Experimental Study of Effects of nozzle Hole Shape on Cavitating Flow

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Abstract In this paper, the influence of nozzle hole shape on internal flow and near-nozzle spray behavior was studied. A flow visualization experimental system with a transparent scaled-up injector was setup. Three nozzles with the same hole outlet diameter but different hole shapes were used. Detailed comparisons of the cavitation and spray characteristics of the three nozzles were conducted under different fuel injection pressures. Results show that cavitation collapsed inside the hole lead to an increment of flow turbulence but have limited effects on spray cone angle. However, when cavitation extends to the hole outlet, the spray cone angle increased sharply.

Introduction

Diesel engine performance and emissions are strongly coupled with fuel atomization and spray processes, which are strongly influenced by injector flow dynamics [1-2].

Recent studies have shown that the cavitating flow in diesel injector nozzles affect spray characteristics and therefore atomization behavior, which is decisive for diesel engine performance and pollutant formation.

At the mention of cavitation phenomenon, two non-dimensional parameters is worth mentioning. One is discharge coefficient Cd, and the other is cavitation number K [3]. The Cavitation number was defined as $K= (P_1-P_v)/(P_1-P_2)$.Where, P1 is the injection pressure, P2 the back pressure, Pv the saturated vapor pressure of the fuel. The value of K decreases as injection pressure increases or back pressure decreases. As K is smaller, the tendency of cavitating is higher. Additionally, studies show that different nozzle structures have different K_{crit}, which indicates the start of cavitation. Another significant parameter is the discharge coefficient C_d. This parameter is defined as the relation between the real mass flow rate and the theoretical one: $C_d= \frac{Q_m}{A\sqrt{2r(P_1-P_2)}}$, where, Q_m is the actual flow rate, A the cross-sectional area, ρ the fuel density.

The object of this paper is to gain a better understanding of the flow and spray characteristics in different shape nozzle holes with visualization of nozzle cavitating flow and near-nozzle spray.

Experimental Setup

Fig. 1 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 (100W) 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 [4-5].

In order to carry out the test at various pressure differences, the injection pressure is varied between 0.15-1.2 MPa. After a short stabilization time, when steady flow conditions have been achieved, flow rate across the injector is measured. Once the flow rate has been obtained for each of the pressure conditions, the value of C_d can be calculated. The density of the fuel is 837kg/m^3,and the viscosity is 3.4mPa·s, the surface tension is 27.39mN/m, and the Saturated vapor pressure is 892Pa.

For the analysis, three nozzles whose holes differ in conicity and inlet diameters were used. The *k*-factor is defined in Fig.2 and the basic information of the investigated nozzles were shown in Table.1.

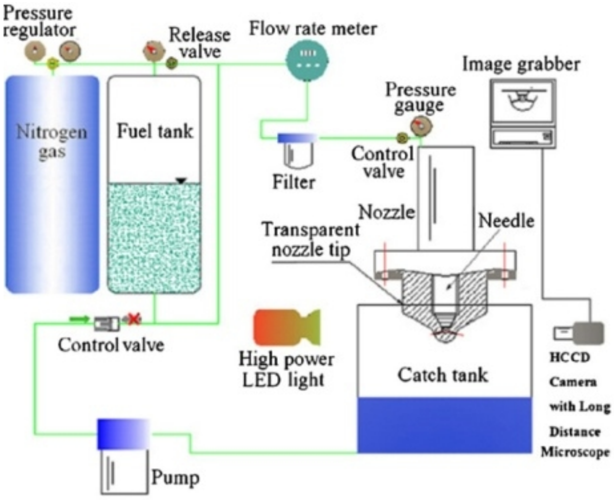


Fig. 1 Schematic diagram of the internal flow and spray visualization setup.

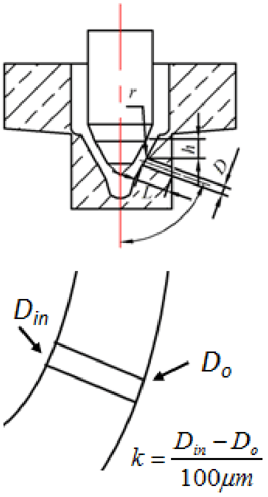


Fig.2 Definition of k-factor

Table.1 Basic nozzle characteristics

Nozzle	Din (mm)	Do (mm)	k-factor
A	2.0	1.8	2
B	1.8	1.8	0
C	1.6	1.8	-2

Results and discussions

Flow behavior and spray characteristics of different hole shape nozzles.

Fig. 3 shows the pictures of flow within cylindrical hole nozzle and of the spray at the nozzle exit for different injection pressures.The internal flow can be divided into four regimes: single phase flow or turbulent flow, cavitation inception, cavitation growth,and hydraulic flip, respectively. In single phase flow regime, the fuel emerges out the nozzle hole almost unimpaired in an intact liquid column. The spray break up are therefore affected primarily by growth of surface waves induced by aerodynamic interaction processes. Cavitation inception was defined as the point where bubbles are generated at the hole entrance. As it shown, for the cylindrical hole nozzle, cavitation begins to initiate on the upper edge of hole when the injection pressure reaches to 0.33 MPa. With increasing of injection pressure, cavitation area began to expand in both the radial and axial direction of hole. The cavitation growth flow can be divided into two stages, according to whether the shedding cavitation reached to the hole outlet or not. In growth stage I, no shedding cavitation reached to the hole outlet, while in growth stage II, some shedding cavitation reached to the hole outlet. Correspondingly, in stage I, the spray cone angle did not alter significantly, but an increase in the surface wave of the upper spray contour can be observed. This increase of surface wave can be attributed to the collapse of cavitation bubbles in the hole which elevate the levels of turbulence of the internal flow. With increasing of injection pressure, cavitation growth entered into stage II, that is, shedding cavitation reached to the hole outlet more or less. In this stage, a noticeable increment of spray cone angle and spray contour irregularities could be observed. This fact can be attributed to the collapse of cavitation bubbles near the nozzle exit. Moreover, when the injection pressure reached to

0.47 MPa, the cavitation region reached to the nozzle exit (super-cavitation), and a maximum spray cone angle formed. Obviously, the disintegration of the spray is most violent for super-cavitation flow, as it has the most abundant and continuous shedding cavitation bubbles reached to the hole exit and collapsed there. With increasing the injection pressure more and more, the flow state suddenly changed to the hydraulic flip flow, a smooth flow without any visible disturbances emerged from the nozzle exit and the spray cone angle decreased sharply. Moreover, further increase of the injection pressure did not make any change to the internal flow state or the spray contour feature.

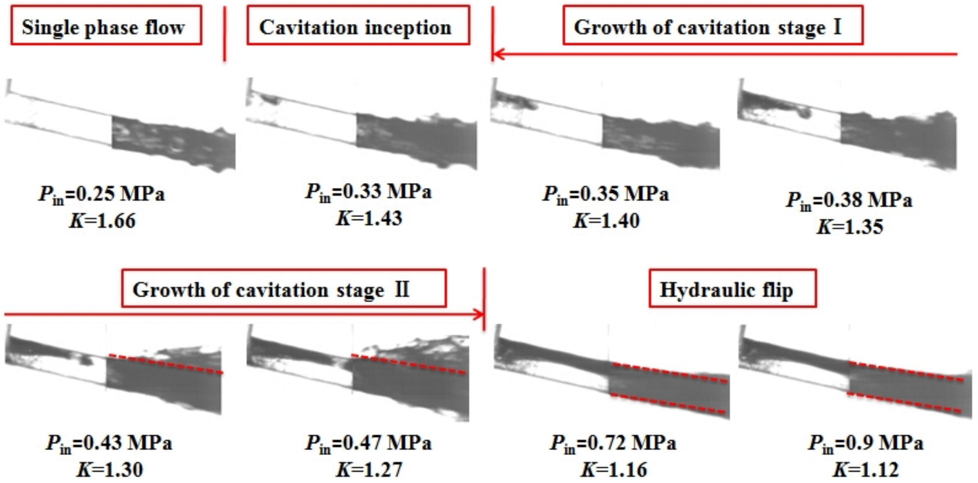


Fig. 3 Cavitation evolution in the cylindrical hole nozzle and its' effect on spray characteristics

The cavitation evolution within divergent hole nozzle and the spray at the nozzle exit were shown in Fig. 4. It can be seen that in the case of divergent hole, the critical pressure of cavitation inception was 0.29 MPa, which was lower than that of cylindrical hole nozzle, which was 0.33 MPa. So, it can be concluded that the critical injection pressure at which cavitation initiates with atmospheric conditions is closely related to the nozzle hole shape, and the divergent hole is more prone to cavitate than the cylindrical hole. In cavitation inception regime, cavitation bubbles mainly collapsed in the hole and the spray cone angle not much changed compared to the spray in single phase flow regime. Due to the promotion effect of divergent hole on cavitation generation and development, shedding cavitation can easily reach to the hole exit and produce great influence on the spray cone angle. With the increasing of injection pressure, the internal flow suddenly changed to the hydraulic flip flow state, which was same with the flow pattern transition process happened in cylindrical hole nozzle. Meanwhile, the spray formed by the hole emerged out in a smooth glassy appearance, and the spray cone angle decreased sharply. Then, further increase of the injection pressure did not make any change to the internal flow state and spray characteristics, similar to the situation happened in the cylindrical hole nozzle.

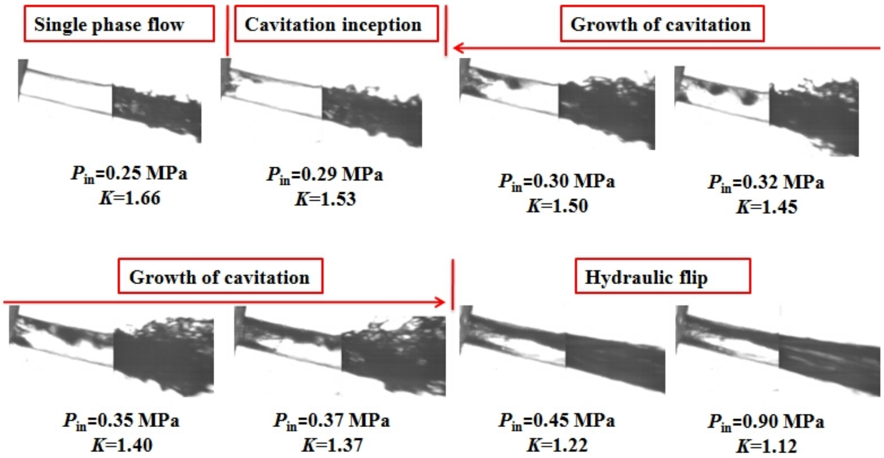
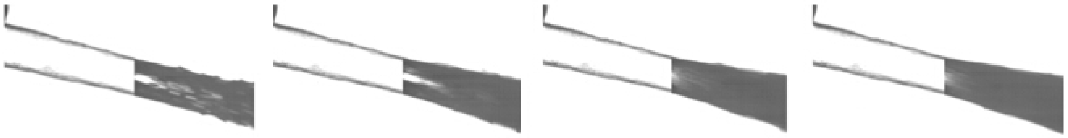


Fig.4 Cavitation evolution and spray characteristics of the divergent hole nozzle

The flow state and near nozzle spray characteristics of convergent hole nozzle were shown in Fig. 5. As it shown, cavitation inception was not observed despite an increase in the fuel injection pressure to 1.0MPa. This results can be explained as the convergent hole prevented the happening of a rapid pressure drop in the hole, and the local pressure was always higher than the saturated vapor pressure therefore prevented the generation of cavitaiton in the flow. Due to the cavitation free flow of the convergent hole nozzle, the fuel emerged out almost unimpaired from the spray hole during the whole injection pressure range, and an approximately constant very small spray cone angle was achieved.



P_{in}=0.2 MPa P_{in}=0.4 MPa P_{in}=0.7 MPa P_{in}=1.0 MPa

Fig.5 Internal flow and spray characteristics of the convergent hole nozzle.

Discharge characteristics of different hole shape nozzles

Figure 6 details the results of the investigation into the non-dimensional discharged coefficient and cavitation number of the three different hole shape nozzles. It should be remembered that as a consequence of the definition of K, cavitation should occur at low values of this parameter, therefore the analysis of these curves should be made from right to left on the horizontal axis. In general, the discharge coefficient of convergent hole is larger than that of cylindrical hole and divergent hole. Moreover, with the appearance of cavitation and the happening of hydraulic flip phenomenon, the difference between the discharge coefficient of the three nozzles widened. For the cylindrical and divergent hole nozzle, the variation trend of discharge coefficient were almost the same: the discharge coefficient initially increased with the decrease of cavitation number, then with the appearance of cavitation the discharge coefficient gradually decreased, when the flow gets separated due to the onset of hydraulic flip phenomenon, the discharge coefficient falls to near-constant values of about 0.59 for the cylindrical hole and 0.53 for the divergent hole. What was different was the discharge coefficient of divergent hole decreased more quickly than that of the cylindrical hole, this corresponds well with the cavitation level in the two holes. The plots corresponding to the divergent hole nozzle confirm the resistance of this geometry against cavitation, since the discharge coefficient increased with the decreasing of cavitation number

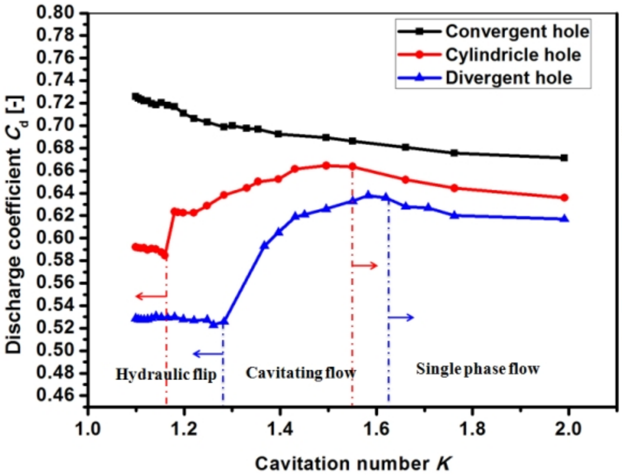


Fig. 6 Correlation between K and C_d of the three different hole shape nozzles.

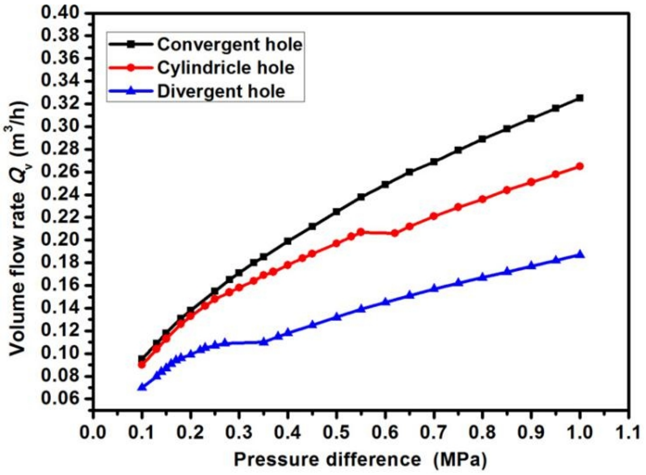


Fig. 7 Comparison of flow rate of the three different hole shape nozzles.

Fig. 7 shows the correlation between injection pressure and volume flow rate of the three different hole shape nozzles. It can be seen that the flow rate of convergent hole is larger than that of the cylindrical hole and divergent hole, and with the increasing of injection pressure, the gap widened gradually. For the convergent hole nozzle, the flow rate increased continuously as the increase of injection pressure. While for the cylindrical hole and divergent hole nozzle, the variation trend of flow rate got a pause due to the happening of hydraulic flip phenomenon. From Fig.6 and Fig. 7, it can be concluded that even though the nozzles were designed to have the same hole outlet diameter, different hole shape can make a huge big difference when it comes to the discharge coefficient and flow rate. Without considering of the spray cone angle, from the flow efficiency levels, convergent hole nozzle present a higher flow stability and an excellent discharge performance than the other two different hole shape nozzles.

Conclusions

From the present study, several important conclusions can be established:

(1) The critical injection pressure at which cavitation initiates with atmospheric conditions is closely related to the nozzle hole shape, and the divergent hole is more prone to cavitate than the cylindrical hole.

(2) The shedding cavitation bubble collapse place dominates the influence level of cavitating flow on the spray cone angle. At small injection pressure, shedding cavitation collapse near the generation place and have little influence on the spray cone angle. With the increasing of injection pressure, more and more cavitation generated and some of the shedding cavitation collapse near the nozzle exit, and the energy released by the collapsed bubble drastically influence the break up of the diesel spray. Moreover, the disintegration of the spray is most violent for super-cavitation flow.

(3)The cavitated flow and hydraulic flip give small value of discharge coefficient. With a same outlet diameter, convergent hole nozzle present a higher flow stability and an excellent discharge performance than the other two different hole shape nozzles.

(4)The cavitation phenomenon has stronger influence on the spray cone angle compared to the turbulence.

Acknowledgements

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References

[1] C Badock, R Wirth, S Kampmann and C Tropea. Fundamental study of the influence of cavitation on the internal flow and atomization of diesel spray [C], Proc.13th ILASS-Europe 97, Florence, Italy, July 8-10, pp: 53-59, 1997.

[2] M. Gavaises and A. Andriotis. Cavitation inside Multi-hole injectors for large diesel engines and its effect on the near-nozzle spray structure. SAE Paper 2006-1-1114,2006.

[3] Nurick,W. H. Orifice cavitation and its effects on spray mixing. Journal Fluids Engineering. pp. 681-687. 1976.

[4] Celia Soteriou, Richard Andrews and Mark Smith. Further Studies of Cavitation and Atomization in Diesel Injection. SAE Paper No. 1999-01-1486.

[5] Zhixia He, Zhuang Shao, Qian Wang, Wenjun Zhong and Xicheng Tao. Experimental Study of Cavitating Flow inside Vertical Muti-hole Nozzles with Different Length-diameter Ratios Using Diesel and Biodiesel. Experimental Thermal and Fluid Science, 60, 252-262, 2015.