable results in modeling exhaust emissions.

This study presents the issue of CFD modeling of a dual-fuel engine powered by diesel and ethanol. In previous works addressing similar issues, a homogeneous alcohol–air mixture typically fills the engine cylinder, and injection is modeled only for the igniting dose of diesel. In this work, the model is extended to apply two separate injection systems, i.e., port fuel injection (PFI) of ethanol into the intake manifold and direct injection (DI) into the engine's combustion chamber. This approach brings the model closer to the actual object, which is the piston engine. The study analyzed the ethanol injection process, the impact of fuel atomization degree, spray penetration, spray shape, and distribution in PFI injection. The influence of ethanol share on the cylinder pressure profile was also evaluated.

2. Materials and methods

The subject of the research is a single-cylinder industrial piston engine (6CT107) with compression ignition, designed to power an electricity generator. The 6CT107 engine model has already been experimentally validated for diesel fueling [14], and the PFI ethanol fueling model was validated in the work of Tutak et al. [15]. This engine operates nominally at a constant speed of 1500 rpm.

Due to the specific operation of the piston engine as a cyclical machine, it was necessary to create geometry for the various phases of the engine's operation: intake, compression, expansion, and exhaust.

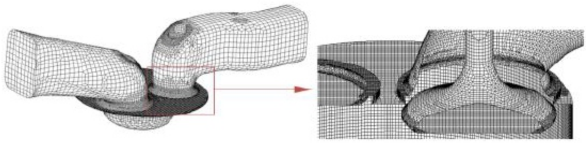

Fig. 1. The view of the computational domain of the modeled engine and the exhaust valve.

TABLE I

The matrix of conducted research.

Case	EEF [%]	Energy dose per cycle [J]	Diesel [J]	Ethanol [J]
Diesel	100	2422	2422	0
DF (40%)	60	2407	1444.2	962.8
DF (80%)	20	2412	482.5	1929.5

Figure 1 shows a view of the computational mesh for the full engine cycle at the top dead center (TDC) position and Table I contains the matrix of research, where DF is dual fuel and EEF ethanol energetic fraction.

The temporal refinement of the mesh occurred during the periods of valve opening and closing. This refinement was dictated by the flow characteristics in the gap forming between the valve seat and the valve face. The computational mesh was optimized in terms of density to avoid its influence on the modeling results [14].

The research was conducted using the AVL FIRE software. This program allows for modeling the entire engine cycle from intake, through compression and combustion, to exhaust stroke. The software code encompasses multiphase flows with mixing and evaporation, combustion, and the mechanisms of forming toxic exhaust components and soot. The primary combustion model employed is ECFM (AVL List GmbH 2013). The ECFM (extended coherent flame model) [16] was developed specifically for modeling the combustion process in compression ignition engines. This model is based on the CFM (coherent flame model) used for simulating combustion in spark ignition engines, and together with sub-models for turbulence processes (e.g., k-zeta-f), sub-models for the formation of toxic exhaust components, knock combustion, and others, it constitutes a valuable tool for modeling and analyzing the thermodynamic cycle of compression ignition piston engines.

To adapt the model for simulating combustion processes in a compression ignition engine, a sub-model describing the mixing process of injected fuel into the combustion chamber was added. The turbulent combustion process in this model is characterized by the timescales of chemical reactions, turbulent processes, and turbulence intensity. The flame front formation is influenced by turbulent interactions within the charge swirls and the interaction between the burned and unburned zones of the charge.

The combustion model for the compression ignition engine has been supplemented with an unburned zone. In the exhaust gases, there are unburned fuel components along with O_2, N_2, CO_2, H_2O, H_2, NO, and CO. The oxidation of fuel occurs in two stages:

- The first stage of oxidation results in the formation of a large amount of CO and CO_2 in the exhaust gases of the mixture zone.
- In the second stage, in the exhaust gases of the mixture zone, previously formed CO is oxidized to CO_2.

The ECFM combustion model is based on the flame front transport equation and a mixing model that describes the combustion of a non-homogeneous mixture and diffusive combustion. The model assumes the combustion area is divided into three zones:

- Fuel-only zone. This zone contains only fuel.
- Air-only zone. This zone consists of air with possible residual exhaust gases from the previous engine cycle.
- Fuel–air mixture zone. In this zone, combustion reactions occur according to the ECFM model concept, involving the fuel–air mixture.

These zones help simulate the complex combustion process in compression ignition engines, taking into account the spatial distribution of fuel and air and their combustion characteristics throughout the engine cycle.

3. Results and discussion

As part of the research, an analysis was conducted on the impact of injector choice, either single- or dual-orifice, on the fueling process through port fuel injection. The study assessed how the injector design influences fuel distribution in the intake manifold. Along the path of the fuel spray, there is an intake valve; the symmetrically directed spray hits the valve stem, causing some fuel not to enter the engine cylinder. In a real engine, this fuel can be drawn in during the intake stroke of the subsequent operating cycle. However, in a simulation where only one cycle is simulated, this poses a challenge. Therefore, a dual-orifice injector was proposed where the fuel spray bypasses the valve stem (Fig. 2).

The injection parameters used in this study are shown in Table II.

Figure 2 illustrates the ethanol injection sprays into the intake manifold performed by single- and dual-orifice injectors. In both cases, the fuel mass was the same. The use of a two-hole injector is justified here.

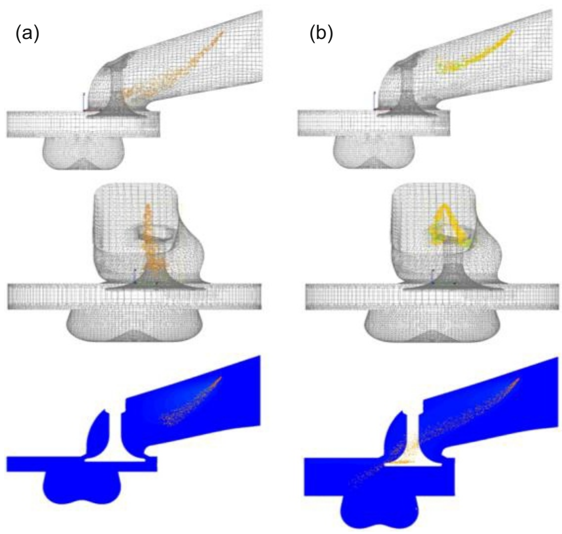

Fig. 2. View of the ethanol indirect PFI flow for single (a) and dual (b) port injectors.

TABLE II

Injection parameters.

Parameter	Property
Fuel	ethanol
SMD	100–300 μm,
SMD	100–300 μm,
Injection time	60 deg CA
C_2H_5OH fraction	40%, 80%

In Fig. 3, the influence of fuel atomization quality in the engine's intake manifold on its evaporation rate is depicted, thereby affecting the potential to create a nearly homogeneous mixture with air during cylinder filling. The injection quality was characterized by the SMD parameter, i.e., the Sauter mean diameter. The nozzle diameters of the injector were assumed to be typical for gasoline injectors.

The stage of cylinder filling shown in Fig. 3a, with an SMD of 200 μm, ensured a significantly high degree of fuel droplet atomization, as evidenced by the mass fraction of evaporated ethanol fuel exceeding 85% of the injected dose.

In Fig. 3b, differences in the evaporation rate between gasoline and ethanol for the same degree of atomization are shown. It can be observed that ethanol is more challenging in terms of evaporation compared to gasoline. Ethanol has a high heat of vaporization, which is over 3 times greater than that of gasoline, leading to a slower evaporation process under comparable conditions. This property of ethanol will affect the temperature of the fresh charge entering the engine cylinder.

In Fig. 4, the influence of fuel type on the temperature of the fresh charge in the engine intake manifold is shown. Similar to the case presented in Fig. 3b, ethanol evaporates more slowly, requiring

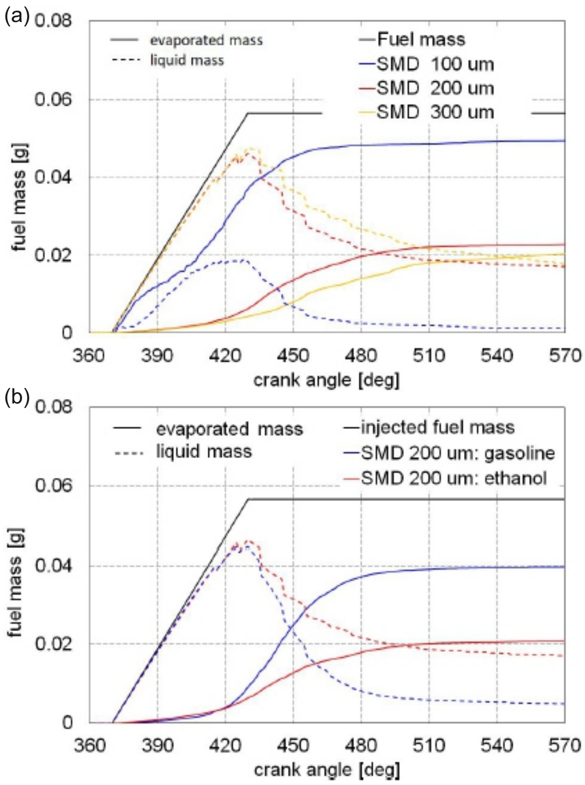

Fig. 3. Influence of SMD on ethanol evaporation rate in the engine intake manifold (a) and influence of fuel type on evaporation rate (b).

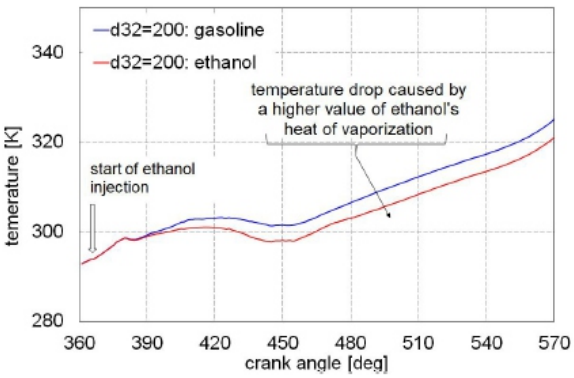

Fig. 4. Influence of fuel type on the temperature of the fresh charge in the intake manifold of a dual-fuel engine for the same mass flow rate.

840 kJ of heat to vaporize 1 kg of fuel, which is reflected in the temperature changes in the intake manifold. For 540 degrees aTDC (after top dead center) angle, the temperature of the gasoline–air mixture was 318 K, while for the ethanol–air mixture, it was 313 K. This cooling effect of ethanol would subsequently affect the temperature inside the engine cylinder, lowering the combustion temperature and influencing the autoignition process by increasing the ignition delay, which is directly related to the charge temperature at the end of the compression stroke. As part of the research,

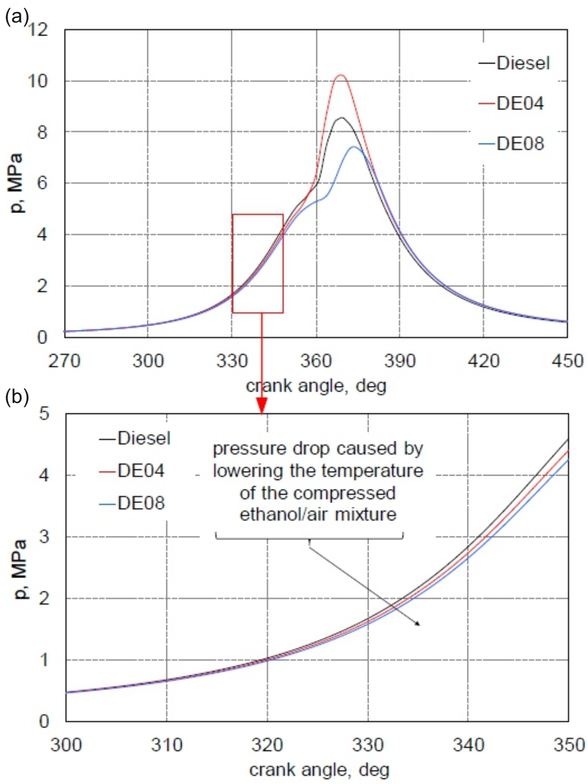

Fig. 5. (a–b) Pressure profiles in the cylinder of a dual-fuel engine fueled with 40% and 80% ethanol content compared to the reference case.

simulations were conducted to analyze the impact of two ethanol energy fractions, from 40% to 80% relative to diesel fuel, on the performance of a dual-fuel engine.

In Fig. 5, the influence of ethanol content on the shape of the combustion pressure profile is illustrated. In all three cases, the energy content remained constant, while the ethanol content varied, altering the fuel composition of the given energy dose.

Ethanol, due to its molecular structure containing oxygen, changes the combustion kinetics. Compared to an engine fueled solely by diesel, the proportion of diffusion combustion decreases in favor of kinetic combustion when ethanol is introduced. For a 40% ethanol content, there was an increase in maximum pressure from 8.54 MPa with diesel fuel to 10.2 MPa. Already in the pressure profiles near TDC (top dead center), the cooling effect of ethanol becomes evident, as higher ethanol content leads to lower temperatures and, consequently, lower pressures.

4. Conclusions

The study presented the results of the analysis of the port fuel injection (PFI) process on the mixture preparation quality and combustion process in a dual-fuel engine. It was found that dividing the fuel stream in the PFI system yielded better results, as confirmed by simulation outcomes. In the case of dual-hole injection, fuel accumulation on the valve is limited. Injector selection is crucial for fuel atomization and evaporation in the engine intake manifold. The fuel-air mixture created during the intake and compression strokes significantly influences the combustion process and heat release in the engine cylinder. An injector providing an SMD of 100 μm was deemed sufficient for fuel atomization. Reducing injector orifice sizes would result in better fuel atomization but would make the injection system highly sensitive to fuel quality.

Acknowledgments

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