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Numerical simulation of cavitation bubble collapse within a droplet

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ABSTRACT

Cavitation bubble always exists in the droplets breaking up from the fuel jet when supercavitation phenomenon occurs. The collapse of cavitation bubble plays an important role in secondary breakup of droplets. The collapse process of cavitation bubble within the diesel droplet considering the phase change or not have been simulated numerically based on the volume of fluid (VOF) method using OpenFOAM. The results show that collapse process without phase change consists of multiple collapse and rebound stages, similar to the vibration process of a damping spring oscillator. Considering the phase change, there is only collapse stage and no rebound stage in collapse process, and the variation of bubble volume with time is no longer cyclic. The collapse speed become faster with the increasing of environmental pressure, while the collapse speed become faster with the decreasing of saturation vapor pressure. The effect of surrounding pressure on collapse process is greater than the effect of saturation vapor pressure.

1. Introduction

The phenomenon of cavitation in injection nozzles of the diesel engine has a strong influence on the formation and atomization of fuel spraying, which results in less pollutant emissions and higher performance because of improving the combustion efficiency [1–3]. The phenomenon of cavitation in the injection nozzle can be divided into supercavitation and onset of cavitation [4]. Supercavitation refers to a kind of flowing state that cavitation bubbles together with the diesel jet leave the injection nozzle. At present, as the injection pressure of fuel increases, it has become very prominent for supercavitation in the process of fuel injection.

An interesting phenomenon appeared in some experimental studies that stronger cavitation gives rise to more atomization of liquid jet [5–12]. For example, Safari [9], Desantes and Payri, et al [10,12] studied the influence of cavitation phenomenon on spray behavior respectively, and their investigation results display that stronger cavitation leads to more atomization of liquid jet. Although the diesel jet turns into bubble-liquid two-phase flow because of supercavitation, which has an important influence on the atomization of fuel spray, it's still unclear for the atomization process of fuel jet under supercavitation.

Cavitation bubble always exists in the droplets breaking up from the fuel jet when supercavitation phenomenon occurs. The collapse of cavitation bubble plays an important role in secondary breakup of droplets. However, it is uncertain for the mechanism of this effect.

As we know that the first analysis of bubble collapse process was made by Rayleigh [13], who analyzed a problem that the collapse of a spherical cavity in a liquid. neglecting of liquid viscosity, compressibility and surface tension, he gave the relation that bubble boundary obeyed [14]

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{p(R) - p(\infty)}{\rho}, \tag{1}$$

where $p(R)$ is the pressure at bubble boundary, $p(\infty)$ is the pressure of liquid far away from bubble boundary, and ρ is the density of liquid. Plesset [14,15] extended Eq. (1) by considering the influences of liquid viscosity and surface tension

$$p(R) = p_{in} - \frac{2\sigma}{R} - \frac{4\mu}{R}\dot{R}, \tag{2}$$

where p_{in} is the pressure within the bubble, σ is the surface tension constant, and μ is the viscosity coefficient, respectively. In addition, Robinson, et al [16] investigated the growing process of a spherical bubble in a liquid, and divided the bubble growth process into surface tension controlled stage, transition stage and heat transfer controlled stage. Zhang [17,18] also studied the growth and collapse process of a bubble in a free flow field. After all, these investigation results are discussed by researching on the growth and collapse process of cavitation bubble in an unbounded liquid.

Nowadays, researches on the collapse process of cavitation bubble within a single droplet are very limited. To our knowledge, these researches are generally conducted by analytical method [19,20]. Nevertheless, it can't be used for analytical method to reveal more details about the collapse process of cavitation bubble

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List of symbols

k	Curvature at the interface (1/m)
V_r	Bubble rebound volume (μm^3)
$\dot{m}$	Mass exchange rate between liquid phase and vapor phase (kg/s)
α	Fluid volume fraction
$\mathbf{n}$	Gradient vector of volume fraction
μ	Dynamic viscosity (Pa·s)
p	Fluid pressure (N/m^2)
ρ	Fluid density (kg/m^3)
p_c	Bubble collapse pressure (N/m^2)
i	Subscript $i=1$, 2 and 3, represent diesel droplet, air and cavitation bubble, respectively
p_r	Bubble rebound pressure (N/m^2)
σ	Surface tension coefficien (N/m)
p_v	Saturated vapor pressure (N/m^2)
∇	Hamilton operator
S	Mass source item
∇^2	Laplace operator
$\mathbf{V}$	Fluid velocity vector (m/s)
D/Dt	Material derivative
V_c	Bubble collapse volume (μm^3)

within a single droplet because of the assumed conditions, which makes it impossible for us to deeply understand the whole bubble collapse process. In addition, the phase change of bubble collapse process is still not clear. Therefore, it is obvious that numerical simulation is very promising to improve the understanding of the collapse process and the phase change of cavitation bubble within a single droplet.

In this paper, spherically symmetric bubble collapse within the diesel droplet has been simulated numerically based on the volume of fluid (VOF) method using the open source CFD toolbox OpenFOAM. The study is organized as follows. The VOF method, problem formulation and governing equations are given in Section 2. The solvability conditions and validation of the numerical method are presented in Section 3. The results and discussions are presented in Section 4 and Section 5, including bubble collapse process with and without phase change. Conclusions are given in Section 6.

2. VOF method and governing equations

2.1. VOF method

By using fluid volume fraction function α, VOF method can track the location of phase interface. The fluid volume fraction function α is listed as follows:

$$\alpha(x,t)=\begin{cases}1, & \text{liquid}-\text{phase}\\ 0<\alpha<1, & \text{gas}-\text{liquid two}-\text{phase}\\ 0. & \text{gas}-\text{phase}\end{cases} \tag{3}$$

The fluid density, ρ, and dynamic viscosity, μ, depending on the fluid volume fraction function, α, can be expressed as:

$$\rho=\alpha_1\rho_1+\alpha_2\rho_2 \tag{4}$$

$$\mu=\alpha_1\mu_1+\alpha_2\mu_2 \tag{5}$$

$$\alpha_1+\alpha_2=1 \tag{6}$$

Then, the gas-liquid interface can be transported by using the following "VOF equation":

$$\frac{\partial\alpha}{\partial t}+(\mathbf{V}\cdot\nabla)\alpha=0 \tag{7}$$

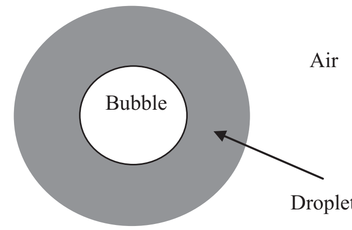

Fig. 1. Schematic of cavitation bubble within the diesel droplet.

Table 1
Summary of physical parameters.

Parameters	Value
Diesel density / (kg·m^{-3})	848
Diesel viscosity / (Pa·s)	2.936×10^{-3}
Surface tension coefficient / (N·m^{-1})	2.689×10^{-2}
Air density / (kg·m^{-3})	1.193
Air viscosity / (Pa·s)	1.845×10^{-5}
Cavitation gas density / (kg·m^{-3})	1.087×10^{-2}
Cavitation gas viscosity / (Pa·s)	1.81×10^{-6}
Bubble radius / (m)	5×10^{-6}
Diesel droplet radius / (m)	1×10^{-5}

where $\mathbf{V}$ is the fluid velocity.

Interface reconstruction and interface advancing with time are two important problems in using VOF method. Here, PLIC method is employed to reconstruct the gas-liquid interface, and the operator non-splitting algorithm is employed to advance the interface with time.

2.2. Governing equations

This paper shows a research on the collapse process of cavitation bubble within the diesel droplet. As Fig. 1 shows, the research object is composed of three parts, including cavitation bubble, diesel droplet and the surrounding air. Here, we assume that there is only one bubble within the diesel droplet, and the effect of gravity can be ignored.

According to the above assumptions, the governing equations for fluid flows can be expressed as:

$$\frac{D\rho}{Dt}+\rho\nabla\cdot\mathbf{V}=0 \tag{8}$$

$$\rho\frac{D\mathbf{V}}{Dt}=-\nabla p+\mu\nabla^2\mathbf{V}+\frac{1}{3}\mu\nabla(\nabla\cdot\mathbf{V})+\sigma k\mathbf{n} \tag{9}$$

$$\frac{\partial\alpha_i}{\partial t}+(\mathbf{V}\cdot\nabla)\alpha_i=0 \tag{10}$$

$$\partial p_3/\partial\rho_3=c \tag{11}$$

Where the subscript $i=1$, 2 and 3, represent diesel droplet, air and cavitation bubble, respectively, p is the fluid pressure, σ is the surface tension coefficient, $k=\nabla\cdot(\mathbf{n}/|\mathbf{n}|)$, is the curvature at the interface, $\mathbf{n}=\nabla\alpha_i$, is the gradient vector of volume fraction, and c is the constant.

3. Solvability conditions and verification

3.1. Solvability conditions

Physical parameters of the fluids are set according to the Ref. [21–25], which are shown in Table 1.

As the research object is composed of three parts, cavitation bubble, diesel droplet and the surrounding air are included into