Atomization Characteristics of Multi-Hole Swirl Injectors for Direct Injection Engines
- Observation of Spray Behavior and Calculation of Injector Internal Flow -

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The new concept for a multi-hole swirl injector, the swirl groove injector, was proposed to improve the fuel spray pattern and its atomization process in a direct injection (D. I.) engine. The spray characteristics and internal flows in multi-hole swirl groove injectors for direct injection engines was studied experimentally and numerically. The experiments were carried out by using 10-times-large acrylic model injectors. The spray characteristics of the standard min sac injector and the swirl groove injectors were observed. Experimental results show that compared with the mini sac injector, the swirl groove injectors enlarge the spray angle and reduce the Sauter mean diameter. The effects of the injector hole configurations on the spray was also investigated. The swirl groove injector with converging holes performs best in terms of the spray angle and the Sauter mean diameter. The injector internal flows were investigated by the three-dimensional simulation. By analyzing the velocity distributions in the injector holes, it was found that the swirl motion of the internal flow is generated by the special design of the swirl groove inside the injector. The best performance in terms of the spray angle and the Sauter mean diameter of the swirl groove injector with converging holes is laid on the facts that this design can generate the largest tangential/ axial velocity component ratio of the swirling flow at the exit of the injector holes.

1. Introduction

For a direct injection engine, the fuel spray pattern and its atomization process have profound influence on fuel efficiency and pollutant emissions. In early researches, it was believed that the stability and the atomization of a jet are caused by the interfacial force between the liquid jet and surrounding air. [1-2] Based on recent investigations, it was found that spray performance is also greatly affected by the injector internal flow pattern. [3-9] Hence, the injector performance can be improved by modulating the injector internal flow, which can be obtained either by optimizing the standard injector structure or by introducing a new injector concept.

In this paper, the new injector concept for a multi-hole swirl injector, the swirl groove injector is introduced. Firstly, the model injectors are illustrated and the principle of the swirl groove injectors is explained. Then, the experimental results are discussed. To evaluate the spray performance of the new design, the spray characteristics of the standard mini sac injector is used as a baseline. The comparisons are made among the measured spray angles, the Sauter mean diameters and the discharge coefficients. The effect of the configuration of the injector hole is also discussed. With the

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aid of a computational fluid dynamics (CFD) software FIRE developed by AVL, the injector internal flow in different injectors are analyzed to obtain a better understanding of the experimental results.

2. Model Injectors Description

The new injector design introduced in this study is named as ‘swirl groove injector’, as a circular discharge hole is preceded by a chamber in which the swirl grooves are used to import a swirling motion to the liquid before it enters the discharge hole. There are three basic components to form a swirl groove injector. They are a needle, a swirl groove bar and a model body. Figure 1 illustrates how the internal flow process is inside a swirl groove injector. The swirl groove bar is fixed with model body. The needle moves up and down along the swirl groove bar to start and stop the injection. After needle begins to move upwards, the injection liquid flows through the swirl groove, the swirl chamber and the discharge hole. Then, it exits the injector and forms the spray plume.

The experiments were carried out by using 10-times-large acrylic model injectors. Four kinds of transparent acrylic model injectors were used. They are a mini sac injector with straight holes (Mini Sac/ Straight Holes), a swirl groove injector with straight holes (Swirl Groove/ Straight Holes), a swirl groove injector with converging holes (Swirl Groove/ Converging Holes) and a swirl groove injector with diverging holes (Swirl Groove/ Diverging holes). The geometries of the model injectors are shown in Fig. 2, which are based on the hole-type direct injection diesel injector geometry. The similarity between the actual diesel injector and the model injector is listed in Table 1. Water instead of fuel was used. The injection pressure was set at 0.3 MPa.

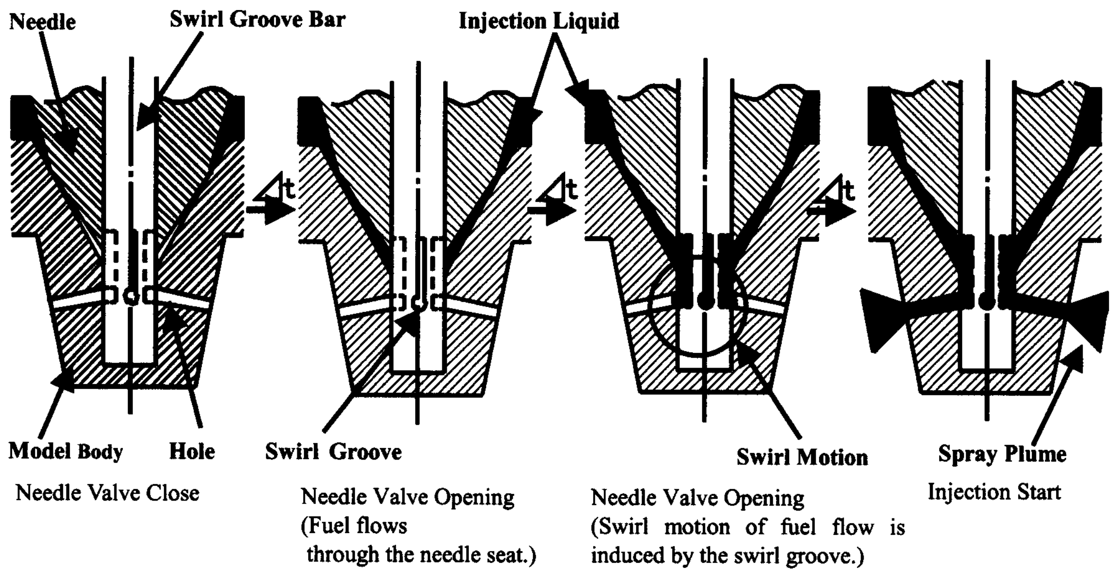

Fig. 1 Illustration of internal flow process in a swirl groove injector

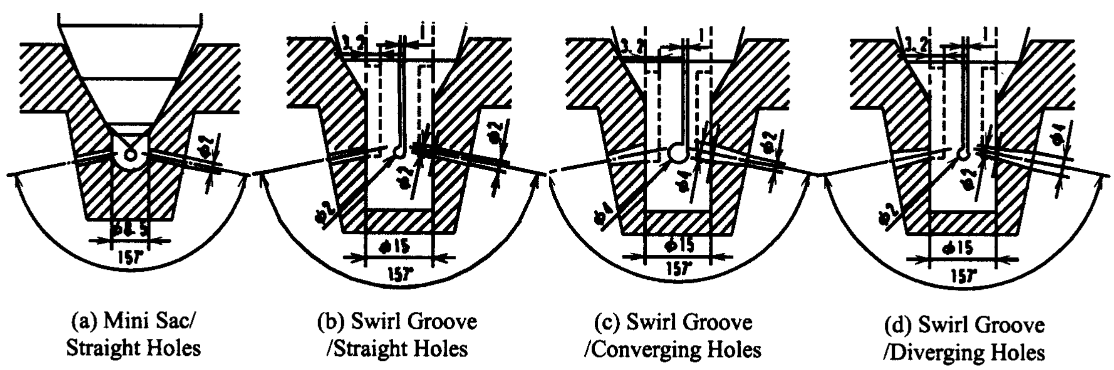

Fig. 2 Geometries of model injectors

Table 1 Experimental condition

	Diesel Injector	Model Injector
Hole Diameter d_n (mm)	0.2	2
Size Ratio	1	10
Injection Fluid	Diesel Fuel	Water
Density ρ_l (kg/m^3)	835	998
Kinematic Viscosity ν_l (m^2/s)	3.0×10^{-6}	1.004×10^{-6}
Differential Pressure of Injection P_l-P_a (MPa)	63.5～172	0.85～0.23
Injection Velocity V_l (m/s)	390～642	13.1～21.5
Reynolds Number Re*	$2.60\sim4.28\times10^4$	$2.60\sim4.28\times10^4$
Cavitation Number K**	1.001～1.003	1.43～2.18

$$Re^* = \frac{V_l d_h}{\nu_l}$$

$$K^{**} = \frac{P_l - P_v}{P_l - P_a}$$

P_l : Pressure in Upstream Chamber
P_v : Vapor Pressure (2.34KPa)
P_a : Ambient Pressure (0.1013MPa)

3. Experiment

Figure 3 shows a schematic diagram of the experimental apparatus. It consists of a water supply system, a model injector, an illumination system and a photographic system. Sequential photographs of the developing sprays were taken using a high speed video camera. The Sauter mean diameter was measured by the laser diffraction based droplet size analyzer at the position of 200 mm away from the discharge hole along the hole axis. The spray angle was obtained of all four model injectors, while the discharge coefficient and Sauter mean diameter of the mini sac/ straight holes, the swirl groove/ converging holes and the swirl groove/ diverging holes model injectors were measured.

3.1 Spray Angle

The spray angles of the spray the four model injectors were measured for different needle lifts under the steady state condition. The results are shown in Fig. 4. It was found that within all ranges of needle lifts, the spray angles of the swirl groove type injectors are larger than that of the mini sac injector. For a mini sac injector with straight holes, the spray angle tends to decrease with the increased needle lifts. However, there exists no such tendency for all three types of the swirl groove injectors, that is the spray angle remains to a constant value.

Among three swirl groove injectors, the model with converging holes has the largest spray angle (around 70 degrees), while the model with diverging holes has the smallest value (around 26 degrees). With the new design of the swirl groove injector with converging holes, the spray angles are widened almost three times compared with that of the mini sac injector. The wider the spray angle is, the larger the surface areas of the spray are. The spray with larger surface areas will evaporate faster. Therefore, the fuel-air mixing processes can be improved by the design of the swirl groove injector.

3.2 Sauter Mean Diameter

The Sauter mean diameters were also measured at three different needle lifts, 0.7 mm, 1 mm and 2 mm. The results are plotted in Fig. 5. Basically, the Sauter mean diameters of the mini sac injector are the largest among all the testing injectors. The exception exists where the needle lift is at 2 mm. At this needle lift, the Sauter mean diameter of the mini sac injector is a value similar to the swirl groove injector with diverging holes. Among the swirl groove injectors, the one with converging holes has the smaller Sauter mean diameter. The experimental results also show that, with the enlarged spray angles, the swirl groove injector generates the spray with the smaller Sauter mean diameter. Among three different designs, the swirl groove injector with converging holes produces the finest spray. The Sauter mean diameter is reduced dramatically comparing with that of the mini sac injector. Such a change is in coincidence with the spray angles.

3.3 Discharge Coefficient

The discharge coefficients of different model injectors are compared in Fig. 6. The mini sac injector has the highest value of the discharge coefficient. For the mini sac injector, the discharge coefficients increase gradually at all the needle lift ranges, while for the swirl groove type injectors, they increase only at the beginning of needle lifting and soon reach a constant. The discharge coefficient for the swirl groove injector with converging holes is 0.4 at a needle lift of 2 mm, which is 48 % smaller than the mini sac injector with straight holes. This is due to the complicated flow path structure of the swirl groove injectors.

According to the experimental results, it is concluded that among three different swirl groove injector designs, the swirl groove injector with converging holes performs the best in terms of the spray angle and the Sauter mean diameter.

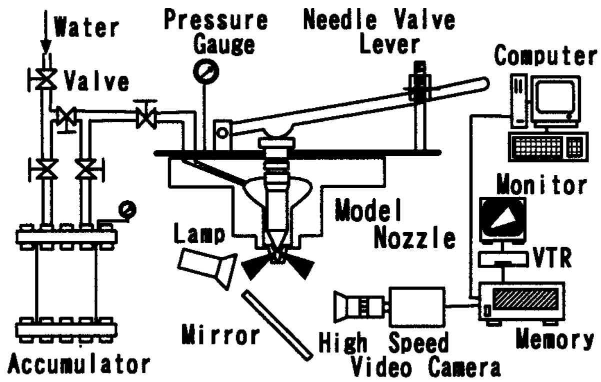

Fig. 3. Experimental apparatus

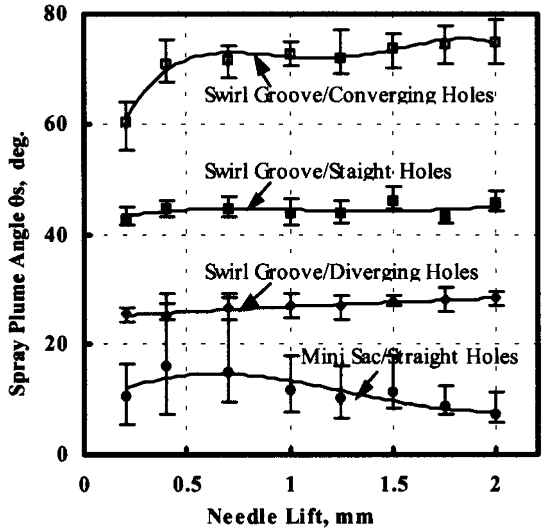

Fig. 4 Comparison of measured spray angles

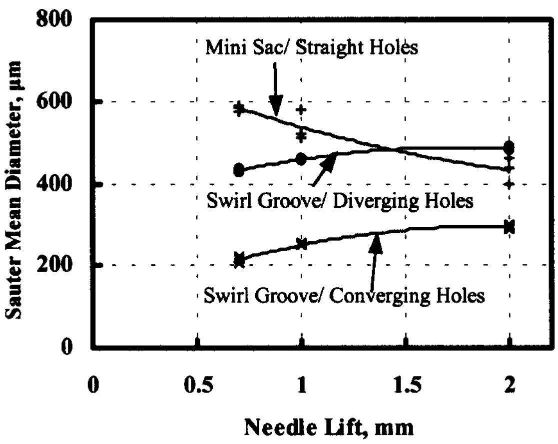

Fig. 5 Comparison of measured Sauter mean diameters

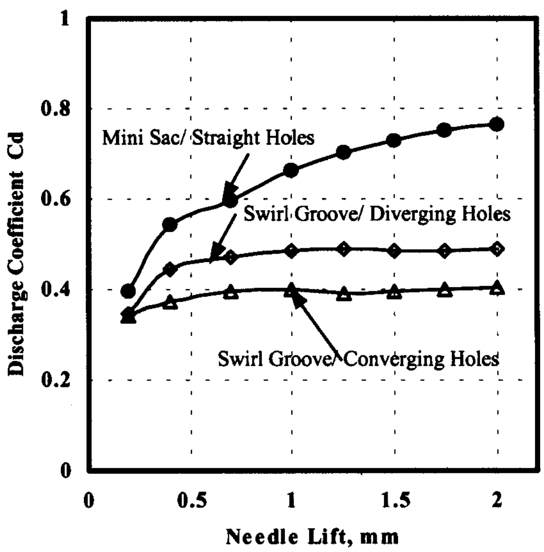

Fig. 6 Comparison of measured discharge coefficients

4. Three-Dimensional CFD Simulation of Internal Flow of Model Injectors

To obtain a better understanding of the injector design effects on the spray behaviors mentioned in the above section, the internal flows of the model injectors are then investigated by using a computational fluid dynamic (CFD) software, FIRE ver.7, released by AVL, Austria. In this study, computation was made on the injector internal flow at the full needle valve opening under the steady flow condition.

Computational meshes were generated according to the dimensions of the 10 times model injectors used in the experiments. The needle lift is 2 mm. As shown in Fig. 7, the calculated discharge coefficients agree with the measured ones well, which verifies the CFD software and the generated models at each case. More calculations were carried out to reveal how the flows occur is the real size injectors, which have the realistic discharge hole diameter in the engine application and the same geometries as the 10-times-large model injectors. The injection pressure was determined by remaining the same Reynolds number of the discharge hole flow as the 10-times model injectors. The needle lift is 0.2 mm. The calculated discharge coefficients are shown in Fig. 7. The values are very similar to the discharge coefficients of the corresponding 10-times-large model injectors.

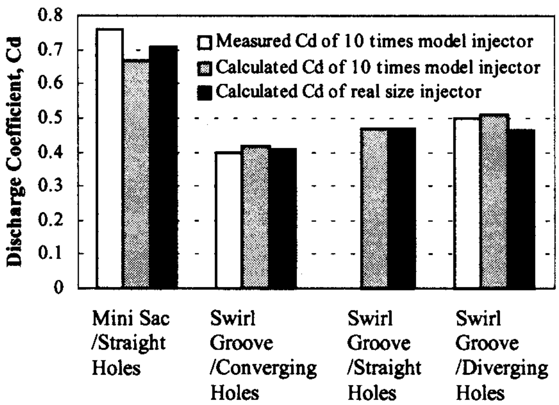

Fig. 7: Measured and calculated discharge coefficients

To understand how the different injector designs affect the spray behaviors, the three-dimensional internal flow details of the different 10-time-large model injectors, such as the velocity patterns and the pressure distributions, were obtained. In this paper, only the velocity pattern will be discussed. In Fig. 8, the calculated internal flow velocity pattern is plotted with the corresponding spray image obtained in the experiment. It is clearly seen that the flow pattern (or velocity distribution) at the injector hole exit has a very large influence on the spray pattern. All of the swirl groove models are able to generate the swirl motion before the injection liquid leaves the discharge hole. The swirl groove model with converging holes provides the strongest swirl, while the swirl groove model with diverging holes has the weakest one. The mini sac injector does not generate the swirl. The images of the steady sprays in the right show the consequent sprays of different model injectors. Due to the swirling motion before the liquid leaves the discharge hole, the liquid emerges from the swirl injectors as an annular sheet which spreads radially outward to form a hollow cone spray. The stronger the swirl generates, the wider the spray angle is.

The particle traces inside the injector holes were calculated, shown in Fig. 9. In the swirl groove injector with converging holes, the particle rotates more than two times inside the injector hole, while around one time in the swirl groove injector with straight holes and less than one time in the swirl groove injector with diverging holes.

From these velocity pattern analyses, the experimental results of the spray behavior can be understood as follows. The swirl motion of internal flow in the discharge hole is generated by the special design of the swirl groove geometry upstream of the discharge hole. The best performance of the swirl groove injector with converging holes is laid on the facts that this design generates the strongest swirl motion of the liquid before it exits injector holes.

The internal flow patterns and the particle traces were also drawn based on the calculation results of the real size injectors, which are not shown in this paper due to the page limitation. Comparison of the internal flow patterns for the real size injectors and the 10-times-large model injectors leads to the conclusion that flows in the discharge holes are very similar. Therefore, as the swirl motions are created in the real size swirl groove injectors, spray characteristics similar to the model injectors observed in the experiments supposedly can be obtained for the real size swirl groove injectors.

As shown in Fig. 5, the spray angle measured in the experiments is different among four model injectors. The calculated tangential / axial velocity component ratios of different model injectors are plotted together with the observed spray angles in Fig. 10. It clearly illustrates the relationship between them. The larger the ratio is, the wider the spray angle is.

5. Conclusions

The new concept for a multi-hole swirl injector, the swirl groove injector, was proposed to improve the fuel spray pattern and its atomization process in a direct injection (D. I.) engine. The spray characteristics and internal flows in multi-hole swirl groove injectors for direct injection engines was studied experimentally and numerically. The experiments were carried out by using 10-times-large acrylic model injectors. The spray characteristics of the standard min sac injector and the swirl groove injectors were observed. Experimental results show that compared with the mini sac injector, the swirl groove injectors enlarge the spray angle and reduce the Sauter mean diameter. The effects of the injector hole configurations on the spray was also investigated. The swirl groove injector with converging holes performs best in terms of the spray angle and the Sauter mean diameter. Both the injector internal flows for the 10-time-large model injectors and the real size injectors were investigated numerically with the aid of a computational fluid dynamics (CFD) software FIRE ver.7. It was found that the swirl motion of the internal flow is generated by the special design of the swirl groove inside the injector by analyzing the velocity distributions and the particle traces in the discharge holes. The best performance in terms of the spray angle and the Sauter mean diameter of the swirl groove injector with converging holes is laid on the facts that this design can generate the largest tangential/ axial velocity component ratio of the swirling flow at the exit of the injector holes.

Acknowledgement

The authors thank Mr. Oga, former student of University of Hiroshima and currently working in Nissan Motor Corp., for his efforts in the experiments. The authors would also like to express their sincere thanks to Ms. Fukumoto and Mr. Yamaguchi, together with all the other engineers in AVL Japan. The support from Japanese Science Promotion Society is highly appreciated as well.

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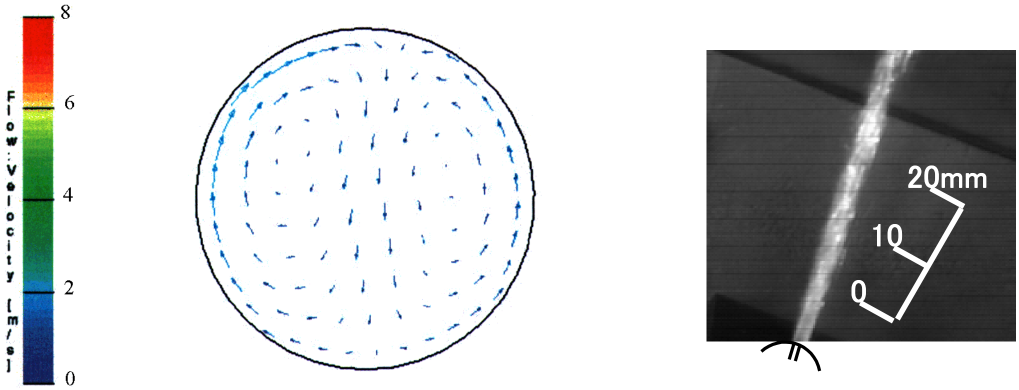
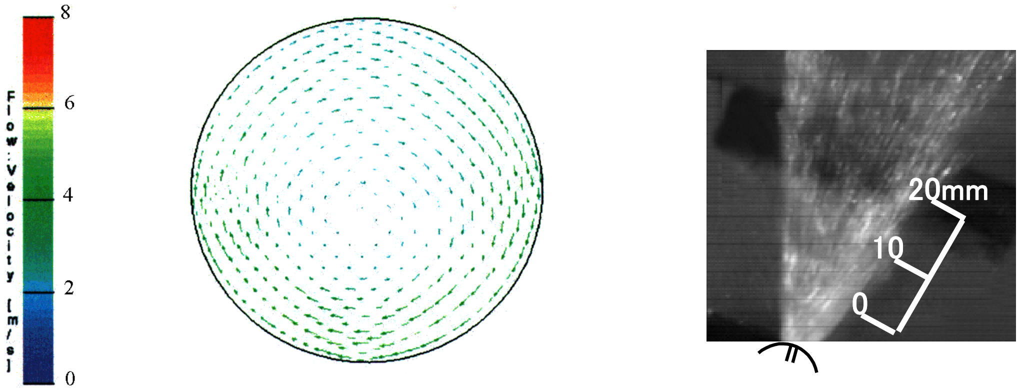
Calculated flow pattern at discharge hole exit

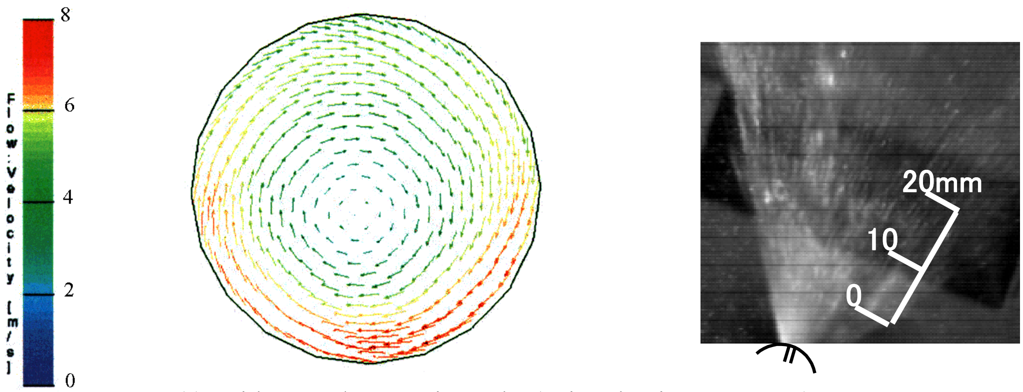
Observed Spray



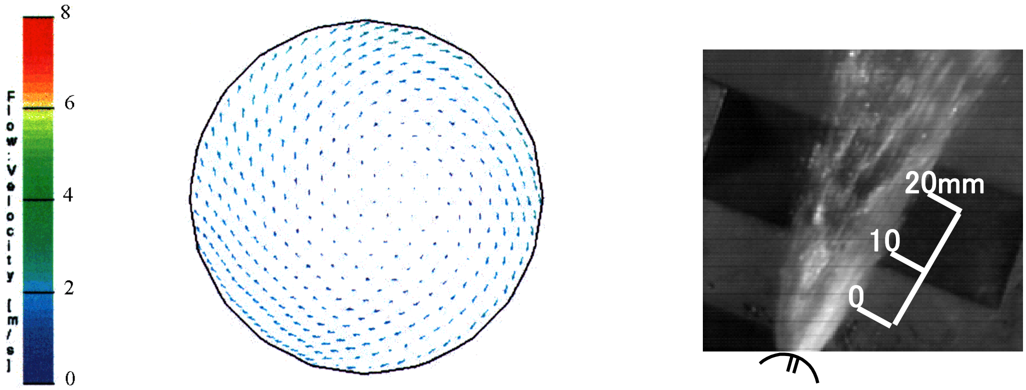
(a) Mini Sac/ Straight Holes (Exit Hole Diameter = 2mm)



(b) Swirl Groove/ Straight Holes (Exit Hole Diameter = 2mm)



(c) Swirl Groove/ Converging Holes (Exit Hole Diameter = 2mm)



(d) Swirl Groove/ Diverging Holes (Exit Hole Diameter = 4mm)

Fig. 8 Calculated internal flow patterns (left) and measured sprays (right)

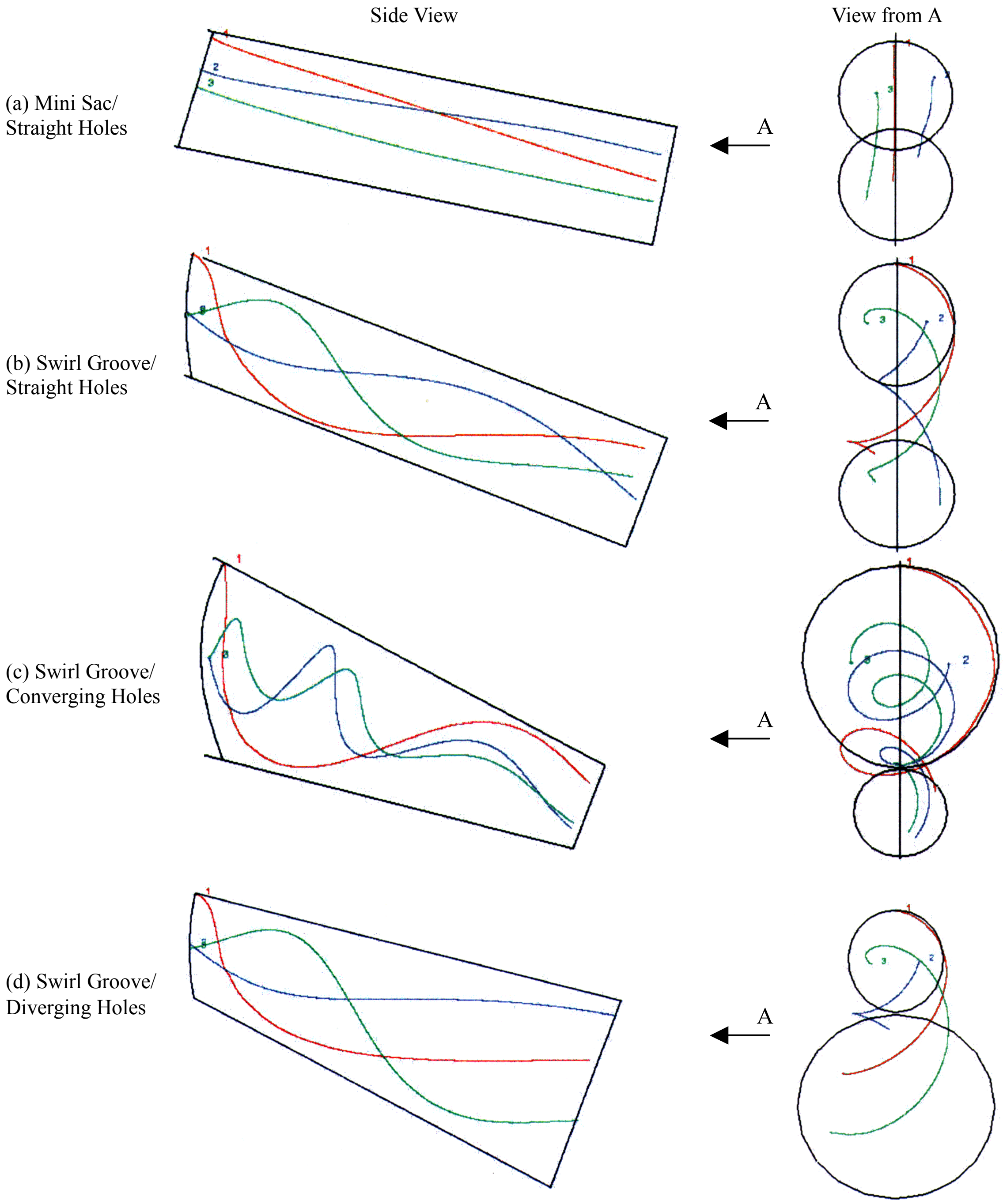


Fig. 9 Particle traces inside injector holes

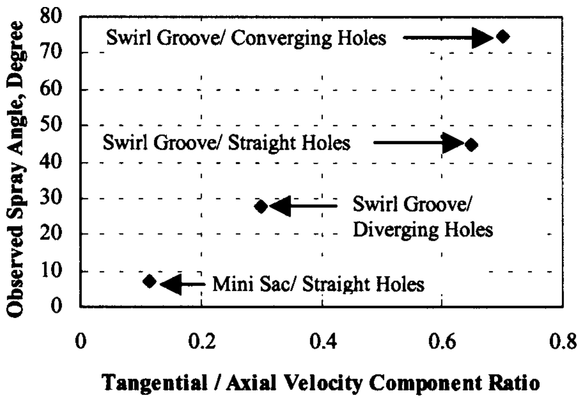


Fig. 10: Relationship between observed spray angles and tangential / axial velocity component ratio