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Research Article

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Characteristics of cavitation of different fuels in injector nozzles for diesel engines

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ABSTRACT

Biofuel is a kind of clean energy which has good application prospects in diesel engines. The cavitation behaviors inside injector nozzle of diesel engine of biofuel and diesel fuel are numerically simulated and compared using homogeneous mixture flow model and full cavitation model. The dimensionless numbers such as cavitation number and discharge coefficient are introduced to analyze the internal flow characteristics of various fuels. The results show that the change pattern of mass flow rate and dimensionless numbers of injection nozzle are variable before and after transition cavitation. The dynamic viscosity was the primary property for the development of cavitation compared with surface tension and saturated vapor pressure.

Key words: cavitation, fuel injection, injector nozzle, numerical analysis, computational fluid dynamics

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INTRODUCTION

Cavitation is the formation of vapor bubbles of a flowing liquid in a region where the pressure of the liquid falls below its saturated vapor pressure[1]. The formation of cavitation in diesel injector nozzles is primary ascribed of breakdown of nonequilibrium of liquid dynamics and the separation of boundary layers due to the geometric characteristics of nozzles[2]. Cavitation is liable to occur when the fuel passes through the nozzle. A number of studies have shown that the cavitation flow in injector nozzles has a strong impact on the spray and atomization characteristics and nozzle wear behavior, which is decisive for engine performance and pollutant formation[3,4]. There are many factors such as injection condition and injector geometric structure parameters which influence the generation and development of cavitation in nozzles[5,6]. Arcoumanis showed that cavitation numbers was a key factor of the formation of different cavitation flow characteristics[7]. The existing research object is mainly for diesel fuel and few for other fuels. Martynov made a cavitation comparison of experiment on similar nozzle structure for water and diesel fuel, which found to be very similar cavitation form despite of different cavitation numbers[8].

In recent years, many researchers aim at making modifications for biofuels to be new alternative fuels for diesel engine for environment protection and alleviating energy crisis. The biofuel has different density, viscosity and surface tension compare to diesel fuel, which should have different cavitation flow characteristics in the injector nozzle. Due to the small size of diesel injector nozzles, Computational fluid dynamics (CFD) is a universally method to simulate the cavitation in real size nozzles[9,10].

In this paper, a homogenous mixture flow method is chosen and the cavitation is forecasted by liquid density or vapor phase volume fraction. A common conservation equation for liquid and vapor is used with the advantage of accurate prediction and high computational efficiency. At the same time, full cavitation model is used to simulate cavitation flow in injector nozzles of two fuels. The dimensionless numbers such as cavitation number (*K*) and discharge coefficient (C_d) are introduced to analyze the internal flow characteristics. The difference of cavitation flow between biofuel and diesel fuel under similar conditions was also compared as well. Besides, the influence of fuel properties on cavitation is also analyzed.

EXPERIMENTAL SECTION

NUMERICAL MODELS

Governing Equation: Isothermal nozzle flow is assumed and there is no any velocity slips between the liquid and vapor phase and no consideration of energy exchange between the two phases.

Continuity equation can be expressed by Eq. (1).

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u_i)}{\partial x_i}=0 \tag{1}$$

Where ρ is the density of mixture flow, u_i represent average velocity, t is the time.

Momentum equation is described by Eq. (2).

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial\tau_{ij}}{\partial x_j} \tag{2}$$

Where u_i and u_j represent average velocity, *p* denotes static pressure of mixture flow, τ_{ij} denotes the stress tensor, which can be expressed by Eq. (3).

$$\tau_{ij}=(\mu+\mu_t)\left\{\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right\} \tag{3}$$

Where μ_t is the turbulence viscosity.

Both RNG $k-\varepsilon$ turbulence model and standard wall function were utilized during simulation.

Cavitation Model: Full cavitation model proposed by Singhal was adopted with consideration of turbulence effect and non-condensable gas[9].

The vapor mass fraction transport equation is as follows.

$$\frac{\partial(\rho f_v)}{\partial t}+\rho\frac{\partial(u_j f_v)}{\partial x_j}=\frac{\partial}{\partial x_j}(\Gamma\frac{\partial f_v}{\partial x_j})+R_e+R_c \tag{4}$$

Where u_j is the velocity vector, f_v is the vapor mass fraction, Γ is the phase diffusion coefficient, R_e and R_c denote vapor generation and condensation rates.

R_e and R_c can be obtained as follows:

$$R_e=C_e\frac{\sqrt{k}}{\sigma}\rho_l\rho_v(1-f_v-f_g)\sqrt{\frac{2(P_v-P)}{3\rho_l}} \tag{5}$$

$$R_c=C_c\frac{\sqrt{k}}{\sigma}\rho_l\rho_v f_v\sqrt{\frac{2(P-P_v)}{3\rho_l}} \tag{6}$$

where p_v is the critical cavitation pressure or phase change threshold pressure of liquid and vapor, f_g is the mass fraction of non-condensation gases, k represents the local turbulence kinetic energy, σ denotes surface tension of liquid, and C_e and C_c are the phase change velocity coefficient of vapor generation and condensation.

Experimental investigation revealed that turbulent flow has considerable influence on cavitating flow. Singhal established a numerical model to represent the phase change threshold pressure as:

$$p_v=(p_s+p_t^{'}) \tag{7}$$

Where p_s is the saturated vapor pressure for given temperature of liquid, $p_t^{'}$ is the turbulent pressure fluctuations denoted as $p_t^{'} = 0.39\rho k$.

DEFINITION OF PARAMETERS

Dimensionless parameters:

The cavitation numbers can be defined by Eq. (8).

$$K = \frac{p_1 - p_v}{p_1 - p_2} \tag{8}$$

Where p_1 is the injection pressure or inlet pressure of nozzles, p_2 is the outlet pressure, p_v is the saturated vapor pressure.

The discharge coefficient can be defined by Eq. (9), which indicates the flow efficiency in nozzles.

$$C_d = \frac{m_a}{m_t} \tag{9}$$

Where m_a and m_t is the actual and theoretical mass flow rate respectively.

RESULTS AND ANALYSIS

Nozzle model and mesh size: The geometry model of nozzle is a simplified axial sac volume nozzle with a single circular orifice. The nozzle have a rounded inlet with a diameter of 0.45mm, the radius of sac volume is 1mm and the rounded radius is 30μm, the nozzle length over nozzle diameter ratio (L/D) is 4. **Figure 1** shows the boundary condition and computational grid of the axial nozzle model. Localized finest meshes are used in the vicinity of nozzle inlet. The governing equations of numerical models are solved using 2D CFD software Fluent 6.3.

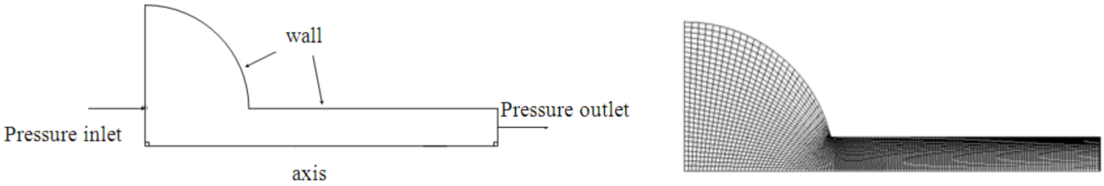

Fig. 1 Boundary conditions and computational grid of injector nozzle

Table 1 shows the fuel properties of biofuel and diesel fuel at 300K.

Table 1. Physical properties of biofuel and diesel fuel

Item	Biofuel	Diesel fuel
Density（kg/m^3）	860	840
Dynamic viscosity（Pa·s）	0.0044	0.003
Surface tension（N/m）	0.045	0.028
Saturated vapor pressure(Pa)	150	300

Hydraulic Characteristics: Figure 2 shows the mass flow rate against injection pressure of the two fuels from single phase flow to super-cavitation flow. It shows how the mass flow rate of two fuels increases when the injection pressure increases, except for different variation property before and after cavitation. The mass flow rate of biofuel is slightly less than that of diesel fuel before cavitation occurs. However, the mass flow rate of biofuel is higher than that of diesel fuel after cavitation.

Variation Characteristics of Dimensionless Parameters: Figures 3 shows the variations of discharge coefficients with the injection pressure of two fuels in nozzles. It can be seen from Figure 3 that discharge coefficient increases with injection before cavitation occurs, and the discharge coefficient of biofuel is lower than that of diesel fuel. When the cavitation occurs, the discharge coefficients of two fuels increase continuously and reach their maximum values of 0.815 and 0.827 respectively at the point of transition cavitation. After the transition cavitation, they both decrease with injection increase and have the similar tendency.

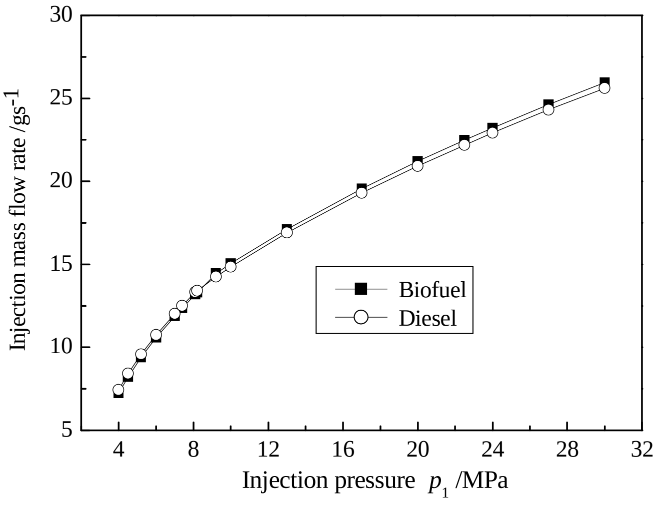

Fig. 2 Relationship between injection mass flow rate and injection pressure

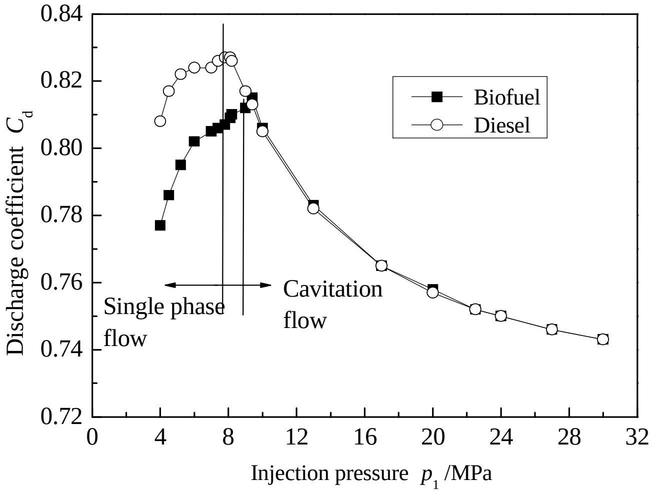

Fig. 3 Relationship between discharge coefficient and injection pressure

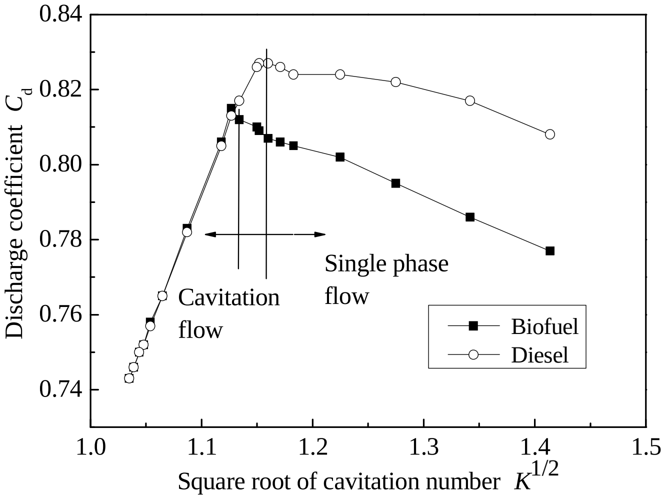

Fig.4 Relationship between discharge coefficient and square root of cavitation number

Figure 4 represents a linear relation of discharge coefficient with the square root of cavitation number after transition cavitation. The discharge coefficient decreases when the cavitation number decrease continuously and has an asymptotic minimum value equal to contracting coefficient of nozzles.

Influence of Fuel Property on Cavitation Based on Cavitation Model: Altering the property of fuel respectively, the according cavitation flow characteristics and mass flow rate are showed in Figure 5. Although there is a evident difference of mass flow rate for different density, their caviation characteristics are quite the same. The results show that the variations of density, surface tension and saturated vapor pressure have no significant effect on cavitation flow inside nozzles which is still in a state of sub-cavitation. Decreasing the dynamic viscosity from 300 Pa to 150 Pa will greatly change the cavitation characteristics. So it can be concluded that the dynamic viscosity of fuel has significant influence on cavitation characteristics.

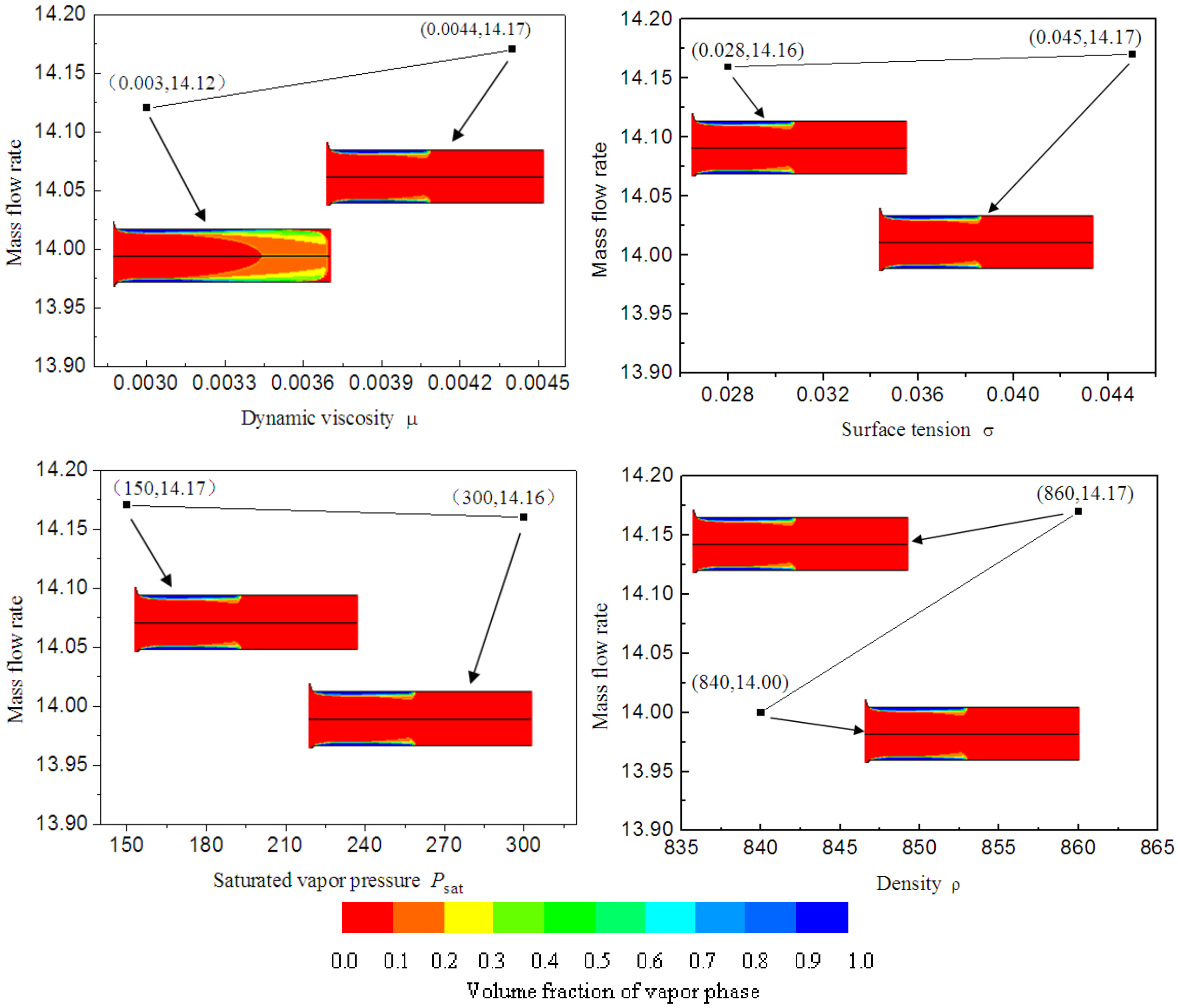

Fig.5 Relationship between discharge coefficient and square root of cavitation number

CONCLUSION

The variation patterns of cavitation flow characteristics are different after transition cavitation compared with those of early cavitation stages; Biofuel required higher injection pressure than diesel fuel on different cavitation stages including inception cavitation, transition cavitation and super-cavitation. The mass flow rate of biofuel is lower than that of diesel fuel before cavitation occurs. The discharge coefficient of biofuel are lower than those of diesel fuel after cavitation. Thus, the overall flow efficiency of biofuel in nozzles is less than that of diesel fuel. The dynamic viscosity of fuel is the most significant factor influencing cavitation characteristics under similar injection conditions.

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