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Experimental study of cavitating flow inside vertical multi-hole nozzles with different length–diameter ratios using diesel and biodiesel

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ABSTRACT

The complicated cavitating flow inside diesel nozzles has long been concentrated on, and cavitating flow characteristics of biodiesel in nozzles with different structures is instructive to the highly efficient use of biodiesel in diesel engines. In this paper, on the visualization experimental system with a transparent scaled-up injector nozzle tip and the high-speed digital camera were used to investigate the cavitating flow in transparent VCO nozzles with different length–diameter ratios (L/D) using diesel and biodiesel, and the energy loss in the occurrence of the hydraulic flip was also analyzed. Moreover, the nozzle cavitating flow characteristics were studied not only during the period of increasing of injection pressure but also decreasing of injection pressure. The hydraulic flip phenomenon occurred in nozzles with L/D of 4 and 6, but not appeared in nozzles with L/D of 8. The cavitation is easier to occur for the diesel than for the biodiesel. The nozzle discharge coefficient for the diesel is higher than that for the biodiesel when the flow is single-phase turbulent flow, while it got much smaller for the diesel than that for the biodiesel when the cavitating flow and the hydraulic flip phenomenon occur. The critical number of cavitation inception is smaller than that of cavitation disappearance.

1. Introduction

Concerns about energy security and environment have attracted worldwide attention in biologically derived alternative fuels. Biodiesel presents a lucrative alternative, particularly for compression ignition engines, because it is a renewable energy source that can be used in these engines without significant changes in their design. Modern diesel engines can operate with 5–10% addition of biodiesel by volume without any loss in performance [1,2]. As is we all known, the injector nozzle is one of the most important parts of the diesel engine and the internal cavitating flow has great effects on the fuel spray behavior and, combustion performance, and consequently has an important effect on pollutant emissions [3,4]. Therefore, it is essential to study the cavitating flow characteristics of biodiesel and compare it with that of diesel fuel.

Ranz [5] firstly connected the nozzle and the downstream spray behavior in 1958, and Bergwerk [6] concluded that cavitation phenomenon can be regarded as the key to connect nozzle flow to spray behavior in 1959. Since diesel nozzles are extremely small, typically about a millimeter long and a fraction of a millimeter in diameter, the flow through the holes moves at very high speeds, on the order of several hundred meters per second. Moreover, the flow is transient with injection duration on the order of a few milliseconds and the internal flow is two-phase and highly turbulent, with a Reynolds number on the order of 50,000. Due to these challenges, it is very difficult to directly observe the cavitating flow inside the real size nozzle holes by visualization experiments [7]. Thus, visual experimental studies of the cavitating flow in scaled-up nozzles and numerical simulations have been widely carried out.

A scaled-up injector tip was used by Arcoumanis et al. [8] to offer detailed experimental results concerning the connection between the upstream condition and nozzle cavitating flow. But a scaled-up injector tip has flow characteristics globally similar to a real injector tip, however, not the same as Arcoumanis et al. [9] conducted in another definitive comparison between large-scale and real-scale nozzles. The results show that the nature of cavitation changes in scaled-up nozzle tips from large voids to bubbly mixtures and bubbles has their own length scales apart from the size of nozzle. Moreover, many visual experimental researches on cavitating flow inside nozzle orifices using water or diesel fuel and its influence on the subsequent spray have been carried out by R. Payri, Chaves, Gavaises, Soteriou and many other researchers in the past half the decade [10–18]. There were still many experiments conducted by C. Soteriou, and R. Payri to

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identify the complexity of cavitating flow [19–21]. The results show that the flow pattern transforms gradually from turbulent flow to cavitating flow together with the increase of injection pressure, until hydraulic flip phenomenon come into being. Many experiments have also been conducted to explore the factors affecting the critical cavitating flow, such as the factors of injection pressure, the back pressure and the physical properties. The results show that cavitation is harder to be incepted with higher injection pressure, higher back pressure and larger kinematic viscosity. Furthermore, the kinematic viscosity also has great effect on the atomization properties. The spray cone angle rises according to decreasing viscosity [22].

However, the researches on the cavitating flow of biodiesel and their effects on spray characteristics are quite limited. And those researches above were conducted to investigate the cavitating flow patterns with the increase of the injection pressure, while the nozzle internal flow patterns with decreasing of fuel injection pressure have not been exactly known. Suh and R. Payri investigated the cavitating flow characteristics for diesel and biodiesel fuels by using two-dimensional planar nozzles, and they both found that biodiesel has almost the same cavitation performance with the diesel [23–25]. Also most of the researches above were conducted in planar nozzles, while the cavitating flow inside multi-hole diesel nozzles and planar nozzles can be different for its asymmetric nozzle effects [4], so actually it is essential to identify the cavitating flow pattern in the multi-hole diesel nozzles.

A computational study of the biodiesel cavitating flow inside the diesel engine nozzle was performed by Som et al. in Argonne national laboratory, on which they found that biodiesel exhibits poor atomization characteristics compared to diesel [26,27]. Suh et al. also conducted the research on the cavitating flow characteristics using planar nozzles with different length–diameter ratios; they found that cavitation is more difficult to occur when the nozzle orifice length getting much longer [28,29].

As the length–diameter ratio is a key parameter of nozzle structures which have direct influences in the internal flow [30], it is essential to investigate its effect on the flow patterns inside diesel nozzles by using diesel and biodiesel. Diesel is much easier to cavitate than biodiesel [26–28], at the same time. The level of the cavitation development in these two kinds of fuels will be different under the same injection pressure, and thus the blocking effect of the cavitation will be different. As discharge coefficient of internal flow depends greatly on the flow characteristics [31,32], and it is a useful evaluating indicator of nozzles as well, it is necessary to identify the effect of cavitating flow inside the nozzle orifice of diesel and biodiesel on mass flow and discharge coefficient.

In the matter of flow pattern inside the nozzle orifice, clearly observing cavitation inception and development, super cavitation and even hydraulic flip phenomenon of diesel and biodiesel in nozzles, and then the acquiring the critical conditions for occurrence of different flow patterns are also very important for the better understanding of the complicated nozzle cavitating flow. Since hydraulic flip phenomenon is observed, Bergwerk and Soteriou [33,34] have conducted many experiments. The results show that atomization quality and flow characteristics can be influenced greatly by the hydraulic flip phenomenon. Moreover, hydraulic flip phenomenon becomes more and more difficult to occur together with the nozzle orifice getting much smaller. But there were still very few researches focusing on the variation of flow pattern and flow losses when the hydraulic flip come into being.

In this paper, experimental study of the cavitating flow and its effect on the subsequent spray in 5-times scaled-up multi-hole VCO (valve covered orifice) nozzles with different length–diameter ratios by using diesel and biodiesel fuels were performed. What is more, cavitating flow characteristics with the decrease of injection pressure and energy loss during the period of the hydraulic flips occurring were firstly taken into consideration.

2. Theoretical background

As cavitation inside the nozzle orifice can improve the level of the turbulent flow and influence the atomization characteristics, a non-dimensional parameter, cavitation number K, is normally introduced to describe the cavitating flow characteristics [35,36] inside the nozzle orifice:

$$K = \frac{p_{\mathrm{i}} - p_{\mathrm{v}}}{p_{\mathrm{i}} - p_{\mathrm{b}}} \tag{1}$$

P_{i}, P_{v}, and P_{b} respectively refer to the injection pressure, fuel vapor pressure, and the pressure of injection ambient.

The nozzle discharge coefficient C_{d} is one of the key factors for consideration in the design of an engine injector. It may change dramatically determined by the cavitation inside the nozzle orifice and can be defined as follows:

$$C_{\mathrm{d}} = \frac{Q_m}{A\sqrt{2\rho\Delta P}} \tag{2}$$

where Q_m, A, ρ, and ΔP represent the fuel mass flow rate, orifice geometrical cross-section area, fuel density, and pressure difference between the upstream and downstream pressure, respectively. The definition of the mass flow rate is the practical discharged liquid fuels mass during a given period of time. As reported by Nurick [37], the discharge coefficient C_{d} decreases as cavitation number K decreases in cavitating flow regime.

In order to much clearly indicate the development degree of cavitation in the injector nozzle orifice, another non-dimensional parameter S is defined here:

$$S = \frac{P_0}{P_{\mathrm{A}}} \tag{3}$$

where P_0 is the total number of cavitation area pixels and P_{A} is the total number of orifice cross-section area pixels. Thus the non-dimensional parameter S increases with the development of cavitation. Gray scale images of the cavitating flow in the visualization experiment can be transferred into RGB format for analyzing the cavitating development by adopting the picture processing and analyzing method. Firstly, a new layer equals to the size of the nozzle orifice was created according to the parameter of original gray images, and then recorded the pixels of new created orifice layer. Due to back lighting, cavitation presents gray and the fuel white in gray image and then the cavitation area and non-cavitation area can be distinguished. Images obtained from visualization are processed by customized software programmed in Matlab. With the modified algorithm, images can be mapped to gray-scale histogram space from pixel space. Pixels of the corresponding cavitation area can be recorded by the setting threshold value [38].

Fig. 1 illustrates the definition of spray cone angle θ. The distance between the outlet of nozzle orifice and the measuring point of spray cone angle is 2 mm. Existing in the upper part of the orifice in VCO nozzles, cavitation has great effect on the top surface of subsequent jet spray. Therefore, the half angle above is defined as the spray cone angle θ.

3. Experimental setup

The visual experimental system with a multi-hole scaled-up transparent nozzle tip for visualizing the nozzle flow was setup as shown in Fig. 2. Apart from the injector with a transparent