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Full Length Article

The influence of in-nozzle cavitation on flow characteristics and spray break-up

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ABSTRACT

In the presented paper, a combined experimental and numerical study was carried out in order to study the influence of in-nozzle flow, cavitation and tested fuel properties on the spray development and primary break up process. The internal flow of neat diesel and neat rapeseed oil biodiesel fuel in single-hole diesel injectors was studied numerically using the AVL FIRE computational program. The spray development and break-up were monitored in a pressure chamber at high pressure using a high-speed camera. An innovative method for obtaining spray length and cone angle was developed using LabVIEW software. The developed method allows us to study the influence of in-nozzle cavitation inception on the symmetry of injected fuel spray. The obtained numerical results show that the geometry of the test injector influences internal fuel flow and cavitation inception highly. Experimental results indicate that tested fuel properties‘ influence spray length and cone angle at high atmospheric pressure is rather small. The cavitation inside the injector nozzle influences the primary spray break-up process further and causes part of the spray, where more cavitation is present in the nozzle hole and its exit, to disintegrate. This confirms that cavitation inside the fuel injector can have a positive effect on the spray break-up and spray disintegration process.

1. Introduction

Global demand for energy is growing. Oil is currently the most consuming energy source, especially in the transport sector, where it represents 95% of all of the energy required [1]. Fossil fuels are also the main energy source in the electricity generation process [2]. The usage of fossil fuels has been proved as one of the biggest sources of produced greenhouse gas emissions [3]. The transport sector contributes around 24% of total produced greenhouse gas emissions. Biofuels, specially second generation biofuels, are considered as medium to long-term alternatives to fossil fuel, which can contribute to a reduction of harmful emission formation [4]. It is believed that they will have the most promising impact on emission formation reduction in future [1]. Currently, first generation biodiesel fuels represent 95% of world biodiesel production and are, considering this, the main source for achieving European demand for their usage and emission reduction [5]. The production of biofuels can also help to reduce region dependence on imported energy sources and their market price variation [6].

Fuel properties have great impact on the emission formation process, which is also influenced by conditions in combustion chamber and fuel injection system properties. They influence fuel flow conditions in the injection nozzle hole and spray formation process, which influences fuel evaporation rate, flame structure, etc. further [7]. Sufficient atomization (dispersion) of fuel droplets can only be achieved by combining high injection pressures with usage of injection nozzles with several small diameter injection holes. This combination promotes cavitation inception and the possibility for cavitation erosion within the nozzle holes. The cavitation phenomena in a fuel injection system can also contribute to a better atomization process of fuel spray [8]. The occurrence of cavitation in an injection nozzle hole is influenced by an engine and its injection system operating conditions [8] and by injection system geometry [9]. Engine operating conditions influence fuel injection pressure which, further, influences cavitation layer evolution speed and intensity [8,9]. Higher injection pressure influences the formation of larger cavitation areas. He et al. in [10] study how different length-diameter ratios of injection nozzle holes influence fuel flow condition in the nozzle hole, cavitating flow pattern and spray characteristics. Spray characteristics can also be manipulated by special fluid control method or special nozzle design, which is capable of manipulating the droplet size by controlling the secondary flow rate in the nozzle hole [11]. Most of the work in this research field combines numerical and experimental studies.

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Experimental studies of fuel flow in nozzle holes are performed using various real size and scaled-up optically transparent nozzles or their models. In real size models, the cavitation appears in the form of cavitation pockets (clouds) [12], while the cavitation in scaled-up models appears in the form of string cavitation [10]. Experimental observation of spray development dynamics can be performed by usage of various techniques. In most of the studies, high-speed cameras are used for monitoring of spray development in specially designed transparent pressure chambers. Conditions inside the fuel injection nozzle can also be observed using the Laser Doppler velocimetry or Particle Image Velocimetry methods [13,14].

In recent decades, numerical models have undergone great development, which has increased their accuracy. Using modern, numerical programs, experimental testing can be replaced with numerical experiments in several research and engineering fields [15,16]. Numerical simulations using Computational Fluid Dynamic (CFD) programs allow us to determine flow conditions like velocity, cavitation inception, etc. without affecting flow. The fuel flow conditions in the nozzle hole and spray development process can be analyzed numerically using RANS or LES approaches [17].

Agarwal et al. [18], tested how usage of Karanja and Jatropha biodiesel fuel in a min-sac nozzle hole with six symmetrical cylinder holes influenced flow conditions, cavitation inception and spray formation. They concluded that the physical properties of fuel have profound influence on nozzle flow condition, cavitation inception, spray atomization and evaporation characteristics. Critical parameters which influence the spray development process are fuel turbulence, velocity and cavitation at the nozzle hole exit. The spreading of a cavitation cloud in an injection nozzle hole is influenced by fuel viscosity. Fuels with higher viscosity inhibit cavitation spread [18]. Xue et al. [19], investigated numerically how an asymmetrical design of injection nozzle influences flow conditions and cavitation inception in each nozzle hole. They concluded that a higher nozzle holes‘ angle, defined as angle between the injection needle and injection holes‘ axes, contribute to a higher degree of cavitation formation and developments in the sac nozzle.

Agarwal et al. [18,20], reported in their study, that higher ambient pressure in the combustion chamber influences the spray development process when using diesel and biodiesel fuels. Higher ambient pressure influences decrease of spray length and increases the spray cone angle. Spray development parameters are also influenced by ambient temperature. Wang et al. in [21] demonstrated that lower ambient temperature has influence on poorer spray dispersion, which leads to formation of larger fuel ligaments. They also concluded that the spray development process is influenced by fuel conditions at the nozzle hole exit, which depends on the fuel flow condition inside the hole.

The increase of fuel mass flow rate (injection rate) results in an increase of fuel velocity from zero to higher values as the mass flow increases. The ambient gas in a combustion chamber is quiescent in the early stage of the injection process. This decelerates fuel droplets and influences the wider spray cone angle at the start of the injection process. With an increase in the fuel injection rate, the ambient gas in the injection (combustion) chamber starts to move. This decreases the drag force acting on the fuel jet and increases fuel spray injection velocity, which reaches its maximal value shortly after the start of injection. After reaching maximal value, the spray injection velocity starts to decrease and reduces the gradient of spray length development [22,23].

In the presented paper, fuel flow conditions of mineral diesel fuel and rapeseed oil biodiesel fuel, as one of the most used biodiesel fuel in the EU, where tested numerically using the AVL FIRE program. The study was performed using the geometry of a single injection hole fuel injector designed for engines with an M-injection system. The main difference between our injector and the injectors used in the presented studies is in the single hole design and its diameter of 0.68 mm. This diameter is 3–4 times greater than in injectors with several injections holes, which influences the different characteristics of fuel flow in the nozzle sac volume and inside the nozzle hole. We expect that the majority of fuel will flow into the injector hole from the bottom and sides of the nozzle sac volume, which will cause the cavitation inception region to be at the bottom side of the nozzle hole. This is different compared to fuel flow in nozzles with several holes, where the majority of the fuel for each hole flows from the upper area between the nozzle needle and injector body. In the second part of the presented study, spray development was monitored experimentally in a transparent high pressure injection chamber. The spray development photos were used for determination of spray cone angle, length and velocity. They also allowed us to monitor the primary spray break-up process dynamic. Numerically obtained results of internal nozzle hole flow were used to study the influence of cavitation inception and nozzle hole influence on spray primary break-up.

The study of fluid flow condition and cavitation inception in a single hole fuel injector, and influence of cavitation on the spray primary break-up process was not found in previously presented studies. It presents new insight on how injector geometry influences fuel flow conditions and the influence of cavitation inception on spray disintegration. In a single nozzle hole fuel injector all fuel flows through only one nozzle hole and forms only one fuel spray. This excludes any interaction between fuel sprays and lowers the amount of fuel vapor in transparent pressure chamber.

2. Tested fuels

During the presented study, neat diesel fuel D2 that contains no additives, and neat rapeseed oil biodiesel fuel B100 produced from rapeseed oil at Biogoriva Rače, Slovenia were used. The tested fuel properties are presented in Table 1 and Fig. 1.

Different test methods, which corresponded to European or other standards, were used to measure fuels' properties presented in Table 1. The fuels' densities were measured at 15 °C according to the European standard EN ISO 12185, kinematic viscosities were measured at 30 °C using a test method confirming the European standard EN ISO 3104, and the fuels' compositions were measured using the test method ASTM D 5291. Other presented fuel properties were supplied by producers of diesel and rapeseed oil biodiesel fuels and were not further tested.

Values of tested fuels' densities and sound velocities presented in Fig. 1 were calculated using equations presented in Ref. [6].

3. Experimental set-up

Experimental measurements of spray development and break-up were performed on an injection system test bed equipped with a high pressure chamber, BOSCH PES 6A 95D 410 LS 2542 high pressure pump and BOSCH DLLA 5S834 injectors with one nozzle hole. The injection system test bed was equipped with a Data Accusation System (DAQ system) which allowed measurements of pressure at the sides of the high pressure tube (p_1 and p_2), needle lift, Camshaft Angle (CA) and the amount of injected fuel per cycle. All measurements were made under full load position, determined by pump rack position. This means that, under a single operating regime, the usage of different fuels can cause that fueling is slightly different. Detailed information about the fuel injection system and fuel injector are presented in Table 2.

Spray development was monitored in a high pressure transparent

Table 1
Tested fuels properties.

Fuel	D2	B100
Density at 15 °C (kg/m^3)	838.8	884.8
Kinematic viscosity at 30 °C [mm^2/s]	3.34	5.51
Lower caloric value [MJ/kg]	42.8	38.2
Cetane number	45	51