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Full Length Article

Experimental study of cavitation formation and primary breakup for a biodiesel surrogate fuel (methyl butanoate) using transparent nozzle

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ABSTRACT

The cavitation formation of fuel flow inside an optically transparent nozzle and the dynamics of spray breakup and atomization at the near-nozzle region were captured by a long working distance microscope and a camera with high spatial and temporal resolutions. The images revealed the formation of a variety of complex cavitation and their temporal evolution. The cavitation initially occurred in the valve seat area and then developed in the whole orifice. The increase of injection pressure led to earlier cavitation inception and enlarged cavitation. A new dimensionless number S was proposed to represent the cavitation intensity in a quantitative manner. The S increased about 10% for every 10 MPa in injection pressure. Image analysis also revealed the relationship between the spray structure at the near nozzle region and the bubble dynamics in the injector orifice. Spray angle, penetration length and spray area were noticeably affected by the injection pressure (30, 40, 50, 60 MPa) as well.

1. Introduction

Combustion and emission performances of internal combustion engines have a strong dependence on fuel breakup and atomization. To produce a homogeneous air-fuel mixture, fuel injectors with small nozzle orifice diameters and high injection pressures (up to 200 MPa) are commonly found in mainstream compression ignition engines. At such high injection pressures, a sudden alteration of flow direction and fuel static pressure will induce cavitation bubbles carried by the fuel flow, which would collapse in the regions of high pressure.

The cavitation in a nozzle is important for the breakup of fuel jets and has a significant impact on the inner flow and macroscopic properties such as the penetration length and the spray cone angle. Abderrezzak et al. [1] found that the breakup of the fuel jet was closely connected to the cavitation intensity by using high-speed visualisation technique with a two-dimensional optically transparent nozzle. Benajes et al. [2] observed that cavitation occurred in both cylindrical and divergent nozzle types and the divergent nozzle was more likely to cavitate than the cylindrical nozzle. He et al. [3] studied the cavitation flow in transparent VCO nozzles with different length–diameter ratios (L/D) using biodiesel and diesel. Badock et al. [4] demonstrated that the interaction of cavitation and turbulence in the flow could improve the fuel jet breakup and atomization for a real diesel injector. Payri et al. [5] evaluated that cavitation increased the hole outlet velocity and the spray cone angle according to numerical simulation. Desantes et al. [6] revealed that the spray-cone angle significantly increased as the cavitation shown at the nozzle outlet. Soteriou et al. [7] examined the inside cavitation flow of nozzle and classified the cavitation into three distinct regions. Park et al. [8] reported that cavitation would promote the spray breakup and atomization for diesel injection systems. Oda et al. [9] analysed the effect of cavitation on spray primary atomization using a large-scale VCO nozzle. Sou et al. [10] revealed that the cavitation originates when the bubble clouds appear at the recirculation zone of a nozzle. Arcoumanis et al. [11] studied the cavitation with a real-size nozzle at the different injection pressure. Linne et al. [12] reported that the enlargement of cavitation at the injector opening improved the spray atomization. Crua et al. [13] studied the fuel exits the diesel injector with mushroom-like structures and proposed that fuel bubbles could remain trapped in the nozzle between two injections. Ghiji et al. [14] found that once the cavitation took place in the injector, the spray cone angle increased considerably and the fuel jet breakup length became short. Desantes et al. [15] found that the mass flow and the momentum flux increased as the needle lifted up to 40%, and further lift had little impact on the outlet flow

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characteristics. The previous simulation conducted by Giannadakis et al. [16] revealed that the needle sealing area may cause acceleration of the fuel, which could promote cavitation formation in a chaotic manner even under stationary conditions.

Previous studies focused on either the cavitation phenomenon inside nozzle or cavitation effects on near-nozzle region spray atomization, yet few studies have demonstrated both cavitation flow and near nozzle spray atomization at the same time. In addition, the literature search identified relatively few studies dealing with the cavitation and spray characteristics of biodiesel fuels compared with petro-diesel fuels. Owing to the noticeable differences in the thermodynamic properties including surface tension, vapour pressure, and viscosity of biodiesel and petrodiesel, the cavitation and turbulence level of these two types of fuels inside the nozzle can be distinct. The nozzle flow characteristics control the boundary conditions at the nozzle exit which has a great effect on the atomization, spray formation, and subsequently on diesel engine performances.

This study mainly focused on the internal flow of nozzle and near-nozzle spray morphology of a biodiesel surrogate fuel (methyl butanoate) by using the real-size fully transparent nozzle. High-speed visualisation with short exposure times and high spatial and temporal resolution enabled the record of cavitation inception, development and some mechanisms for primary breakup at the nozzle outlet. The injection pressure impact on spray characteristics of the near-nozzle region was also analysed.

2. Experiment setup

An optical transparent nozzle was used to visualise the in-nozzle flow characteristics under different injection pressures. The nozzle tip was replaced by perspex simulating a sac and injector orifice (Fig. 1). The main reasons for choosing the perspex for the optical nozzle are threefold: firstly, the Perspex has a high light transmittance of 93% which ensure clear photograph; secondly, the refractive index of perspex (1.481) was close to the refractive index of the test fuel (refer to Table 1), which make the photograph more realistic; thirdly, the perspex has such a high mechanical strength that the nozzle with the perspex orifice can work at the injection pressure of up to 80 MPa. The nozzle orifice diameter *d* is 0.4 mm, and the orifice length *L* is 2.4 mm and hence the *L*/*d* is constant at 6, which is the same with a real light duty diesel injector with *d* being 0.165 mm and *L* being 1 mm. Apart from geometric similarity, the flow dynamics of the optical nozzle is also similar to that of real injector nozzle as Reynolds numbers are comparable. The injection pressure was kept constant at 60 MPa while the chamber pressure was at an atmospheric pressure of approximately 0.1 MPa. The nozzle spray angle was 60° and it is defined as the angle degree between the axis of the nozzle hole and the injector. The temperature of the test fuel was room temperature, which was approximately 20 °C.

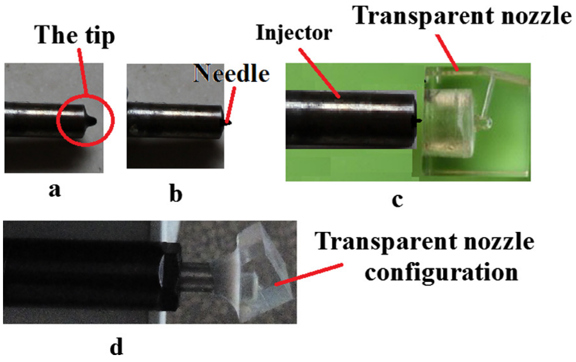

Fig. 1. Different components of the transparent nozzle tip assembly.

Table 1
Physical properties of biodiesel surrogate fuel (methyl butanoate) [18].

Fuel property	Diesel	Biodiesel surrogate fuel (methyl butanoate)
Carbon content (wt%)	87	76.74
Density @ 15 °C (kg/m^3)	822.7	877.2
Oxygen content (wt%)	0	11.25
Surface tension @ 25 °C (N/m)	0.002	0.00296
Hydrogen content (wt%)	13	12.01
Dynamic viscosity @ 40 °C (cP)	1.69	5.626
Vapour pressure @ 25 °C (Pa)	892	230
Refractive index	1.479	1.408

Table 1 presents the physical properties of the biodiesel surrogate fuel (methyl butanoate) used in this study. Fuel properties and vapour phase properties were calculated based on previous research (Battistoni et al. [17]). The soy-biodiesel primarily includes five methyl esters, and methyl butanoate as a surrogate for soy-biodiesel is close to those of soy-biodiesel components in terms of physical properties and chemical structure.

Fig. 2 illustrates the experimental visualisation setup which included three parts. The first part is a common-rail direct injection system, which consists of a fuel reservoir to store fuel, both a low-pressure and high-pressure diesel pumps driven by electric motors, a high-pressure common rail, and a single-hole diesel injector. The second part is the optical imaging system, which consists of a Nano Pulse Light (NPL) and Lamphouse (light source), a canon 700D camera with Electro-Optical System (EOS) and a microscope (QUESTAR QM-100) lens with large focal length. The light source is controlled by an NPL with a pulse duration of 180 ns. The NPL is triggered by injection signal from Electronic Control Unit (ECU). The original camera lens is replaced by a long distance microscope. The working distance of the microscope lens varies from 15 to 35 cm and the magnification factor is up to 381. The resolution of the microscope is 1.1 μm and the maximum pixel of the camera is 5184 × 3456 pixel^2. During the experiment, a camera equipped with microscope lens was arranged in 180° position with respect to the light source and the backlighting technique was employed to attain better quality images of spray formation. The signal delay control system constitutes the third part of the overall setup, which is made up by an in-house single chip microcomputer and two solid-state relays (SSR). The main function of the signal delay is to synchronise the mechanism of injector and camera which control the precise time of fuel advent at the nozzle exit. During injection tests, Lamphouse and camera systems are synchronised using the Programmable Time Unit (PTU) by the signal delay control system. The precise control over camera and injection energising made it possible to correlate the images for the nozzle flow and near-nozzle spray, which were captured separately. Preliminary results showed that the reproducibility and repeatability of the images were high enough to verify the correlation between internal flow images and near-nozzle spray ones.

The photographs were captured using backlighting in a dark room. Firstly, the nozzle with transparent tip was put between the Lamphouse and the microscope, and the focal length of the microscope was adjusted according to the test condition. Secondly, the shutter mode of the Camera was set to manual mode and set to 1/32 s (higher than the exposure time). When the fuel injector received fuel injection signal, the needle valve opened. The injection signal was sent simultaneously to the Nano Pulse Light by the flash control system to trigger the flashing Lamphouse light. A flow image inside nozzle or near nozzle fluid jets was then captured. Finally, the shutter of the Camera was closed and then the delay signal was adjusted through the flash control unit to take