# SPATIAL VELOCITY MEASUREMENT OF INTERNAL CAVITATING FLOW AND CHARACTERISTICS OF LIQUID JET ATOMIZATION OF 2-D HOLE NOZZLE

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## Abstract

Information of instantaneous bubble structures and spatial velocity distributions is obtained for cavitating flows inside a 2-D (2 dimensional) transparent hole nozzle using a specially installed PTV (Particle Tracking Velocimetry) system. The influence of cavitation bubble on breakup of liquid column and the internal cavitating flow inside the nozzle hole are examined. Moreover effects of the turbulent mesh, which is mounted just upstream of the hole entrance, are discussed. Effects of tracer particles, which are suspended in ejecting liquid, on breakup length of the liquid jets are examined for PTV measurement. Thus it is noted that the tracer particles do not affect the breakup length. The liquid flow in the nozzle hole is decelerated where there exists the edge of the bubble at a relatively low injection pressure. The stream-wise velocity remains almost constant if there exists the edge of the bubble near the exit of the hole at relatively high injection pressure without mesh condition. However the spatial fluctuation of the velocity increases with stream-wise distance. In contrast to the non-mesh condition, the nozzle with the mesh shows that the stream-wise velocity slightly decreases with stream-wise distance. The mesh reduces average value and fluctuating value of stream-wise velocity while a cavitation bubble is yielded inside the hole, so that atomization is restrained.

### Introduction

The performance of direct injection diesel engines is strongly influenced by atomization process of fuel, and information of internal flow velocity with cavitation of the hole type nozzle is very important for predict the atomization of diesel sprays. Furthermore experimental data is very significant for computer simulations. For instance, Ruiz et al. [1] showed 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 the flow pattern in the nozzle hole [2-8]. Soteriou et al. [2] performed studies for cavitating flow in nozzle holes, which had various sizes, geometries and hole number. Badock et al. [3] showed 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 the atomization with cavitation in the nozzle hole has been obtained.



Figure 1. Schematic of the injection system.

Figure 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 the nozzle hole were measured by a piezoelectric type acceleration transducer [4] and a piezoelectric type ultrasonic type transducer [9] 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 nozzle hole to disturb the cavitating flow. Nishida et al. [9] measured the 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 [10] and Walther et al [11]. He and Ruiz [10] used a laser Doppler anemometry to obtain a spatial distribution of flow velocity around a fixed cavitation inside of 2-dimensional orifice. Walther et al. [11] measured flow velocity in an original scale diesel nozzle by the particle image velocimetry. However relation between a flow field and cavitation bubbles have not been cleared because flow is very complicated by fluctuation of cavitation bubbles.

The following work will describe an experimental study of the slot type 2-D (2 dimensional) hole nozzle. Specially installed PTV imaging system will be used to investigate the cavitating flow inside of the nozzle hole, so that the effects of cavitating flow on atomization may be clarified quantitatively. Spark photographs of cavitation bubble, which will be obtained at the same time as the PTV (Particle Tracking Velocimetry) images, will be demonstrated. Evaluation of the breakup length of the liquid column and the instantaneous shape of liquid jet will be demonstrated. Additionally the effects of tracer particles for PTV measurement will be examined by evaluating jet atomization. Finally the influence of the turbulent mesh, which will be mounted upstream of the hole entrance, to disturb a cavitating flow will be discussed.

#### **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 pressure regulator. 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 into quiescent air under atmospheric conditions.

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 whole 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 tracer particles, which had diameters of 75-150  $\mu$ m and specific gravity of 1.01. The particles were introduced through a mixing chamber between the needle valve and the nozzle. The PTV measurements were carried out at the particles concentrations of approximately 6 g/l. The value of the concentration contains some error.

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 of the breakup length 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, so that a breakup point was defined as the position downstream at which the liquid jet was discontinuous 50 % of the time (i.e., a current could be passed between the nozzle and this position for 50% of the time). Thus the breakup length of the liquid column was defined as the distance from the nozzle exit to the breakup point.

Figure 3 demonstrates the schematic diagram of the photographic system for images of PTV tracers and cavitation bubbles inside the nozzle hole. The system was used to separately obtain a scattering image of the bubbles and a fluorescent image of tracer particles as follows. The system consisted of two Xe flashes, a retarder, four band pass filters and two steel cameras. The system used pulsed illumination to record images on 35 mm filmes: two Xe flashes 1 and 2 as white-light sources for front-view imaging. The Xe flashes were used to provide a 2  $\mu$ s flash duration. The illumination axis of Xe flash 2 lay in the gap-wise direction to obtain a shadow image of cavitating bubbles while that of Xe flash 1 lay nearly in the gap-wise direction. The time delay between the pulses of Xe flashes 1 and 2 could be arbitrary varied from 1  $\mu$ s to 1s by the retarder.

Light from the Xe flash 1 passed through the band pass filter 1, which had the wavelength range between about 380nm and 560nm. The rhodamine F3B, which was painted on the tracer particles, absorbed light in the wavelength region between about 490nm and 550nm, so that the tracer particles emits fluorescence in the wavelength region between about 570nm and 670nm. Another part of light, which passed through the band pass filter 1 and had the wavelength range between about 380 nm and 490 nm, was scattered by particles. The

fluorescent and scattered light passed through roof purism. In the passage of fluorescent light, the band pass filter 3 was located to eliminate any scattered light by the bubbles and the tracer particles. In the scattered light passage, the band pass filter 4, which had the wavelength range between about 320 nm and 420 nm, was put to prevent transmission of fluorescent light. However the intensity of the tracer particles was low compared with that of the bubbles. Thus the image of fluorescence by the tracer particles and that of scattering by the bubbles were captured by the camera 1 and 2, respectively.

Delayed light from the Xe flash 2 passed through the band pass filter 2, which had the wavelength range between about 500nm and 560nm. The light through the band pass filter 2 was absorbed by the particles while the light could not be scattered. The tracer particles emitted fluorescence, so that the fluorescent light was captured by the camera 1. Therefore a double pulsed PTV image of the fluorescent particles and a instantaneous image of cavitation bubbles were obtained by the system.



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



Figure 4. Photographic system of liquid jets.

Figure 5. Photographs of liquid jets.



Figure 6. Effects of tracer particles on breakup length. Figure 7. Spark photographs of cavitation bubbles.

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, as shown in Fig. 4. A Xe flash, which existed nearby the camera, was used to provide a 2  $\mu$ s flash duration.

#### **Results and Discussion**

Figure 5 presents the photographs of liquid jets. There is the 2-D nozzle above each photograph, and the step side of the nozzles is left of each photograph. 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. At an injection pressure of 0.8MPa without the mesh condition, surface disturbance becomes more pronounced. Furthermore many ligaments are yielded, and there exist many drops around the liquid column. Thus the liquid jet becomes a spray. Appearances of liquid columns obtained by many photographs similar to Fig. 5 suggest two breakup regimes in our investigation: one is called "the turbulent regime" and another is called "the spray regime". At the injection pressure of 0.8MPa, the liquid jet with the mesh condition has similar appearance to that without the mesh condition. However surface disturbances seems to diminish by the mesh.

Figure 6 illustrates the effects of tracer particles on the breakup length of liquid column. The 2-D nozzle without mesh condition exhibits a conventional stability curve as explained follows. The breakup length increases with injection pressure up to 0.02MPa, as the transitions of the liquid jet from the turbulent 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. It is noted that tracer particles hardly influence the values of the breakup length both with and without mesh condition; i.e., breakup of liquid column is not affected by tracer particles. Therefore the tracer particles may not influence cavitation in our investigation.

Figure 7 shows photographs of cavitation bubbles. All cavitation regions begin at the entrance corner. Darkness of each surface is similar near the entrance of the hole because the liquid-vapor interfaces have smooth surfaces. However disturbances are visible on the surfaces except for regions near the entrance. A finger-like segmented structure is apparent at the injection pressure of 0.4 MPa. An edge of the bubble is located at a stream-wise distance of about x=13 mm from the entrance. At the injection pressure of 0.8 MPa, cavitation bubbles extend near the hole exit both with and without mesh condition.

Figure 8 demonstrates results of PTV measurement at the same time as each photograph depicted in Fig. 7. The tendency of stream-wise liquid velocity at each width-wise location can not appeared. The stream-wise velocity of about 30 m/s are archived until a stream-wise distance of x=13 mm as illustrated in Fig. 8a. The flow is decelerated from about 30 m/s to 20 m/s at the distance of 13 mm where there exists the edge of the bubble as

shown in the left fhotograph of Fig. 7, and then after the stream-wise velocity approaches constant until the exit of the nozzle hole.

As illustrated in Figure 8b, the stream-wise velocity remains almost constant because there exists the edge of the bubble near the exit at injection pressure of 0.8 MPa without mesh condition (Middle photograph of Figure 7). Moreover the thickness of the bubble may be kept constant independently on the stream-wise location. However the spatial fluctuation of the velocity increases with the stream-wise distance.

In contrast to the non-mesh condition, the nozzle with the mesh shows that the stream-wise velocity slightly decreases with increasing stream-wise distance as depicted in Fig. 8c. Average value and fluctuating value of stream-wise velocity are reduced by the mesh while a cavitation bubble is yielded inside the hole, so that atomization is restrained by the mounted mesh, in contrary to the results of Tamaki et al [4].



(a)  $\Delta P_{inj}=0.4$  MPa, without mesh condition.



(c)  $\Delta P_{inj}=0.8$  MPa, with mesh condition.

Figure 8. Spatial distributions of stream-wise velocity in cavitating flows inside of the nozzle hole.



Figure 9. Effect of the mesh, which was mounted 1 mm upstream of the hole entrance, on stream-wise velocity near the hole exit.

Figure 9 shows the effect of the mesh, which was mounted upstream of the hole entrance, on the flow velocity near the hole exit (x=20-25 mm). The stream-wise velocity obtained by PTV measurement agrees with average



(b)  $\Delta P_{ini}=0.8$  MPa, without mesh condition.

velocity estimated from the flow rate and the cross section of the hole. It seems that the mesh diminishes the velocity fluctuation similar to the average value of the flow velocity.

## 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, so that the influence of cavitation bubble on breakup of liquid column and the internal cavitating flow inside the nozzle hole have been discussed. Moreover effect of the turbulent mesh, which was mounted 1 mm upstream of the hole entrance, has been demonstrated experimentally. The effect of tracer particles, which were suspended in ejecting liquid, on breakup length of the liquid jets has been examined.

1. Tracer particles hardly influence the values of the breakup length both with and without mesh condition; i.e., the tracer particles do not affect the breakup of liquid column in our investigation.

2. The liquid flow in the nozzle hole is decelerated where there exists an edge of a cavitation bubble at a relatively low injection pressure without mesh condition.

3. The stream-wise velocity remains almost constant if there exists an edge of a bubble near the hole exit at relatively high injection pressure without mesh condition. However spatial fluctuation of the stream-wise velocity increases with a stream-wise distance.

4. In contrast to the non-mesh condition, the nozzle with the mesh shows that the stream-wise velocity slightly decreases with the stream-wise distance. Average value and fluctuating value of flow velocity are reduced by the mounted mesh while a cavitation bubble is yielded inside the hole, so that atomization is restrained.

## Nomenclature

- *L<sub>b</sub>* Breakup length
- $L_h$  Thickness of the heater plate
- V Liquid velocity
- *x* Stream-wise distance from the entrance of the nozzle hole
- y Width-wise distance from the centreline of the nozzle hole
- *z* Gap-wise distance from the centreline of the nozzle hole
- $\Delta P_{inj}$  Injection pressure

## References

- [1] F. Ruiz and N. Chigier, "The mechanics of high speed cavitation", *3rd International Conference on Liquid Atomization and Spray Systems*, 1985, pp. VIB/3/1-15.
- [2] C. Soteriou, R. Andrew and M. Smith, "Direct injection diesel sprays and effect of cavitation and hydraulic flip on atomization", *SAE paper 950080*, (1995).
- [3] C. Badock, R. Wirth, S. Kampmann and C. Tropea, "Fundamental study of the influence of cavitation on the internal flow and atomization of diesel sprays", *Annual Conference on Liquid Atomization and Spray Systems-Europe 97*, 1997, pp.53-59.
- [4] N. Tamaki, K. Nishida, H. Hiroyasu, and M. Shimizu, "Effects of the internal flow in a nozzle hole on the breakup processes of a liquid jet", 7th International Conference on Liquid Atomization and Spray Systems, 1, 1997, pp.417-424.
- [5] M.E. Henry and S.H. Collicott, "Visualization of internal flow in a cavitating slot orifice", *Atomization and Sprays*, 10-6, 545-563, (2000).
- [6] Z. Huang, Y.M. Shao, S. Shiga, H. Nakamura and T. Karasawa, "The role of orifice flow pattern in fuel atomization", *6th International Conference on Liquid Atomization and Spray Systems*, 1994, pp.86-93.
- [7] M. Arai, M. Shimizu and H. Hiroyasu, "Break-up length and spray formation mechanism of a high speed liquid jet", *4th International Conference on Liquid Atomization and Spray Systems*, 1988, pp.177-184.
- [8] C. Arcoumanis and M. Gavaises, "Cavitation in Diesel Injectors: Modeling and Experiments", Annual Conference on Liquid Atomization and Spray Systems-Europe 98, 1988, pp.6-8.
- [9] K. Nishida, S. Ceccio, D. Assanis, N. Tamaki and H. Hiroyasu, "Effects of the internal flow in a nozzle hole on the breakup processes of a liquid jet", *7th International Conference on Liquid Atomization and Spray Systems*, 1, 1997, pp.417-424.
- [10] L. He and F. Ruiz, Effect of cavitation on flow and turburence in plain orifices for high-speed atomization, *Atomization and Sprays*, 5-6, pp.569-584, (1995).
- [11] J. Walther, J.K. Schaller, R. Wirth and C. Tropea, "Investigation of internal flow in transparent diesel injection nozzles using fluorescent particle image verocimetry (FPIV)", 8th International Conference on Liquid Atomization and Spray Systems, 2000, pp.300-307.
- [12] M. Simizu, M. Arai and H. Hiroyasu, "Measurement of break-up length of high speed liquid jet", *Trans. of the Japan Society of Mechanical Engineers*, Ser. B, 49-448, pp.2886-2892, (1983). (in Japanese)