Numerical investigations of cavitation in a nozzle on the LNG fuel internal flow characteristics

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Abstract. The internal flow characteristics of an LNG (liquefied natural gas) nozzle strongly influence spray formation and atomization. A numerical simulation model of an LNG nozzle was created to investigate the location of cavitation in the nozzle and analyse the causes after the feasibility of the numerical simulation method had been verified. Meanwhile, the effects of cavitation were investigated under three different injection pressures. The results show that because of the influence of the pressure gradient field, cavitation occurs in the lower portion of the hole, and subsequently, in the upper portion of the hole. In particular, cavitation causes the outlet fuel mass flow to widely fluctuate.

Introduction

Cavitation is known to occur inside various injector nozzles featuring micro-hole channels [1]. Cavitation in the nozzle critically influences spray combustion [2]; it is believed to improve fuel atomization in the combustion chamber [3]. Natural gas is the world's third largest energy resource following coal and oil. Owing to its higher heat value, natural gas has broad prospects for development as an alternative to diesel. Therefore, investigation of the effect of nozzle cavitation on the internal flow characteristics of LNG is important.

A visualization experiment using a nozzle is very difficult to perform. In recent years, a few researches have focused on experimentally studying the phenomenon of cavitation in real-sized injection orifices made of transparent materials using fuels such as diesel and methanol [4.5]. Owing to the low vaporizing temperature of LNG, it is difficult to visualize cavitation experimentally. Thus, in the present study, the phenomenon within the LNG nozzle is simulated using computational fluid dynamics. A few studies [6] have demonstrated two distinct forms of cavitation. One is caused by nozzle structure, and the other one is due to vortex cavitation. The former represents an identical form of cavitation in identical nozzle holes. In contrast, vortex cavitation is considered a flow characteristic unaffected by nozzle geometry. The nozzle used in this study is cylindrical with no chamfer at the entrance. The internal flow characteristics of this type of nozzle were obtained and verified experimentally as well as analytically (using AVL_Fire) [7]. The injection pressure significantly influenced the nozzle's internal flow characteristics and atomization [8]. When phase change occurs because of a pressure drop in the flowing liquid under a constant temperature, cavitation is said to have taken place [9]. The effects of three different injection pressures on internal flow in an LNG nozzle are investigated to develop different injection pressure models for atomization.

Theoretical background

It has been [10] indicated that the occurrence of cavitation in a nozzle depends mainly on the dimensionless cavitation number k. k is defined by Nurik and expressed as Eq. 1, where P_{inj} is the injection pressure, P_v is the vapour saturation pressure of fuel, P_{back} is the backpressure. The discharge coefficient decreases with a decrease in k, and cavitation is obvious at low values of k in experimental and numerical simulation studies of two different diesel nozzle structures [11]. The

relationship between k and the spray cone angle at the nozzle outlet was researched through a visualization experiment [12]. The results show k is the key parameter for determining cavitation, and there is a direct relationship between k and cavitation. R.ayri, F.J. et al conducted a visualization experiment based on the cavitation number k and Reynolds number Re using four different fuels [13]. The results showed that cavitation had a strong dependence on the two aforementioned dimensionless parameters. Re is given by Eq. 2, where D_0 is the outlet diameter of the nozzle hole, ρ_f is fuel density, v_f is dynamic viscosity, and $\Delta p = P_{inj} - P_{back}$.

$$k = \frac{P_{inj} - P_v}{P_{inj} - P_{back}} \tag{1}$$

$$Re = \frac{D_0 \cdot (2 \cdot \nabla p)^{1/2}}{\rho_f^{1/2} \cdot v_f} \tag{2}$$

It can be seen that cavitation has a direct relationship with the fuel properties and injection environments introduced above. The numerical investigations in this paper are based on this theoretical background.

Calculation model

The simulation in this study considered the mass-, momentum- and energy conservation laws by using the k-ε turbulence model and standard wall model to closure. Because the flow involved mixing and interaction of different components, the system also complied with the component conservation law. Because the flow here is multiphase, our simulation also involved the mass-, momentum- and turbulence interfacial exchange models. Accounting for the influence of the inertial item in the mass exchange model, we used the non-linear cavitation model in Fire2013, which was obtained by transforming the Rayleigh linear equation and considering the effects of turbulent fluctuations. The turbulent dispersion force accounted for diffusion of the dispersed phase (liquid) owing to the turbulent mixing process, so the Gas_Liquid1 model was activated.

Nozzle simulation model

The nozzle size mainly refers to the size of the original medium speed diesel engine nozzle. Its main parameters are listed in Table 1. Considering the spray orifice is an axially symmetrical and to save computing time, we established the 1/18 nozzle simulation model shown in Figure 1-a. For better coupling with spray and combustion in the combustion chamber, in the constant volume bomb at the outlet of nozzle, temperature and pressure at top dead centre in the combustion chamber are used. The chamber had sprayed diesel as an initial condition of 930 K and 15.7 MPa. The original coupled engine is a medium-speed diesel engine running at 900 rpm and having injection duration of 12°. The temperature of LNG flowing into the spray nozzle is 111 K. The physical parameters of LNG and CNG (compressed natural gas) are listed in Table 2.The needle lifting law is shown in Figure 1-b (the minimum needle lift is 0.01 mm owing to the grid restrictions).

Table 1 Main parameters of nozzle geometry

Number of holes	Hole diameter [mm]	L/D of hole	Nozzle cone angle [°]
9	0.8	3	160
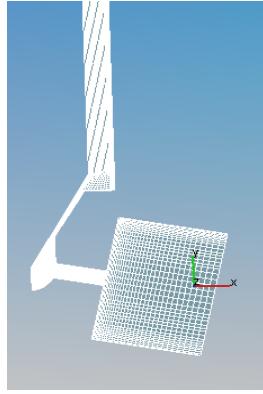
a. Nozzle grid model
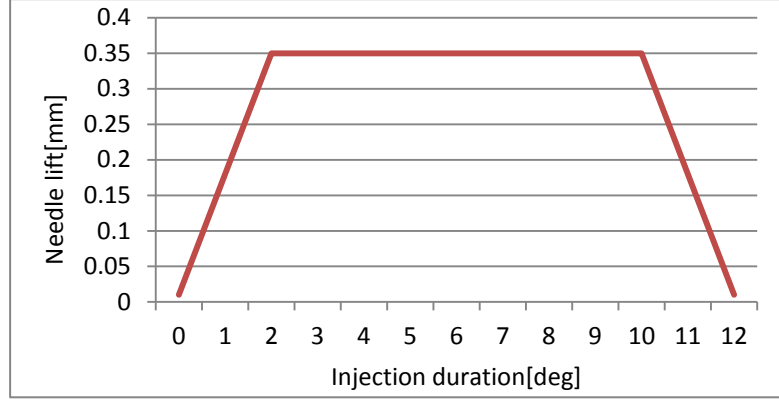
b. Needle lifting law

Figure.1. Nozzle grid model and needle lifting law

Table 2 Main properties of fuel

| Name	Density [kg/m^3]	Dynamic viscosity [Pa·s]	Vapor saturation pressure [bar]
LNG	428	0.00111	0.884
CNG	0.814	1.0255 x 10^{-5}	no

Model Validation

It is difficult visualize internal flow in an LNG nozzle, so we verified the accuracy of the simulation model used in this study against the results of the experiment of diesel in [2].

Figure 2-a shows the flow characteristics [2]; the L/D is 2.7. The characteristics are identical to those shown in Figure 2-a. Figure 2-b is the flow characteristics from the simulation established in [2]. The internal flow characteristics obtained analytically are identical to the experimental results. As the evaporation model was not activated in the constant volume bomb, the spray cone angle is not as large as that in the experiment, but it is easier to see the impact of cavitation on the spray cone angle. Therefore, the mathematical and analytical methods used in this study to investigate the internal flow characteristics in an LNG nozzle are feasible.
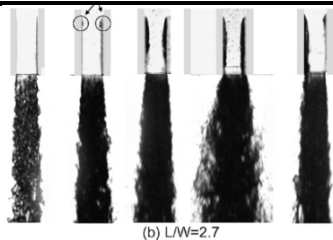
a. experiment
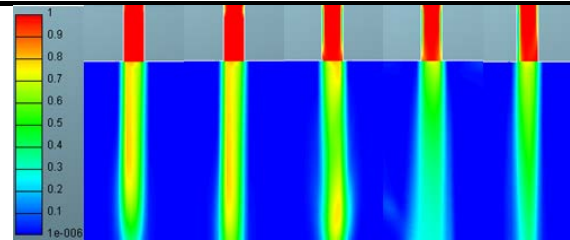
b. simulation

Figure.2. Flow characteristics in nozzle by experiment and simulation

Effects of injection pressures

From Eqs. 1 and 2, the injection pressure has a direct impact on cavitation. In this study, we employed pressures of 70 MPa, 80 MPa and 90 MPa.

Figure 3 shows the outlet mass flow under three injection pressures. The smaller the injection pressure, the smaller is the mass flow. In early injection, the fluctuation of mass flow is obvious. The larger the injection pressure, the dramatic is the change. The cavitation distribution figure below shows that the larger the injection pressure, the faster is the generation of cavitation and the more dramatic is the change in the position and size of cavitation. When the position and size of cavitation stabilize, the fluctuations of mass flow are basically identical.
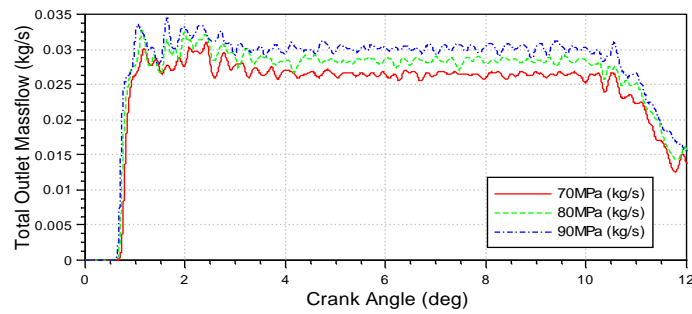
Figure.3. Outlet mass flow at different injection pressures

Figure 4-a shows that in three cases, the pressure at the bottom of the nozzle is larger than that in other places. The pressure field is established quickly and changes dramatically, which will leads to vortex formation. Before the injection hole in the lower part, cavitation occurs, as can be seen in Figure 4-b owing to lower pressure, reduced cross-sectional area, and varying flow direction. The change in pressure gradient is more obvious with increasing injection pressure and therefore so the cavitation under 90 MPa is more widely distributed. Moreover, pressure gradient fields are established in the inlet part of the upper hole. Cavitation will occur there owing to the interaction of the pressure gradient fields.

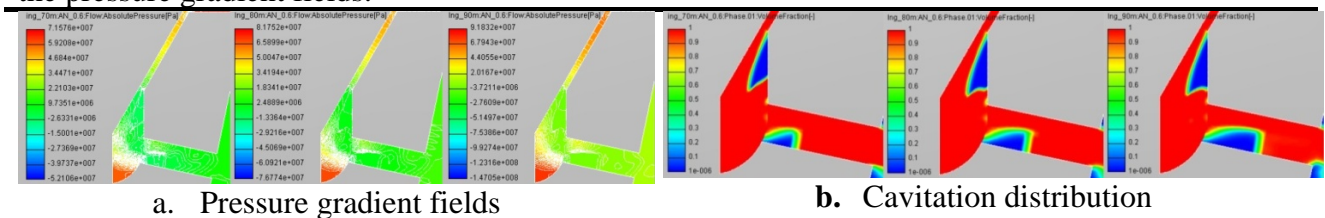a. Pressure gradient fields **b.** Cavitation distribution

Figure.4. Pressure gradient fields and cavitation distribution at 0.6° under three injection pressures

In Figure 5, the needle has lifted to the highest position. The two parts of cavitation in the upper nozzle have merged. The larger the injection pressure, the more obvious is the cavitation. The cavitation extending toward the nozzle outlet breaks owing to the pressure drop. It's important to determine that incomplete cavitation wherein the liquid is dominant is more conducive for increasing the spray cone angle.
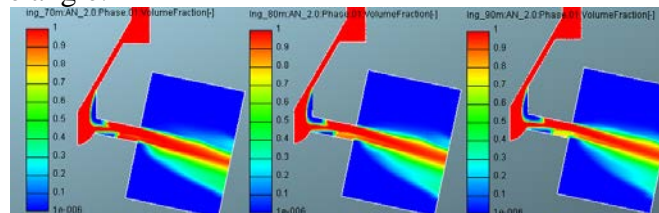

Figure.5. Cavitation distribution at 2° under three injection pressures

Conclusions

Cavitation occurs quickly in the lower part of hole owing to rapid establishment of a pressure field and dramatic changes in the pressure gradient. Cavitation occurs in the upper part of hole with needle lift. The fluctuation of mass flow is obvious owing to the effect of variation in cavitation. Within a certain range, the greater the injection pressure, the more obvious is the occurrence of cavitation. Incomplete cavitation is more conducive for increasing the spray cone angle.

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