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Numerical investigation on relationship between injection pressure fluctuations and unsteady cavitation processes inside high-pressure diesel nozzle holes

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ABSTRACT

The relationship between injection pressure fluctuations and unsteady cavitation processes inside the high-pressure diesel nozzle holes have been numerically analyzed by using a two-fluid approach. In order to improve prediction of nozzle hole cavitation content under high-pressure injection conditions, a new adjustment model of bubble number density has also been developed through the analysis of cavitation bubble dynamics and internal flow characteristics of nozzle hole. Model validation results verify that this model is applicable for a wide range of diesel injection pressures. Based on simulation results, it has been found that cavitation bubbles in recirculation zone and its wake flow show totally different responses to the variations of upstream pressure, and the evolution of cavitation content shows a close association with the time derivatives of upstream pressure.

1. Introduction

In modern direct injection diesel engines, the geometrical sharpness of the fuel injection nozzle entry, along with increasing injection pressure differences or appropriate flow conditions, often creates an important phenomenon known as cavitation inside the fuel injection nozzle holes. Over the last few years, it has been pointed out through a number of experimental studies that this cavitation phenomenon modifies internal flow structure of the nozzle hole and greatly affects atomization process of the discharged fuel jet [1–5]. A better knowledge of the nozzle hole cavitating flow is therefore essential to further clarify the atomization mechanism of high-pressure diesel jets. For this reason, considerable effort has been, and still is being, devoted to the study on physics of the nozzle hole cavitating flow under the realistic diesel injection conditions [6–8].

Up to now, there has also been clear experimental evidence that under the realistic diesel injection conditions the pressure close to the entrance of injection nozzle hole usually fluctuates at very high frequencies [9–11]. Furthermore, the high-frequency fluctuation of pressure upstream the injection nozzle hole has been identified as an important factor that influences the diesel spray shape stability. Since both the high-frequency pressure fluctuation and the cavitating flow are closely related to the development of a diesel jet, it is of interest to firstly clarify the relationship between these two phenomena happening inside the diesel injector. Ramamurthi and Patnaik [12] studied the influence of periodic pressure disturbances on the transition from attached flow to cavitating flow in sharp-edged injection orifices. Yuan and Schnerr [13] carried out a numerical simulation of the effect of injection pressure fluctuations on the cavitation process in injections nozzles. Both of the two studies have revealed that the upstream pressure disturbances have a significant impact on the cavitation processes within the injection nozzle holes. However, the inlet pressure pulses adopted in these two studies are characterized by small average values (less than 9 MPa) or relatively low frequencies, which usually do not represent the main features of pressure field immediately upstream of the high-pressure diesel injection nozzle hole. Wang and Su [14] firstly studied the effects of injection pressure fluctuations on cavitation inside a nozzle hole at diesel engine conditions. Though interesting unsteady behavior of partial cavitation and supercavitation, induced by the injection pressure pulses, has been presented and widely discussed in this study, the detailed correlations between injection pressure pulses and unsteady cavitation processes in the diesel nozzle hole still remain unclear.

Because of the complexity of cavitating flow and extreme small scale of the diesel injection nozzle hole (∼100 μm), it is very difficult to obtain detailed information from this flow, even using recent experimental techniques. Under this condition, time accurate numerical solutions of flow through the diesel injection nozzle hole are of great interest. By using a single-fluid approach or a two-fluid approach, several cavitation models based on the asymptotic Rayleigh–Plesset bubble dynamics equation have been developed in the past few years and successfully applied for simulation of three-dimensional transient cavitating flows [15–18]. The major

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Nomenclature

A	amplitude of inlet pressure wave
B	proportional constant in the expression of nuclei number density distribution function
C_C	Nurick contraction coefficient
C_d	nozzle hole discharge coefficient
C_D	drag coefficient
C_{TD}	turbulent dispersion coefficient
C_R	condensation reduction factor
D	nozzle hole diameter
f	frequency of inlet pressure
$\mathbf{F}^D$	drag force
$\mathbf{F}^{TD}$	turbulent dispersion force
$\mathbf{g}$	gravitational acceleration
K	cavitation number
k	turbulent kinetic energy
L	nozzle hole length
l_m	maximum of needle lift
$\mathbf{M}$	momentum interfacial exchange
N	bubble number density
n_0	initial bubble number density
n_0^*	reference initial bubble number density
p	pressure
p_i	nozzle inlet pressure
p_i^*	reference inlet pressure
p_o	nozzle outlet pressure (back pressure)
p_o^*	reference outlet pressure
p_{avg}	average inlet pressure
p_{min}	minimum pressure in nozzle hole
p_v	vapor pressure
q_m	actual mass flow rate of nozzle hole
R	bubble radius
R_{max}	maximum bubble radius
R_{min}	minimum bubble radius
S	surface tension coefficient
s	cross-section area of nozzle hole
t	time
$\mathbf{T}^t$	Reynolds stresses
$\mathbf{V}$	velocity vector

Greek symbols

α	volume fraction
ρ	density
τ	shear stress
χ	nuclei number density distribution function
Γ	mass exchange

Subscripts

1	vapor
2	continuous liquid
k, l	phase index

Abbreviation

EMI	einspritzmengenindikator

advantage of this type of models is allowing the effects of cavitation bubble nuclei to be incorporated, which is essential for the correct description of the onset of cavitation. But in these models the initial number density of cavitation bubbles, n_0, is usually treated as an adjustable model parameter. Experience in simulation of different cavitation flows reveals that the parameter n_0 can vary in a wide range. For example, Yuan et al. [15] have used $n_0 = 1.5 \times 10^{14}\ \mathrm{m}^{-3}$ for water to fit the experimental data of Roosen et al. [19] on cavitation flow in a plain and small-size nozzle; Basuki et al. [20] have applied $n_0 = 1 \times 10^8\ \mathrm{m}^{-3}$ for water in simulations of the flow over a hydrofoil; Grogger and Alajbegovic [21] have set n_0 equal to $1 \times 10^9\ \mathrm{m}^{-3}$ for water in calculation of the cavitating flow in Venturi geometries; Alajbegovic et al. [16] have applied $n_0 = 1 \times 10^{12}\ \mathrm{m}^{-3}$ for diesel in simulations of the flow inside a fuel injector. Actually, the large dispersion in the values of n_0 decreases the reliability of cavitation models and accordingly limits the range of their possible application. On the other hand, the forementioned simulation experience obviously implies that the value of n_0 depends not only on the liquid type, but also on the flow condition. Therefore, an adjustment model of bubble number density that can rationally match changes in hydrodynamic and liquid quality effects corresponding to different cavitation flows is very useful to expand the application range of related cavitation models.

The present numerical study aims to further investigate unsteady cavitation processes inside diesel nozzle holes, especially under high-pressure injection conditions. Firstly, a new adjustment model of bubble number density has been developed in order to correctly predict the cavitation content of diesel nozzle holes. Secondly, the two-fluid model, together with the above new adjustment model, has been applied for simulations. The relationship between the injection pressure fluctuations and unsteady cavitation processes is particularly discussed in the present study.

2. Models for cavitating flow

2.1. The two-fluid model

The mathematical model in the current study is based on the two-fluid formulation for multiphase flows, which includes two sets of conservation equations, one for the liquid phase and one for the vapor phase. The outline of this model is as follows.

Mass conservation equation:

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{V}_k) = \sum_{l=1, l\neq k}^{2} \mathbf{\Gamma}_{kl} \tag{1}$$

Momentum conservation equation:

$$\frac{\partial(\alpha_k \rho_k \mathbf{V}_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \mathbf{V}_k \mathbf{V}_k) = -\alpha_k \nabla p + \nabla \cdot \alpha_k (\tau_k + \mathbf{T}_k^t) + \alpha_k \rho_k \mathbf{g} + \sum_{l=1, l\neq k}^{2} \mathbf{M}_{kl} + \mathbf{V}_k \sum_{l=1, l\neq k}^{2} \mathbf{\Gamma}_{kl} \tag{2}$$

In Eq. (1), $\mathbf{\Gamma}_{kl}$ is the interphase mass transfer term and is modeled by the following formula:

$$\mathbf{\Gamma}_{12} = \rho_1 \frac{N}{C_R} 4\pi R^2 \frac{\partial R}{\partial t} = -\mathbf{\Gamma}_{21} \tag{3}$$

where N is bubble number density and is calculated with the formula suggested in Ref. [22]. It reads as follows:

$$N = \begin{cases} n_0 & \alpha_1 \leqslant 0.5 \\ 2(n_0 - 1) \cdot (1 - \alpha_1) & \alpha_1 > 0.5 \end{cases} \tag{4}$$

This is a rather heuristic formula used to model coalescence effects at higher volume fraction levels. n_0 is the initial bubble number density, which depends both on liquid quality and flow conditions.