M6-004 Numerical Investigation of Cavitation in a Nozel

By One-Way Bubble Tracking Method

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ABSTRACT

Numerical calculation of bubble dynamics of two-phase flow in an injection nozzle is presented. The model consists of large eddy simulation (LES) and a bubble tracking method. Liquid turbulent flow field is solved by using LES with the Smagorinsky model. Then the one-way bubble tracking method is applied to predict cavitation bubble motion. An extended Rayleigh-Plesset equation describes the behavior of a spherical cavitation bubble. The results of simulation show the good agreement with the experimental observations.

Keywords: Bubble dynamic, two-phase flow, injection nozzle, bubble tracking method.

1. Introduction

To reach future emission standards for diesel engines, the sizes of fuel droplets injected in combustion chambers must be controlled appropriately. It is important to understand and predict cavitations phenomena in the hole of diesel injector nozzles, which plays a dominant role on liquid jet atomization.

Internal cavitating flow in the diesel injection nozzle is a very complex process including turbulent flow, cavitation inception and bubble collapse. Numerical simulation of two-phase fluid dynamics can provide detailed information on the phenomena in the nozzle, which is not easily obtained by physical experiment. Therefore, the numerical simulation of the two-phase flow, including cavitation inception and bubble tracking is an attractive research topic.

Some of the computational works on cavitation have been carried out by Tomiyama, 1998, Hosokawa and Tomiyama (2003), Sou and Tomiyama (2003), Liu et al. (2004), and Sou et al (2006). Their results motivated the development of a turbulent cavitating flow model based on numerical simulation method.

The purpose of this study is to develop a mathematical model based on one-way bubble tracking technique and cavitation model in order to predict the incipient cavitation inside a nozzle. Large Eddy Simulation (LES) was introduced to predict turbulent flow in a nozzle, and modified Rayleigh-Plesset equation was used to calculate cavitation bubble dynamics. Calculated results were compared with measured results obtained in the laboratory.

2. Numerical Modeling

For the turbulent incompressible fluid flow, the governing equation consists of the filtered continuity and momentum equations. Subgrid viscosity for LES is calculated based on the Smagorinsky model. An extend Rayleigh-Plesset is applied to calculate bubble dynamics.

2.1 Large Eddy Simulation

Filtered mass conservation (continuity) equation and momentum equation used in large eddy simulation for incompressible flow are:

$$\nabla \cdot \overline{\mathbf{u}}_L = 0 \qquad (1)$$

$$\frac{\partial \overline{\mathbf{u}}_L}{\partial t} + \overline{\mathbf{u}}_L \cdot \nabla \overline{\mathbf{u}}_L = -\frac{1}{\rho_L}\nabla P + \mathbf{M}_{VIS} + \mathbf{M}_{SGS} + \mathbf{g} \qquad (2)$$

Where $\mathbf{u}_L$ is liquid velocity, P the pressure, $\mathbf{M}_{VIS}$ the viscous diffusion, $\mathbf{M}_{SGS}$ the subgrid viscosity and $\mathbf{g}$ the gravity force. These forces are given by

$$\mathbf{M}_{VIS} = \nabla \cdot \nu_L \left[\nabla \overline{\mathbf{u}}_L + \left(\nabla \overline{\mathbf{u}}_L\right)^T\right] \qquad (3)$$

$$\mathbf{M}_{SGS} = \nabla \cdot \nu_{SGS} \left[\nabla \overline{\mathbf{u}}_L + \left(\nabla \overline{\mathbf{u}}_L\right)^T\right] \qquad (4)$$

In the present study, Smagorinsky model is employed for the estimation of subgrid viscosity ν_{SGS},

$$\nu_{SGS} = \left(C_s \Delta\right)^2 \left|\overline{D}_{ij}\right| \qquad (5)$$

Here C_S is the Smagorinsky constant, Δ the filter width and $\overline{D}_{ij}$ the strain tensor. Numerical value of 0.15 has been set for C_S.

2.2 Rayleigh-Plesset Equation

A approach to predict cavitation inception is proposed in this study by taking into account the effect of pressure difference due to the filtering of LES into the Rayleigh-Plesset equation,

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho}\left[P_{CAV} - P_L + K\rho\frac{C_\nu}{C_\varepsilon}\Delta^2\left(2\sum_{i=1}^{3}\overline{D}_{ii}^2\right) - \frac{4\mu\dot{R}}{R} - \frac{2\gamma}{R}\right] (6)$$

where R is the bubble radius, ρ the liquid density, P_{CAV} the cavitation pressure (sum of the vapor pressure P_v and the gas pressure P_G inside the bubble), P_L the liquid pressure, μ the viscosity and and γ the surface tension.

2.3 Bubble Tracking Method

Each cavitation bubbles and nucleus are tracked using a bubble tracking method. In this method, particle are tracked using the following equation of motion:

$$\left(\rho_{CAV}^{n} + C_V \rho_L\right)\frac{d\mathbf{u}_{CAV}^{n}}{dt} =$$

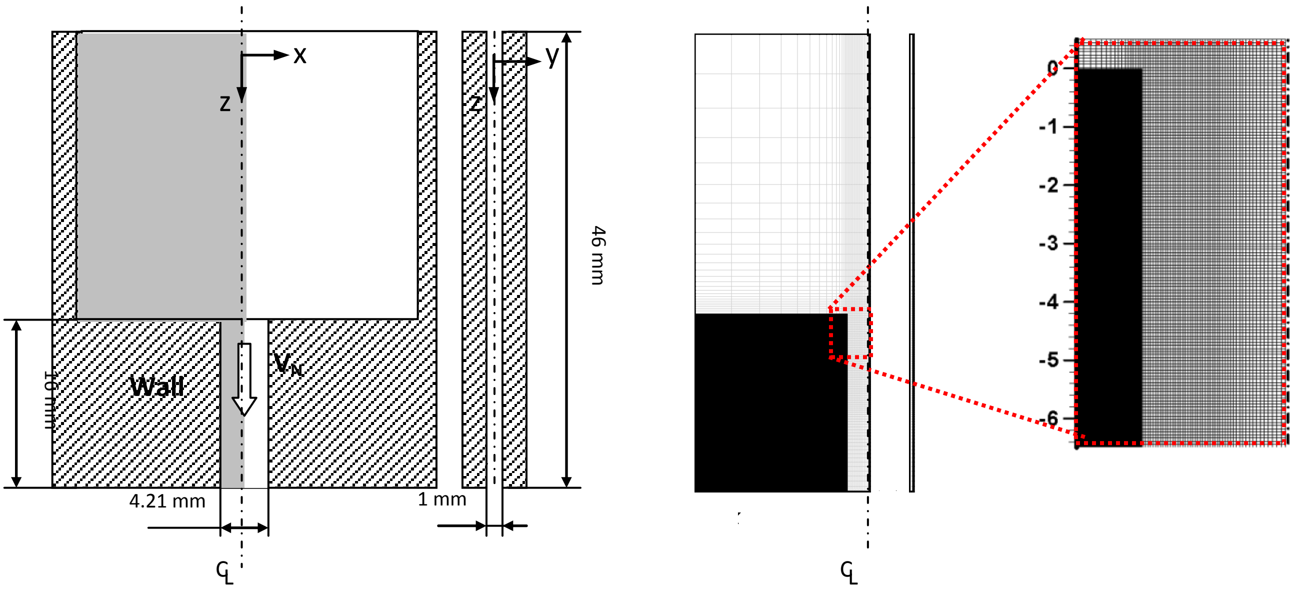

Fig.1 Computational domain

$$\left(1 + C_V\right)\rho_L \frac{d\bar{\mathbf{u}}_L}{dt} - \mathbf{m}_D^{n} - \mathbf{m}_{LF}^{n} + \left(\rho_L - \rho_{CAV}^{n}\right)\mathbf{g} \qquad (7)$$

where $\square_{CAV}$ and V_{CAV} are the bubble density and bubble velocity, $\mathbf{m}_D$ is drag force and $\mathbf{m}_{LF}$ the transfer lift force.

The drag force $\mathbf{m}_D$ is evaluated with the following equation,

$$\mathbf{m}_D^{n} = \frac{3}{4d^{n}} C_D^{n} \rho_L \left|\mathbf{u}_{CAV}^{n} - \bar{\mathbf{u}}_L\right|\left(\mathbf{u}_{CAV}^{n} - \bar{\mathbf{u}}_L\right) \qquad (8)$$

The lift force $\mathbf{m}_{LF}$ is given by

$$\mathbf{m}_{LF}^{n} = C_{LF}^{n} \rho_{CAV}\left(\mathbf{u}_{CAV}^{n} - \bar{\mathbf{u}}_L\right) \times rot\bar{\mathbf{u}}_L \qquad (9)$$

where C_{LF} is the lift coefficient.

3.Computational Domain and Boundary Condition

3.1Domain

The geometry of the simulation is shown in Fig.1, based on the one of the two-dimensional nozzle used in the experiments by Sou et al (2004, 2006). The computational domain was 16 x 0.5 x 46 mm, in x, y and z direction, respectively.

3.2Boundary Condition

Numerical simulations require initial and boundary conditions. In this study no slip condition is used for the solid walls. Tap water is fed from the upper boundary flowing to downward direction. The ambient pressure on the lower boundary (nozzle exit) is 0.1 MPa.

4. Result and Discussion

Figure 2 shows measured and calculated mean streamwise velocities in the nozzle. The measured result was obtained by LDV (Laser Doppler Anemometer). It can be seen that the predicted mean streamwise velocity agree with the measured value. This confirms good ability of the numerical model to predict turbulent flow in the nozzle.

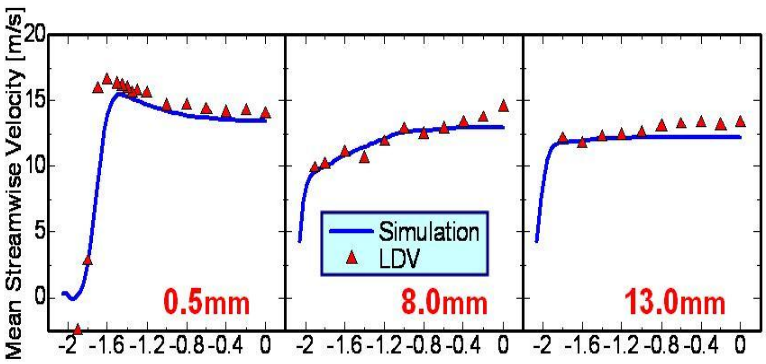

Fig.2 Measured and calculated mean velocity distribution in the nozzle hole

Figure 3 shows the time progression of the bubble distribution. As shown in Fig. 3(a) inception of cavitation along the outer edge of separated boundary layer near the nozzle edge were simulated. Generation of bubble clouds in the vortices shedding from the tail of recirculating flow is also observed. These phenomena were observed in the previous experiment (Sou et al., 2004) shown in Fig.3 (b).

Figure 4 shows the calculated pressure, SGS kinematic energy and void distributions. The pressure takes the value between –40 and 180 kPa. Cavitation bubbles are formed in the regions where pressure is much lower than vapor saturation pressure or turbulence is strong.

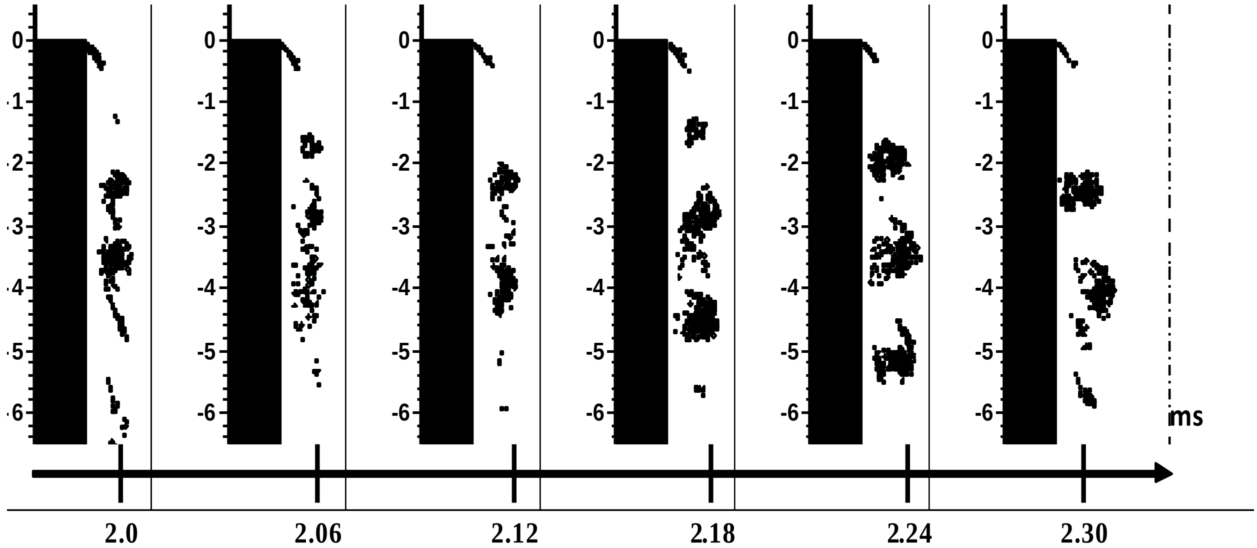

Fig.3a Bubble distribution near the nozzle edge : Calculated result

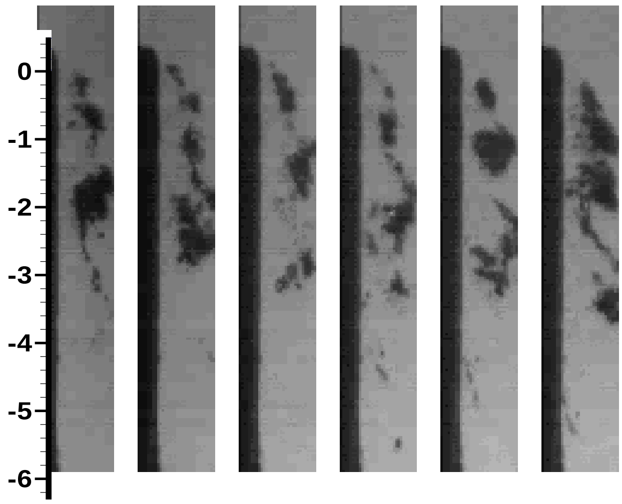

Fig.3b Bubble distribution near the nozzle edge: Experimental result (t = 0-125 □ s)

5. Conclusion

In this paper, turbulent cavitating flow in a two dimensional nozzle was simulated using LES, an extended Rayleigh-Plesset equation and one-way bubble tracking method. Calculated results of liquid velocity and bubble distributions agree with the experiment by Sou et al. (2004).

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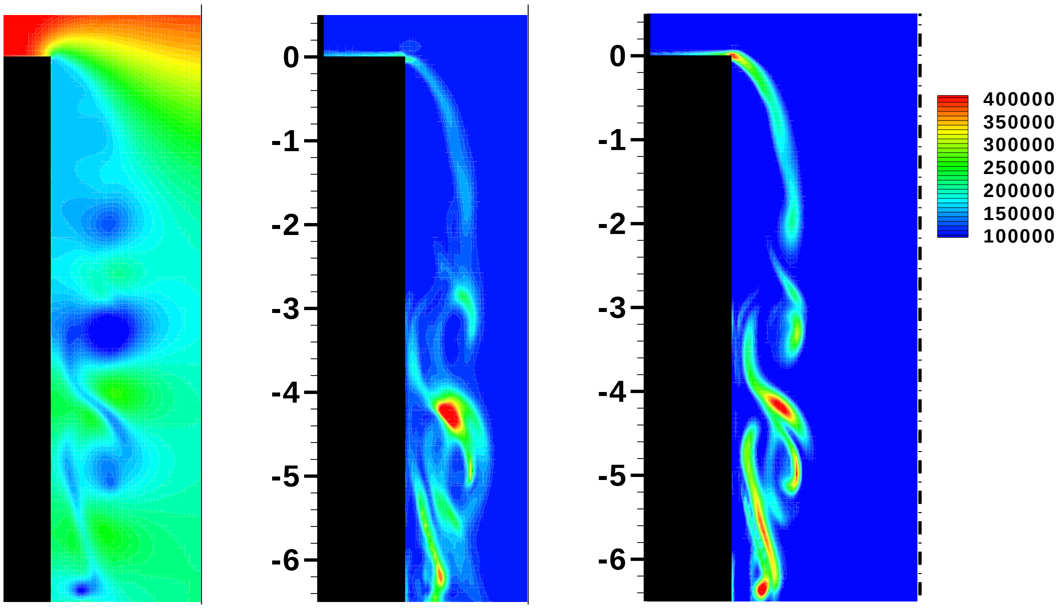

(a) Pressure (kPa) (b)SGS Kinematik (m^2/s^2) (c) Void fraction (1/s)

Fig. 4 Pressure, SGS kinematic energy and void fraction profile

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