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Experimental and numerical study of cavitation inception phenomenon in diesel injector nozzles☆

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ABSTRACT

In this paper the experimental and numerical methods were combined to investigate the critical conditions of cavitation inception in diesel injector nozzles. It was found that at the beginning of cavitation inception, the discharge coefficient presents a slight increase and then a special turning point appears which can therefore be taken as the critical point for cavitation inception. Effects of needle lift, length–diameter ratio, orifice inclination angle, back pressure, and scaled-up times on critical cavitation number were studied through the experimental method. Due to the difficulties in manufacturing, influence of inlet rounding radius was investigated by using the numerical simulation method. Based on all the experimental and numerical simulation data, a correlation of critical cavitation number with above 6 geometrical and dynamic parameters for nozzle flow was developed through statistical analysis using the Quasi-Newton (BFGS) and Universal Global Optimization (UGO) methods. The relative error between predicted results and experimental data is less than 7%. These results indicate that the derived expression has good accuracy to predict the start of cavitation.

1. Introduction

It is well known that the characteristics of the internal nozzle flow have great influences on the spray and its atomization characteristics [1–3]. This is particularly true when cavitation occurs in the nozzle orifice of an injector operating under very high injection pressures [4–6]. Due to the fact that the primary break-up of liquid fuel jet can be improved by the enhanced turbulence caused by the cavitation within the flow, cavitation has been recognized as a key factor in advancing the development of the fuel spray. However, cavitation can also reduce the flow efficiency due to its effect on the exiting jet. Moreover, imploding cavitation bubbles inside the orifice can cause material erosion and then reduce the life and performance of the injector [7–9]. Thus, investigation of cavitation phenomenon is vitally important.

The mass flow rate of a nozzle and whether the cavitation occurs or not in nozzle holes are dependent on not only injection pressure and back pressure but also the nozzle geometry and needle effect. Kayhan and Michael [10] pointed out that the critical injection pressure at which the cavitation initiates for a fixed back pressure depends on the nozzle geometry. Ohrn et al. [11] studied the effect of nozzle inlet shape and length–diameter ratio on discharge coefficient and found that inlet rounding radius had a much larger effect than did length–diameter ratio. They also noticed that even slight defects in the inlet edge of sharp inlet nozzles could cause a substantial variation in discharge coefficient. Nurick [16] commented that increasing *r*/*D* (inlet rounding radius to hole diameter ratio) delayed the onset of cavitation to smaller critical cavitation numbers (or higher injection pressures). Bergwerk [12] reported that longer nozzles delay the onset of cavitation to higher injection pressures. Although useful information has been obtained from large scale nozzle experiments, scale effects have been recognized to be very important [13]. Arcoumanis et al. [14] compared the cavitation structures between the real-size nozzle and enlarged nozzle. They concluded that cavitation structures differ between large scale nozzles (clouds of bubbles) and real scale nozzles (cavitation pockets). Despite these differences, Soteriou et al. [15] showed that the discharge coefficient is independent of the scale of the model. They reported that cavitation number controlled the nozzle discharge. Moreover, according to Soteriou's [15] and Nurick's [16] studies, the discharge coefficient only depends on the Reynolds number for non-cavitating conditions, while for cavitating conditions, discharge coefficient increased with the increase of cavitation number. Therefore, a decrease of discharge coefficient has been used traditionally as a hydraulic criterion to detect the start of cavitation. Based on this criterion, Nurick's and Kayhan's [10] experiments both indicate that onset of cavitation is likely to occur in a cavitation number range of 1.3–2 for sharp inlet diesel nozzles. To predict the flow pattern in diesel nozzles, Macian et al. [17] obtained a correlation of critical cavitation number. Payri et al. [18] refined the

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Nomenclature and unit

A	cross-sectional area of a nozzle hole, m^2
C_d	discharge coefficient of a nozzle
L	nozzle hole length, mm
D	nozzle hole diameter, mm
h	needle lift, mm
k	turbulence kinetic energy, m^2/s^2
K	cavitation number
Q_v	volume flow rate, m^3/h
$\dot{m}$	actual mass flow rate of a nozzle, kg/s
Re	Reynolds number
P_{in}	injection pressure, Pa
P_v	vapor pressure, Pa
P_b	back pressure, Pa
t	time, s
u^+	velocity component tangential to the wall, m/s
u_z	friction velocity constructed from the wall stress, m/s
y^+	dimensionless distance from the wall surface
Greek letters	
ϕ	nozzle hole inclination angle, degree
ρ	fuel density, kg/m^3
μ	dynamic viscosity, Pa·s
ε	dissipation rate, m^2/s^3
σ	surface tension of the fluid, N/m
Subscript	
crit	critical parameter
l	liquid phase
in	upstream location of a nozzle
back	nozzle hole outlet

correlation. However, only three or four parameters were considered in their correlation, which is not so convincing.

The work presented here aims to provide a quantitative criterion for the judgment of internal flow state. To achieve this, the experiment combined with numerical simulation was carried out to investigate the influence of nozzle geometrical and dynamic parameters on critical conditions for inception of cavitation. Then based on all the obtained data, a correlation of critical cavitation number with the 6 geometrical and dynamic parameters was developed through statistical analysis using the Quasi-Newton (BFGS) and Universal Global Optimization (UGO) methods.

2. Theoretical background

At the mention of cavitation phenomenon, two non-dimensional parameters are worth studying. One is discharge coefficient C_d, and the other is cavitation number K.

The discharge coefficient represents the relation between real mass flow and ideal mass flow. It can be obtained by combining the Bernoulli equation and the mass conservation equation:

$$C_d = \frac{\dot{m}}{A\sqrt{2\rho_l(P_{in} - P_{back})}} \tag{1}$$

where $\dot{m}$ is actual mass flow rate, A is the cross-sectional area of orifice, ρ_l is the fuel density, P_{in} is the upstream pressure (injection pressure) and P_{back} is the orifice outlet pressure (back pressure).

The cavitation number K is a non-dimensional parameter defined based on the pressure difference along the nozzle orifice. To some extent, it represents the cavitation conditions in an injector. In the current work, we use the definition proposed by Nurick [19]:

$$K = \frac{P_{in} - P_v}{P_{in} - P_{back}} \tag{2}$$

where P_v is the vapor pressure of fuel. Obviously, the value of K decreases as the injection pressure increases or back pressure decreases. For a nozzle, smaller K means larger pressure differential across the orifice and therefore higher tendency to cavitate.

Using the definition of K, Nurick expressed the discharge coefficient as:

$$C_d = C_c\sqrt{K} \tag{3}$$

where C_c is the contraction coefficient. Literatures show that for sharp-edged orifices the value of C_c is about 0.61 [13]. The trends predicted by this relation are quite distinctive, it indicates that the C_d relates to K directly and decreases as a linear function of the root of K from the beginning of cavitation. Nevertheless, for non-cavitation flow, the discharge coefficient is a direct function of the Reynolds number [20–22]. For this reason, a decrease in C_d is expected when the flow reaches the cavitation inception situation. However, Payri's [18] study show that cavitation bubbles appear at less critical conditions. They concluded that there must be a high amount of bubbles in the throttle section in order to produce mass flow choking.

In fact, it was found on our test rig that at the beginning of cavitation inception, there is a slight increase for the discharge coefficient. This strange phenomenon may be explained as very small amount of cavitation bubbles smoothed the internal flow therefore discharge coefficient increased. Based on the comparison between visualization images and variation trend of discharge coefficient, the criterion to detect cavitation inception for the current work is a transition point of discharge coefficient and then in this case the cavitation number can be defined as the critical cavitation number, as it shown in Fig. 1. Obviously, cavitation will not occur unless the cavitation number is lower than the corresponding critical cavitation number K_{crit}.

3. Experimental investigation

3.1. Experimental setup

Fig. 2 shows the schematic diagram of the nozzle flow and spray characteristic visualization system used for the current work. The injector was enlarged to match the scaled-up nozzle tip replicas which are made of acrylic that has almost the same index of refraction as diesel fuel. Bottled nitrogen is used to pressurize the fuel in the pressure container to supply fuel to the testing nozzle. The pressure gauge installed near the injector was used to adjust and obtain the injection pressure.

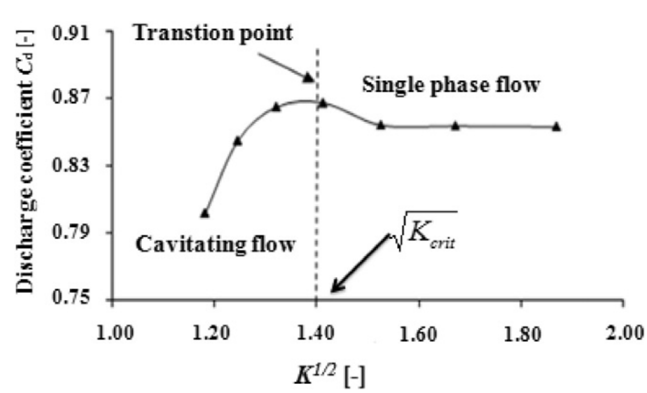

Fig. 1. The criterion to detect cavitation inception.