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Experimental study on the effect of nozzle geometry on string cavitation in real-size optical diesel nozzles and spray characteristics

Zhou Chen[a], Zhixia He[b,*], Weiwei Shang[a], Lian Duan[b], Han Zhou[a], Genmiao Guo[a], Wei Guan[a]

[a] School of Energy and Power Engineering, Jiangsu University, Zhenjiang 212013, China
[b] Institute for Energy Research, Jiangsu University, Zhenjiang 212013, China

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ABSTRACT

Cavitation is quite important for the diesel spray atomization and the combustion of air–fuel mixture. In this study, a high-speed CMOS camera equipped with a long-distance microscope was utilized to capture the transient cavitating flow and spray characteristics in real-size optical nozzles with needle motion. The transient cavitation images, including geometry-induced cavitation and vortex-induced string cavitation, were captured clearly in cylindrical-orifice nozzles and tapered-orifice nozzles, respectively. Besides, the agglomerated phenomenon of geometry-induced cavitation was visually captured and analyzed for the first time. It was found that the string cavitation in nozzle excites the instability of spray cone angle and it is synchronized with increase of spray cone angle. In addition, it is the string cavitation but not geometry-induced cavitation has a much larger contribution to the increase of spray cone angle. It is interesting that the influence of agglomerated geometry-induced cavitation on spray cone angle was prominent. Furthermore, both the nozzle orifice L/D ratio and sac types have significant influences on string cavitation and spray characteristics. The smaller L/D ratio and VCO-type nozzles are prone to incur the stronger string cavitation, and then spray cone angle is obviously larger.

1. Introduction

Pollutant emission reduction is currently considered to be one of the most important challenges of our society. The spray atomization characteristics of the diesel injector plays an essential role for the good spray combustion and pollutant emissions performance [1]. New combustion modes have been suggested for energy-saving and emission-reduction, such as premixed charge compression ignition (PCCI) [2,3], partially premixed combustion (PPC) [4] and homogeneous charge compression ignition (HCCI) [5] and low temperature combustion (LTC) [6]. Certainly, it is indispensable for realizing these new combustion modes to prepare the suitable combustible mixture. Actually, diesel injector nozzles have a significant influence on the quality of spray and preparation of air–fuel mixture [7]. It is well known that fuel atomization processes is directly influenced by the nozzle geometry and cavitating two-phase flow [8,9]. Especially, the near-field spray atomization is extremely influenced by cavitation and turbulence in nozzles [10]. Therefore, it is indispensable to conduct the investigation of cavitating flow in diesel nozzles. Especially, the string cavitation, has a great contribution to spray cone angle, deserves more attention in the future.

Focus on the geometry-induced cavitation in diesel nozzles, many studies have been reported [11–13]. Gavaises et al. [14,15] utilized the optical nozzles to explore the effects of the needle motion on the transient cavitating flow. Experiments indicated the links between cavitation and turbulence in the sac, moreover, the anticipated enhancement of turbulence through the onset of cavitation was identified only at the entrance of the nozzle orifice [14]. In addition, the differences of flow characteristics between the real-size nozzles and large-scale transparent nozzles were stressed [15]. Based on the large-scale nozzle, Xin Zhang et al. [16] reported that the higher fuel temperature means a lower critical injection pressure for cavitation inception, in addition, the higher fuel temperature could induce the larger cavitation region under the same injection condition. However, the scale effects could not be negligible in large-scale transparent nozzles. Therefore, the experiments and simulations based on the real-size diesel nozzle were performed. W. Yu et al. [17,18] proved that the injection pressure and ambient pressure could influence both the internal nozzle flow and the spray propagation. Mitroglou et al. [19,20] studied the cavitating flow in diesel optical nozzles as well and found that the initial bubbles exist inside the nozzle before start of injection. Besides, the life time and the most probable appearance location of string cavitation have been estimated. Besides, the effects of several factors on geometry-induced cavitation were investigated by CFD [21], including injection pressure,

* Corresponding author.
E-mail address: zxhe@ujs.edu.cn (Z. He).

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Nomenclature

K-factor	conicity factor of nozzle hole
D	nozzle hole diameter
L	nozzle hole length
I_{string}	intensity of string cavitation
$\bar{\rho}$	mean density of fuel
$\bar{V}$	mean velocity of fuel
A	cross section area of nozzle orifice
D_{sac}	sac diameter of nozzle
S_{string}	area of string cavitation in 2D image
$S_{orifice}$	area of nozzle orifice in 2D image
$P_{injection}$	injection pressure

Subscripts

o	outlet of nozzle orifice
in	inlet of nozzle hole orifice

Abbreviation

VCO	valve closed orifice nozzle
L/D	length-diameter ratio of nozzle orifice

roundness of nozzle inlet, discharge coefficient of orifice, the L/D ratio, and the roughness of orifice inner wall. Although the investigations based on the real diesel nozzle have made large progress, there is little mention of vortex-induced string cavitation and its effect on spray characteristics. Focus on string cavitation, He et al. [22] subsequently found that the string cavitation has a strong relationship with the location of needle, the injection pressure, and the sac size. Applying a VCO nozzle (Valve closed orifice nozzle) [23], the effect of multi-injection strategy on cavitation development in diesel injector nozzle orifices was studied. After that, Watanabe et al. [24] explored the effect of needle tip shape on string cavitation and the spray characteristics. Furthermore, the spray characteristics based on metal nozzles were discussed in order to get a closer operation condition to diesel engine. Westlye and Payri [10,25] found that a tapered orifice had a higher spray tip penetration compared to a cylindrical nozzle orifice. However, it showed that the spray cone angle was inversely proportional to the spray tip penetration. Sedarsky et al. [26] researched the spray velocity profile from a high-pressure single-orifice diesel injector, and the results revealed a strong asymmetry in the spray profile of the test injector, there are distinct fast and slow regions on opposite sides of the spray. Crua and Ding [27,28] used single-orifice metal nozzles to investigate diesel spray formation, spray transient fluctuation and mushroom spray tip at initial stage of injection. However, because of absence of visible data about nozzle transient flow, above spray phenomena cannot be well explained and all spray characteristics have not been well connected with the nozzle internal flow. In general, previous studies have made numerous interesting achievements in multi-phase nozzle flow. But several aspects, such as the agglomerated phenomenon of geometry-induced cavitation, the occurrence mechanism of string cavitation and their effects on subsequently initial spray characteristic, are still not clear and deserve further investigations.

In this paper, the real-size optical nozzle tips, equipped to the high pressure common rail fuel injector, were made for visual investigations of string cavitation characteristics with considering the effects of geometric parameters of nozzle, including L/D ratio, conicity factor (K-factor), and nozzle sac geometry. Furthermore, the effects of those parameters and the agglomerated phenomenon of geometry-induced cavitation on near-field spray characteristics were analyzed in details. Finally, the ensemble average images of string cavitation were analyzed as an important statistical description.

2. Experimental setup and methodology

2.1. Facilities and fuel

Based on the 250 MPa common rail injection system (BITEC-GY250-2), the nozzle flow and spray visualization experiment system was established (Fig. 1). According to the shadow photography, the tested nozzles were placed between the LED light and the high-speed COMS camera (FASTCAM SA-Z) equipped with a long-distance microscope (QM-1, QUESTAR). The maximum camera shooting rate is 210,000 frames per second with 384 × 160 pixels. For the sake of capturing higher resolution images and larger shooting rate, the shooting rate is 100,000 frames per second and the images have a resolution of 640 × 280 pixels in this experiment.

The 0# fossil diesel fuel (Automobile diesel fuelV, China) was employed in this experiment. The properties of diesel fuel and test conditions are given in Table 1. The ambient pressure of all injections is atmospheric pressure. Under such an injection condition, the turbulence and cavitation in nozzle were considered to be the main reasons of near-field spray atomization [10].

2.2. Optical nozzle tips

The metal nozzle tip of solenoid injector was cut and replaced by the real-size optical acrylic nozzle tip shown in Fig. 2, so that the transient cavitating flow inside the nozzle could be captured visually. For guaranteeing the good sealing performance between needle valve and needle seat of nozzle during the injection process, the cutting position of origin nozzle tip must be below the sealing line (Fig. 2). All of the optical nozzles were made of raw acrylic cubes, because of its good light transmittance (> 92%), good compression resistance and a similar refractive index (1.48–1.52) to diesel fuel (1.49–1.51). The optical nozzles were manufactured by precision drilling machine. Subsequently, the optical nozzle tips and injector could be assembled by a fixture. Specifications of the test nozzles were shown in Table 2. It must be noted that when investigate effects of nozzle orifice L/D ratio on string cavitation, the nozzle 1 and nozzle 3 were reworked with shortening the orifice length after finishing experiment of nozzle 2 and nozzle 4, respectively. So that guarantee the same geometry of other nozzle

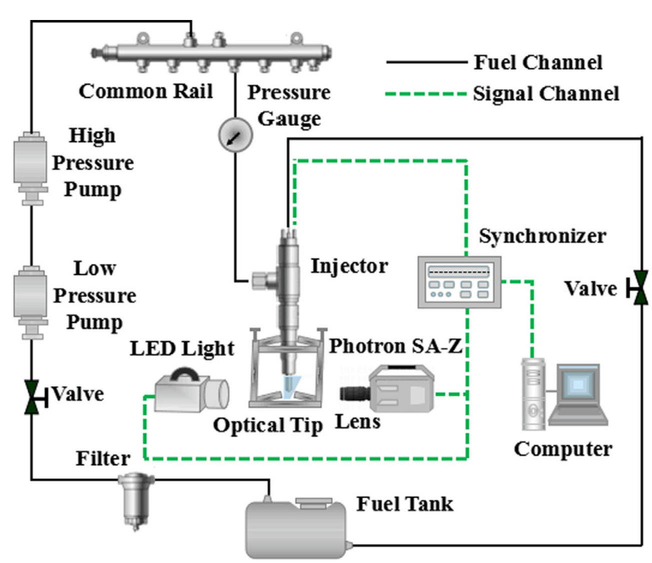

Fig. 1. Schematic of visualization system for internal flow.