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Study of the effect of nozzle hole shape on internal flow and spray characteristics☆

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ABSTRACT

The presence of cavitation and turbulence in a diesel injector nozzle has significant effects on the subsequent spray characteristics. In this paper, the influence of nozzle hole shape on internal flow and near-nozzle spray behavior at stationary conditions was studied. A flow visualization experimental system with a transparent scaled-up injector was setup. Three min-sac nozzles with the same hole outlet diameter but different hole shapes (cylindrical, convergent, and divergent) were used for the investigation of influence of nozzle hole shape on internal flow and spray. A detailed comparison of the cavitation and spray characteristics of the three nozzles was conducted under a variety of fuel injection parameters. Results show that cavitation collapsed inside the hole leads to an increment of flow turbulence but has limited effects on spray cone angle. However, when cavitation extends to the hole outlet, the spray cone angle increased sharply. These results indicate that the collapse of cavitation bubbles contributes to the disintegration of the spray mainly through causing a local breakup. Furthermore, the hydraulic flip phenomenon was also investigated.

1. Introduction

Diesel engine performance and emissions are strongly coupled with fuel atomization and spray processes, which in turn are strongly influenced by injector flow dynamics [1,2]. This is particularly true when cavitation occurs in the orifice of an injector operating under very high injection pressures [3,4].

Many experimental and theoretical investigations have been performed to explain cavitation flow in a nozzle. Ohrn et al. [5] measured 40 different plain-orifice atomizers. They commented that the shape and the condition of the nozzles inlet have a strong effect on discharge coefficient than do length–diameter ratio and Reynolds number. Kato et al. [6] measured the pressure distribution in the nozzle sac and discharge hole and found that cavitation at the hole inlet is sensitive to both the nozzle sac geometry and the inlet hole configuration. Payri et al. [7,8] reported that cavitation leads to an increase in the spray cone angle as well as flow outlet speed. Bergstrand [9] investigated five nozzles with different hole shapes. He commented that hole shapes resulting in lower fuel flow rates can yield lower fuel consumption and lower emissions than orifice shapes that have larger fuel flow rates. Benajes et al. [10] compared the flow characteristics of a cylindrical and conical nozzle. They reported that the value of discharge coefficient is higher in the conical nozzle than that in the cylindrical nozzle. Sibendu Som et al. [11] studied the effects of nozzle hole conicity and hydro-grinding on spray and combustion processes through numerical method by coupling the injector flow and spray simulations. They found that conicity and hydro-grinding reduce cavitation and turbulence inside the nozzle hole, which slows down primary breakup, increasing spray penetration and reducing dispersion. Despite the significant amount work, it is still unclear whether the collapse of cavitation bubbles contributes to the disintegration of the jet though an increase in turbulent kinetic energy or by causing a local breakup.

The objective of this paper is to gain a intuitive understanding of the conditions in different shape nozzle holes and the spray cone angle at the nozzle exit. This objective will be accomplished by combining measurements of injection flow rate of different scaled-up transparent nozzles with visualization experiments.

2. Theoretical background

There are two mechanisms that cause cavitation in diesel fuel injection equipment. According to the generation mechanisms, the cavitation can be clarified into dynamically induced and geometry-induced cavitation [12,13]. Dynamically induced cavitation is the one more commonly recognized in the diesel fuel injection equipment. It occurs only in transient flow and is usually caused by pressure wave activity or valve movement. Geometry-induced cavitation can occur in steady state as well as in transient flow. It is initiated by local high velocities within the separated boundary layers. Boundary layer separation occurs downstream of sudden changes in the flow path geometry, and it can

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Nomenclature

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
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

exist with or without cavitation. Fig. 1 shows a simple diagram of the flow separation in the boundary layer. It creates a region of high velocity re-circulating flows. These high velocities can result in sufficiently large reductions in local pressure to cause the formation of vapor bubbles. The bubbles may collapse near the geometrical feature, which gave rise to them, or they may be carried along in the flow before they reach a region of higher pressure, where they eventually collapse and single phase flow is reinstated.

At the mention of cavitation phenomenon, two non-dimensional parameters worth mentioning. 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 nozzle orifice. To some extent, it represents the cavitation conditions in an injector. In the current work, we use the definition proposed by Nurick [14]:

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

Where P_v is the vapor pressure of fuel. For cavitating nozzles, the critical cavitation number is defined as K_{crit}, corresponding to the pressure drop at which cavitation starts in the injector hole. This phenomenon happens at a given value of the injection pressure, and it is detected by the stabilization of the mass flow rate across the hole, despite the further decrease in discharge pressure. Hence, cavitation will not be produced unless the cavitation number, corresponding to these pressure conditions, is lower than the critical value.

3. Investigation method

3.1. Experimental setup and test method

Fig. 2 shows the schematic diagram of internal flow and spray visualization setup. The experimental setup comprises of pressure container with fuel, nitrogen gas source for pressurizing the fuel, and a feed line fitted with flow control valves for supplying fuel at different pressure conditions to the nozzle hole. The scaled-up nozzle tip replicas were made of acrylic that has almost the same index of refraction as diesel fuel. The nozzle hole discharges into the ambient atmosphere and placed between a light source (100 W) and a high-speed camera (10000Hz), giving back lighting. By adjusting the focal plane, the internal flow and spray of a testing nozzle could be obtained. The flow in the nozzle is transparent as long as no cavitation occurs and is white on the pictures. The cavitation bubble appear black on the pictures because the light is refracted at the vapor–liquid interface and does not reach the camera lens. Moreover, the high-speed camera was connected with a long distance microscope (12 times) so as to ensure the high quality of images.

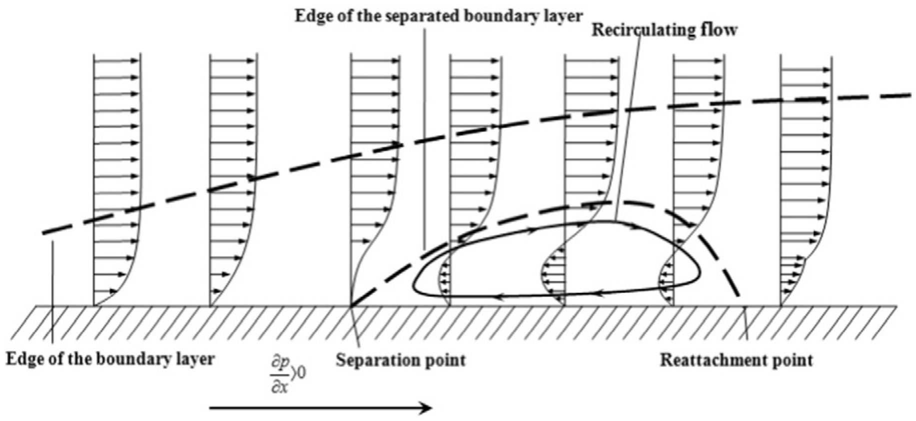

Fig. 1. Simple diagram of the flow separation in the boundary layer.