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Internal flow and spray characteristics for elliptical orifice with large aspect ratio under typical diesel engine operation conditions

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ABSTRACT

The nozzle orifice geometry has great impact on the internal flow and spray characteristics, and thus affects the fuel-air mixture quality for diesel engines. This paper presents experimental and numerical research on the internal flow and spray behaviors with biodiesel for elliptical orifice with large aspect ratio and circular orifice of diesel nozzles, under high injection pressure and backpressure conditions. Large Eddy Simulation (LES) and Schnerr and Sauer cavitation model were adopted to study the internal flow, and the numerical models were validated firstly in terms of the mass flow rate, center line pressure and cavitation morphology. The elliptical spray images at the minor and major planes were acquired simultaneously with two CCD cameras through shadowgraph method. The results showed that the discharge coefficient of elliptical orifice was higher than that of circular orifice, which indicated that the elliptical orifice has better flow performance as compared to circular orifice. In addition, the vapor volume fraction at the circular orifice exit was larger than that of elliptical orifice, while the vorticity magnitudes were consistent lower than that of elliptical nozzle at the same injection pressure. And also, the elliptical orifice has more turbulence vortex structures near the nozzle exit than that of circular orifice, and the number of turbulence vortex structures increased as the injection pressure increases. Moreover, the cavitation distribution in the elliptical orifice in the direction of major axis shows longer length than that in the minor axis direction. The cavitation morphology at the elliptical orifice exit showed a unique horseshoe shape, while the cavitation morphology for circular orifice was still distributed symmetrically. Another important point is that the cavitation domain was similar with distribution of the turbulence vortex structures. Furthermore, the variation trend of elliptic spray cone angle proved that the elliptical spray underwent axis-switching even under high injection pressure and backpressure. Finally, the circular orifice spray held longer spray tip penetration in comparison to elliptical spray, while the elliptical exhibited much larger spray cone angle in all view planes. Because the elliptical spray underwent greater air dynamic drag induced by larger spray surface area. And the higher vorticity magnitude and more turbulence vortex structures at the elliptical orifice exit could also promote the initial spray breakup and thus inhibit the development of spray tip penetration. The axis-switching of elliptical spray can also increase the air entrainment ratio, which was conductive to increase the spray cone angle.

1. Introduction

The emissions performances of modern diesel engines are mainly influenced by air-fuel mixture quality, which largely governed by diesel nozzle internal flow and spray characteristics [1]. Previous research results showed that nozzle orifice geometry has influences on the internal flow and spray behaviors [2,3]. Since the elliptical sprays held better fuel-air mixing quality, which could lead to decrease emissions and improve fuel consumption of diesel engine at certain loads [4–6]. Therefore, the research on the impact of the elliptical orifice nozzle on the internal flow and spray characteristics has been brought into focus of experts and scholars.

Hong et al. [7] carried out an experiment to study the effects of cavitation flow with circular and elliptical orifice on spray characteristics based on enlarged transparent nozzles with diameter of 3 mm, at the injection pressure of 0.5 MPa. The results showed that the cavitation domain in the major view plane became longer than that in the minor view plane. Hong et al. [8] also studied the impacts of circular and elliptical orifices on internal cavitation flow by using numerical method. Their results showed that the cavitation sharp inside the

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Symbols and abbreviations

A	Nozzle cross section area
ASOI	After Start Of Injection
CCD	Charge Coupled Device
CFD	Computational Fluid Dynamics
Cs	Smagorinsky constant
d	The distance to the closest wall
k	Von Kármán constant
L	Spray tip penetration
LED	Light Emitting Diode
LES	Large Eddy Simulation
LMD	Laser Micro-Drilling
SIMPLE	Semi-Implicit Method for Pressure Linked Equation
θ	Spray cone angle
Δ	local grid scale

elliptical orifice was different from circular one. And also, for elliptical orifice, the radial velocity distribution was different between the major and minor view planes at the orifice inlet corner, while for circular orifice, they were similar to each other. Kim et al. [9] studied the cavitation length in different elliptical orifice and the corresponding discharge coefficient under the injection pressure of 0.4 bar with a large transparent nozzle. The results indicated that the cavitation in the circular nozzle extended longer than that of elliptical nozzle under the same pressure conditions. Ku et al. [10] performed an experiment to study the spray behaviors and internal flows emerging from elliptic and circular orifices under high injection pressure. They observed that the internal cavitation structures have great influence on the disintegration of spray characteristics for all orifices. Molina et al. [11] conducted a numerical study on the internal cavitation flow in different elliptical orifices and positions, the results indicated that the elliptical orifice with horizontally oriented major axis was easier to experience cavitation and also had higher discharge coefficient.

Wang et al. [12] experimentally performed the spray process issuing from non-circular orifices under low injection velocity. They found that the axis-switching wave length for triangular orifice increased as the injection velocity increased, while the oscillation frequency decreased as the injection velocity increased. And the using of non-circular orifice could decrease the spray breakup length. Sharma and Fang [13] studied experimentally the diesel spray behaviors discharging from triangular, square and rectangular orifices at the backpressure of 0.1 MPa. They observed that these non-circular orifices had larger spray width and cone angle than circular orifice, and the non-circular orifice were more likely to have better air entrainment ratio and atomization quality. Sharma et al. [14] also presented an experimental investigations on the water liquid jet behaviors emerging from different non-circular orifices under low pressure conditions. The experimental results showed that the jet breakup length of non-circular orifice was shorter than that of circular one, and also revealed that the jet issuing from non-circular orifice could induce greater instabilities of jet, and thus resulting in better spray quality. Rajesh et al. [15] conducted an experimental investigation on the liquid jet oscillation characteristics of non-circular orifices. They found that the jet oscillation wave length increased as the injection velocity increased. Kasyap et al. [16] studied the spray characteristics issuing from elliptical orifices with various aspect ratios under low injection conditions. They found that the elliptical spray experienced axis-switching process, which was helpful to accelerate the liquid breakup rate. Kasyap et al. [17] also studied the elliptical spray breakup behaviors at still ambient air condition. They found that the using of elliptical nozzle was conductive to accelerate the liquid breakup rate.

The literature review indicates that while the effects of elliptical orifice on the cavitation and spray behaviors have been examined to some extent. In particular, the review showed that the cavitation morphology distribution in elliptical orifice was different from that in the circular one. In addition, they revealed that the spray breakup length of elliptical orifice was shorter than circular orifice, and also the using of elliptical orifice could enhance the spray instabilities and increase the air–fuel mixing quality. However, the equivalent diameter of elliptical orifices used in these works were most quite far from the standard diesel nozzle diameters (from 0.1 mm to 0.2 mm), and also the injection and back conditions were much less than that of real diesel engine operation conditions. On the one hand, considering the minification of orifice diameter and the increasing of injection and back pressures, the turbulence intensity inside the elliptical orifice became more complex than those under traditional conditions. On the other hand, the significant differences in the orifice geometry between elliptical orifice with large aspect ratio and circular orifice, the corresponding internal cavitation and turbulent vortex structures distribution inside the elliptical orifice and their effects on the nozzle exit flow patterns and spray formation can be exactly differ from circular orifice.

Therefore, the present research work was to study the effects of elliptical orifice with large aspect ratio and circular orifice on macro spray characteristics combining with internal cavitation flow patterns at various high injection pressures and backpressures. The macro spray behaviors conducted through a spray visualization system (Shadowgraph method), and to investigate the internal cavitation flow patterns by adopting a validated numerical method. Firstly, the numerical model was validated in terms of mass flow rate, orifice central line pressure and cavitation morphology. Secondly, the effects of elliptical orifice with large aspect ratio and circular orifice on internal cavitation flow patterns were numerical studied and compared, including the discharge coefficient, vapor volume fraction and vorticity magnitude, as well as the turbulence vortex structures and three-dimensional cavitation distribution inside the orifice. Thirdly, the macro spray characteristics of elliptical orifice with large aspect ratio and circular orifice were deeply analyzed combining with the internal cavitation flow patterns under the high injection pressures (50 MPa, 70 MPa, 90 MPa) and the high backpressures (1MPa, 2 MPa, 3 MPa).

2. Computation model

In the numerical research work, the mixture model [18] was used to simulate the multiphase flow inside the nozzle, SIMPLE algorithm was employed to calculate pressure field coupled with velocity. To capture more information of the flow field, LES was used, and Smagorinsky-Lilly Model [19] was used as subgrid-scale model. Schnerr and Sauer model [20] was selected as cavitation model. A no-slip condition between the liquid and vapor phases was also assumed [21], a more detailed description was presented in our previous research work [3], and the whole calculation process was conducted with ANSYS Fluent 14.0.

2.1. Large Eddy Simulation model

The Smagorinsky-Lilly model [22–24] was adopted as the subgrid-scale model, where the SGS stress in Eq. (1) is defined as:

$$\tau_{ij}-\frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t\overline{S_{ij}} \tag{1}$$

$$\overline{S_{ij}} = \frac{1}{2}\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right) \tag{2}$$

Where μ_t is the sub grid-scale turbulent viscosity, defined as:

$$\mu_t = \rho L_s^2|\overline{S}| \tag{3}$$