Experimental Investigation on Structure of Cavitating Flow and Velocity Field inside a 2-D Hole Nozzle

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An experimental study was performed to clarify the structure of cavitating flow inside the hole type nozzle on atomization. Specially installed PTV (Particle Tracking Velocimetry) system was applied for the internal cavitating flow of the 2-D (2 dimensional) transparent nozzle hole. Therefore a spatial velocity distribution of liquid flow and a spark photograph of cavitation bubbles were obtained at the same time in each test. The breakup length was measured to evaluate the atomization. A bubble of the sheet cavitation, which has the “finger-like” structure, is yielded since this study is mainly carried out at a relatively low injection pressure. Near the hole entrance, the stream-wise velocity increases with stream-wise distance, and then the stream-wise velocity approaches constant up to the trailing edge of the bubble. However the flow is decelerated around the trailing edge, hence the stream-wise velocity reaches constant again where there dose not exists the bubble until the exit of the hole. Spatial variation of the stream-wise velocity decreases downstream the bubble, while the maximum variation appears near the trailing edge. A sheet cavitation exhibits different latitude profiles of the stream-wise velocity, which appears just upstream and downstream the trailing edge of the cavitation bubble. In comparison with the case without the turbulent mesh, there are frequent variations of velocities throughout width-wise location in the case with the turbulent mesh.

1. Introduction

Combustion in direct injection diesel engines is strongly influenced by atomization process of fuel, and information of internal flow velocity with cavitation of the hole nozzle is very significant for predicting characteristics of a diesel spray atomization. Furthermore experimental data is very important for computer simulations. Ruiz et al. [1] demonstrated the occurrence of cavitation and the effects on discharge coefficient in a diesel nozzle over most of its operating range. Experiments have been performed by using transparent nozzles in order to identify flow patterns in the nozzle hole [2-7]. Soteriou et al. [2] exhibited studies for cavitating flow in nozzle holes, which had various sizes, geometries and hole number. Badock et al. [3] demonstrated the growth of cavitation bubbles by high-speed photographs. These studies showed that cavitation could occur at the hole for certain flow conditions, and is beneficial in improving of atomization. However little quantitative information about atomization with cavitation in the nozzle hole has been obtained.

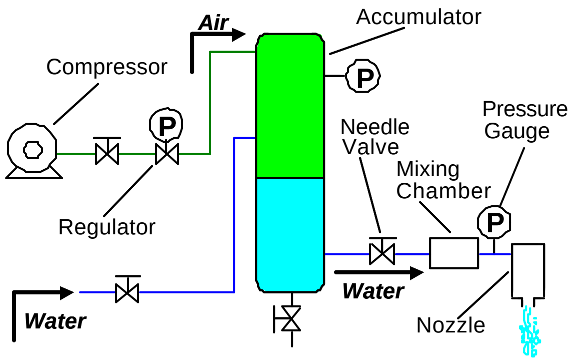


Fig. 1 Schematic of the injection system.

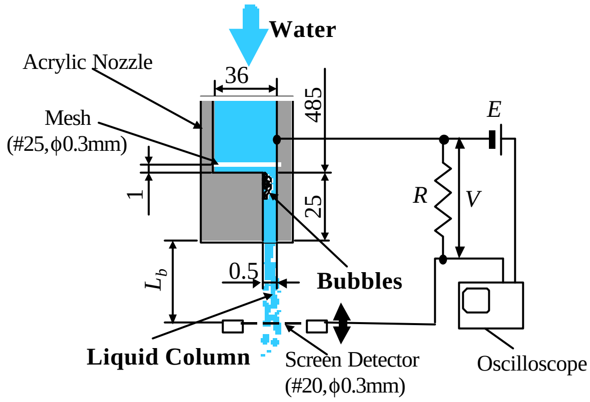


Fig. 2 Schematic diagram of the 2-D hole nozzle and the measuring system of a breakup length of a liquid column.

The vibration accelerations associated with disturbances in a nozzle hole were measured by a piezoelectric type acceleration transducer [4] and a piezoelectric type ultrasonic type transducer [8] which were mounted on the nozzle body. Moreover Tamaki et al. [4] demonstrated that atomization was promoted by a wire mesh installed on the entrance of the hole to disturb the cavitating flow. Nishida et al. [8] measured impedance across the internal cavitating flow by installing a pair of electric wires onto both sides of the nozzle hole wall.

Flow velocity with cavitation bubbles, which were yielded in nozzle holes, was measured by He and Ruiz [9] and Walther et al [10]. He and Ruiz [9] used a laser Doppler anemometry to obtain a spatial distribution of flow velocity around a sheet cavitation inside of 2-dimensional orifice. Walther et al. [10] measured flow velocity in an real size and visible diesel nozzle by the PIV (particle image velocimetry) measurement. However relation between a flow field and cavitation bubbles has not been cleared because flow is very complicated by fluctuation of cavitation bubbles. Disturbance and spatial change in velocity profiles due to the cavitation bubbles must occur inside a nozzle hole, hence the flow structure must have important influences on turbulence of internal liquid flow at exits of nozzle and primary breakup.

Our previous study [11] described the specially installed PTV (Particle Tracking Velocimetry) imaging system to investigate the cavitating flow inside of the slot type 2-D (2 dimensional) hole nozzle, and demonstrated spark photographs of cavitation bubble, which have been obtained at the same time as the PTV particles images. Moreover effects of tracer particles, which are suspended in ejecting liquid, on the breakup length of the liquid column and the exit velocity of the nozzle were examined for the PTV measurement. Thus it is noted that the tracer particles do not affect the breakup length and the exit velocity.

Main objective of this work is to elucidate the influence of flow structure with cavitation inside a hole on primary breakup. With this objective, detailed velocity profiles of an internal cavitating flow, which are obtained by means of the PTV system for the 2-D nozzle, is revealed, and spark photographs of cavitation bubbles are demonstrated. Spark photographs of liquid jet and the breakup length are presented to evaluate the atomization. In addition, the influence of disturbance, which is induced just upstream the hole entrance by means of mounting a turbulent mesh, on velocity profiles inside the hole is investigated to discuss the structure of the internal cavitating flow and the liquid atomization.

2. Apparatus

Figure 1 shows the experimental setup for the present study. An accumulator containing water, which was employed as the test liquid, was pressurized by air. The air was supplied by a compressor and was controlled by a regulator at a fixed pressure. The liquid from an accumulator was introduced steadily into our test nozzle as shown in Fig. 2 through a needle valve and Bourdon-type pressure gauge which were used to control the flow rate of the liquid. Finally, the liquid was ejected downward the atmospheric quiescent air.

The single side cavitation region in the slot type 2-D hole nozzle is depicted in Fig. 2. The 2-D nozzle was a transparent acrylic resin one. The nozzle hole had a gap thickness of 0.5 mm, a length of 25 mm and a width of 5 mm. Although the pre-nozzle region, which is defined as the upstream region of the nozzle hole, had the same width as the hole, thickness of the pre-nozzle region is 36 mm. The directions are defined as follows: the direction from the hole entrance to exit is stream-wise direction x; across the width direction of the hole is called width-wise direction y; across the gap direction of the hole is gap-wise direction z.

The attachment turbulence mesh could be mounted 1 mm upstream of the hole entrance to discuss the influence on cavitation and atomization. The mesh consisted of 25 stainless wires every inch, which had diameters of 0.3 mm. For the PTV measurements water was seeded with rhodamine F3B coated polystyrene particles as tracers. The tracers were introduced through a mixing chamber between the needle valve and the nozzle.

The breakup length of the liquid column, which was the continuous part from nozzle exit, was measured by the electrical resistance method, which was similar to that used by Shimizu et al. [12], as shown in Fig. 2. The measuring system consisted of a mesh-type (#30mesh, and wire diameter of 0.3mm) electrical conductive detector, a resistor and a DC power supply. The mesh-type conductivity detector was moved along a one-dimensional traverse. Voltage across a resistor was monitored by an oscilloscope to find the breakup point. Thus the breakup length of the liquid column was defined as the distance from the nozzle exit to the breakup point.

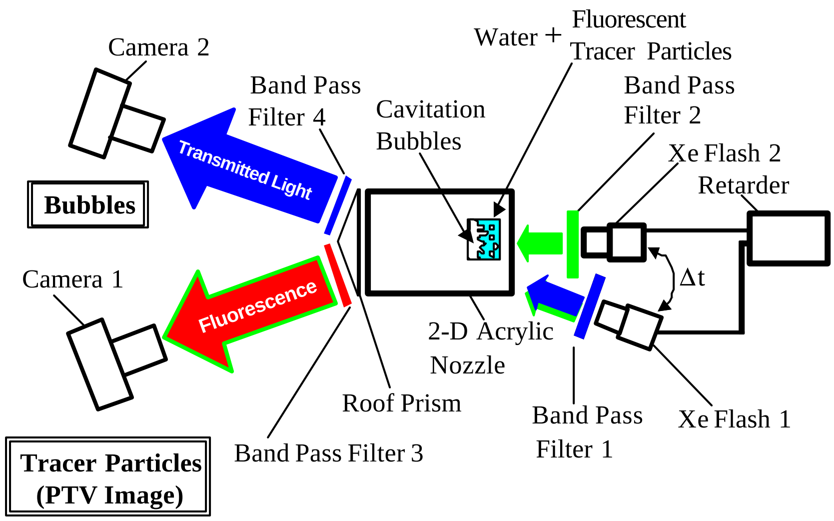


Fig. 3 Schematic diagram of the photographic system for images of PTV tracers and cavitation bubbles.

Figure 3 demonstrates a schematic diagram of the photographic system for images of PTV tracers and cavitation bubbles inside the nozzle hole [11]. The system consisted of two Xe flashes, a retarder, four band pass filters, a roof-shaped prism and two steel cameras. Two Xe flashes 1 and 2 were used to provide 2 μs flash durations. Time delay between the pulses of the Xe flashes 1 and 2 could be arbitrary varied from 1 μs to 1s by the retarder. Therefore a shadow image of the bubbles and a fluorescent image of tracers are separately obtain.

To obtain an instantaneous shape of liquid jet, front-lit spark photographs were taken by a steel camera, which lay in the gap-wise direction. A Xe flash, which existed nearby the camera, was used to provide a 2 μs flash duration.

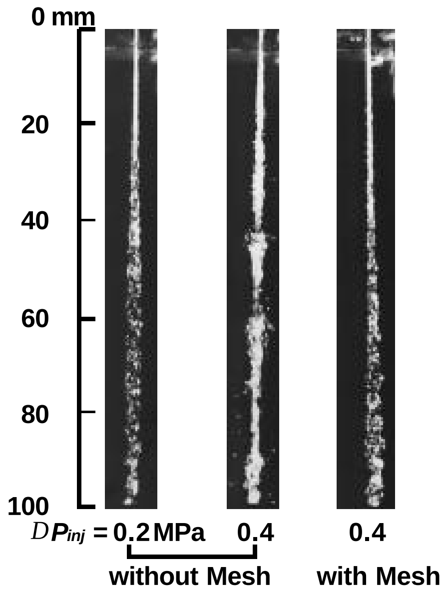


Fig. 4 Photographs of liquid jets.

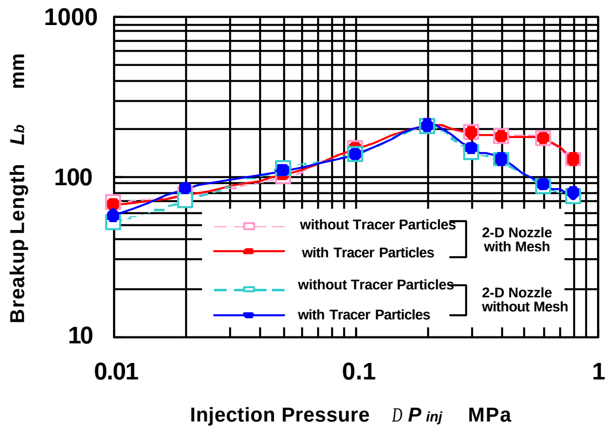
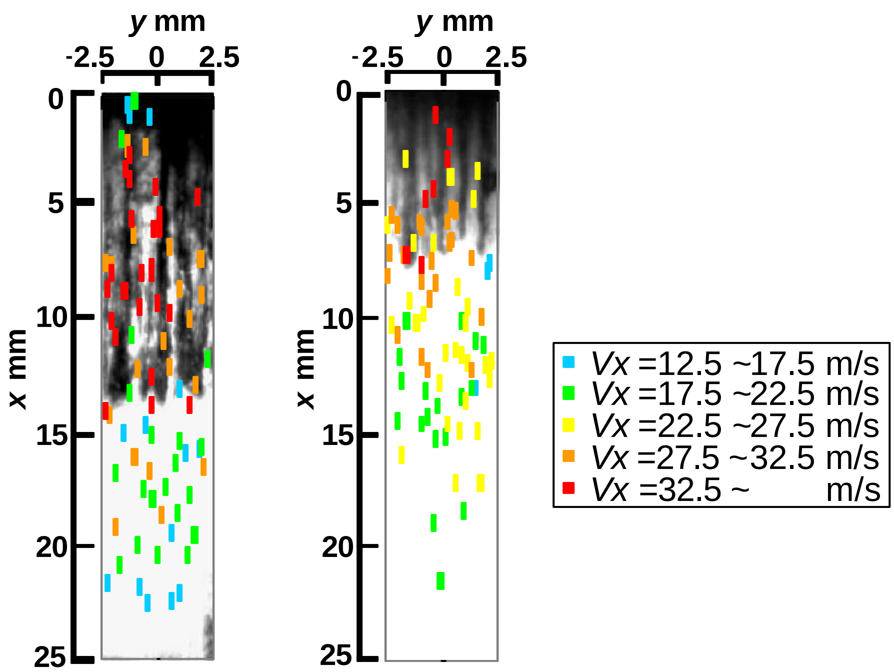


Fig. 5 Effects of injection pressure on breakup length.



without turbulent mesh with turbulent mesh

Fig. 6 Spark photographs of cavitation bubbles and distribution of the stream-wise velocity. (ΔP_{inj}=0.4MPa)

3. Results and Discussion

Figure 4 presents the photographs of liquid jets. There is the hole exit of the 2-D nozzle just above each photograph, and the step of hole entrance to produce cavitation bubble is located on the left-hand side of the nozzle. The turbulent liquid jets have ruffling surface at an injection pressure of 0.2MPa without the mesh condition. When the injection pressure is increased, distortions develop on the surface of the liquid column. Hence appearances of liquid columns suggest the "turbulent regime". At an injection pressure of 0.4MPa without the mesh condition, surface disturbance becomes more pronounced. Furthermore ligaments are yielded, and there exist many drops around the liquid column. Thus appearances of liquid columns suggest the "spray regime". At the injection pressure of 0.4MPa, the liquid jet in the case with the turbulent mesh has similar appearance to that in the case without the turbulent mesh. However surface disturbances is diminished owing to the turbulent mesh.

Figure 5 illustrates the effects of injection pressure on the breakup length of liquid column. In the case without turbulent mesh, the 2-D nozzle exhibits a conventional stability curve as explained follows. The breakup length increases with injection pressure up to 0.2MPa, as the transitions of the liquid jet from the "turbulent regime" to the "spray regime". Thereafter, the breakup length decreases. Although the breakup length of the liquid column shows similar trends with and without mesh condition, the value of the breakup length markedly increases by mounting the mesh.

Figure 6 indicates that "sheet cavitation bubbles", which are produced inside the nozzle hole, and distributions of the stream-wise velocity in the case without and with the turbulent mesh at the injection pressure of 0.4 MPa. However relatively large spherical bubbles, "traveling cavitation bubbles", and small bubbles, "cloud cavitation bubbles", can not be observed in both photographs. Cavitation region of each photograph begins at the entrance corner, i.e. the leading edge of the bubble is located at the entrance.

Disturbance is visible on the surface of the bubble except for regions near the entrance in each case. The trailing edge of the bubble is located at a stream-wise distance of about x=13 mm from the entrance in the case without the turbulent mesh. On the other hand, the trailing edge is located at a stream-wise distance of about 7 mm in the case with the turbulent mesh, so that the turbulent mesh diminishes the length of the bubble. Furthermore width of each bubble is reduced and number of finger-like bubbles is increased. This seems to indicate that large bubbles in the case without the turbulent mesh may be divided into slender bubbles.

Although a vector diagram of velocity fields can be obtained by means of a PTV analysis, axial components of all velocity vectors show significantly larger values than latitude components. As a result, clear flow structure can hardly appear on the vector diagram. Figures 7, 8 and 9 are obtained from the distributed velocity data as shown in Fig. 6.

The stream-wise velocity increases strongly with stream-wise distance, therefore the maximum stream-wise velocity of about 30 m/s are archived until a stream-wise distance of 4 mm as illustrated in Fig. 7. And then the stream-wise velocity relatively reaches constant up to about 10 mm. The flow is decelerated from about 30 m/s to 20 m/s at the distance of 13 mm where there exists the trailing edge of the bubble as shown in the left photograph of Fig. 6. Further downstream, the stream-wise velocity approaches constant until the exit of the nozzle hole while variation of the stream-wise velocity is suppressed.

In comparison with the case without the turbulent mesh, an increase of the stream-wise velocity can not be determined crealy and there is a strong variation of the velocity near the hole entrance in the case with the turbulent mesh. Variation of the stream-wise velocity is very large especially at the location above x=7 mm, where there exist the trailing edge of the bubble. Further downstream the velocity and its variation decrease.

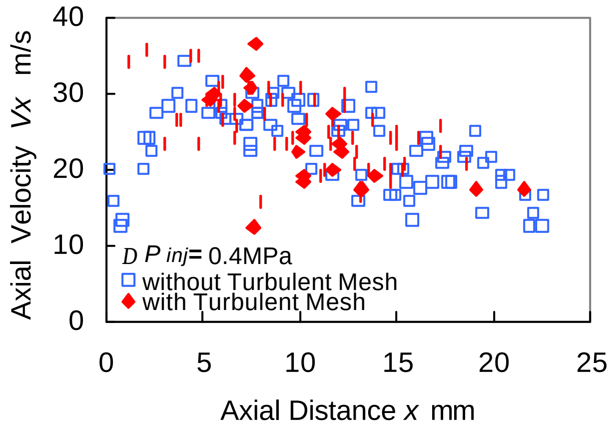


Fig. 7 Axial distributions of stream-wise velocity in cavitating flows inside the nozzle hole. (ΔP_{inj}=0.4MPa)

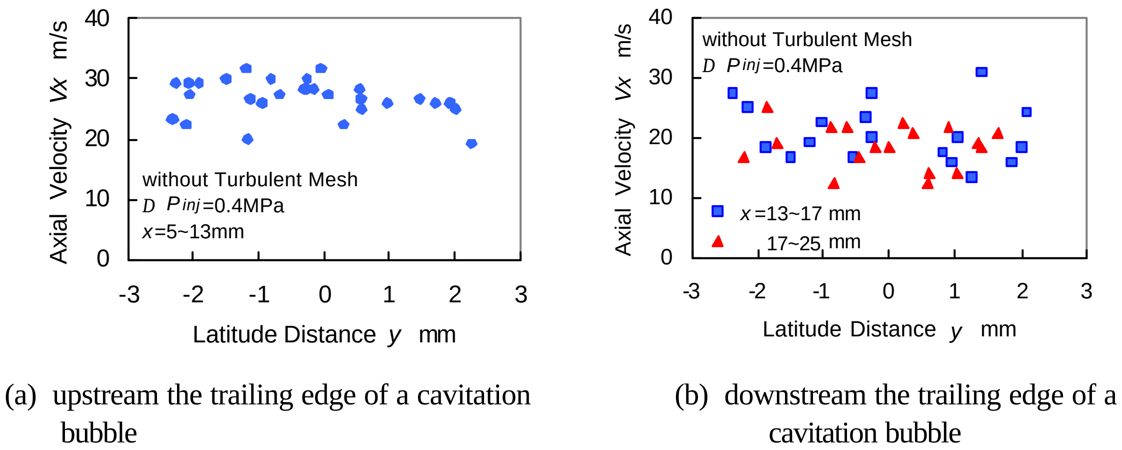


Fig. 8 Latitude distributions of stream-wise velocity in cavitating flows inside the nozzle hole. (the case without the turbulent mesh, ΔP_{inj}=0.4 MPa)

Figure 8(a) shows a latitude distribution of the stream-wise velocity near the trailing edge of the cavitation bubbles in the case without the turbulent mesh. The stream-wise velocity is almost uniform, V_x= 27 m/s, except for the both side near the walls of the hole (x=-2.5 mm and 2.5 mm). However there exist relatively large variations in the velocity around latitude locations of –0.8 and 0.5 mm, that are the regions between the “fingers”. Consequently, the liquid may move slowly between “fingers” rather than between the bubble and the opposite wall of the hole.

Figure 9 reports a latitude distribution of the stream-wise velocity near the trailing edge of the cavitation bubbles in the case with the turbulent mesh. There are frequent variations of velocities throughout latitude location, because it seems that the large “fingers” in the case without the mesh (left photographs of Fig. 6) may be divided into the slender “fingers” due to mounting the mesh (right photographs of Fig. 6).

In contrast to the profile as shown in Fig. 10(a), random variations of the stream-wise velocity appear at axial locations below the bubble as depicted in Fig. 10(b), i.e. the latitude profile below the trailing edge hardly resembles that above that. Therefore it is noted that a sheet cavitation, which has a “finger-like” structure, exhibits different latitude profiles.

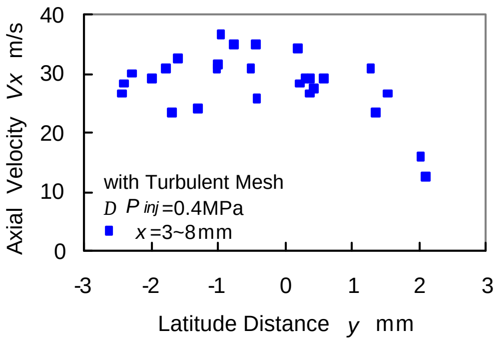


Fig. 9 Latitude distributions of stream-wise velocity upstream the trailing edge of a cavitation bubble inside the nozzle hole. (the case with the turbulent mesh, ΔP_{inj}=0.4 MPa)

The change in velocity profile, relaxation, may occur around the trailing edge of the cavitation bubble. The flow emerged between "fingers" and the reattachment flow just downstream the trailing edge must improve disturbance of the liquid flow, so the disturbance may induce the bubble instability. Moreover surface disturbance on the bubble promotes the flow disturbance. On the other hand, there is reduction of disturbance below the bubble corresponding to the distance between the edge and the hole exit. Finally the exit disturbance causes the liquid column to disintegration.

4. Conclusions

Information of bubble structures and spatial velocity distributions have been obtained for cavitating flows inside a slot type 2-D nozzle, which has a cross section of 5 mm x 0.5 mm, using a specially installed PTV (Particle Tracer Velocimetry) system. Therefore a spatial velocity distribution of inside liquid flow and a spark photograph of cavitation bubbles were obtained at the same time in each test. The breakup length was measured to evaluate the atomization. Moreover effect of the turbulent mesh, which was mounted just upstream the hole entrance, has been demonstrated experimentally.

A bubble of the sheet cavitation, which has the "finger-like" structure, is yielded since this study is mainly carried out at a relatively low injection pressure. Near the hole entrance, the stream-wise velocity increases with stream-wise distance, and then the stream-wise velocity approaches constant up to the trailing edge of the cavitation bubble. However the flow is decelerated around the edge of the bubble, therefore the stream-wise velocity reaches constant again where there dose not exists the bubble until the exit of the nozzle hole. Spatial variation of the stream-wise velocity decreases downstream the bubble, while the maximum variation appears near the edge of the bubble.

A sheet cavitation exhibits different latitude profiles of the stream-wise velocity, which appears just upstream and downstream the trailing edge of the cavitation bubble. In comparison with the case without the turbulent mesh, there are frequent variations of velocities throughout width-wise location, because the width of each bubble is reduced and number of finger-like bubbles is increased due to mounting the turbulent mesh. Along the width-wise direction, the stream-wise velocity is almost uniform just upstream the trailing edge of the cavitation bubble. However there exist relatively large variations in the velocity around latitude locations between the "fingers". In contrast to the profile just upstream the trailing edge, random variation of the stream-wise velocity appears below the cavitation bubble.

Nomenclature

L_b Breakup length
V Liquid velocity
x Stream-wise distance, axial distance, from the entrance of the nozzle hole
y Width-wise distance, latitude distance, from the centerline of the nozzle hole
z Gap-wise distance from the centerline of the nozzle hole
ΔP_{inj} Injection pressure

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