# Atomization phenomena with plate nozzle with a several ten micrometer slit

N. Iki*
Energy Technology Research Institute,
National Institute of Advanced Industrial Science and Technology (AIST)
1-2-1, Namiki, Tsukuba, Ibaraki, 305-8564, JAPAN
T. Ebara
Maruwa Electronic Incorporated
D. Shimizu
Graduate School of Kogakuin University

**Abstract**

Disintegration phenomena of thin liquid jet were investigated with optical instruments and thin planar nickel plate nozzles fabricated by electroforming process. The thickness of the nozzle is 0.02mm. The sizes of the rectangular slits are 0.02mm x 0.05mm, 0.02mm x 0.1mm and 0.04mm x 0.1mm. Ion exchanged water is sprayed vertically downward into static atmospheric air from small holes of thin plate nozzle. Injection pressure ***Pi*** is below 2MPa. Photographs of disintegration phenomena of the water jets are taken by digital camera and laser sheet of YAG laser. Sauter Mean Diameter ***SMD*** is measured by laser diffraction method. Mass flows rate of thin plate nozzles with slits are larger than those with circular hole. The coefficient of contraction of the slit of is roughly around 0.8. Therefore the slit is effective to increase mass flow rate of thin plate nozzle. Water jet from thin plate nozzle with silt is already disintegrated into droplets at 6mm of ***Lx*** (distance from the nozzle hole exit). The droplets move in-line. The interval of the droplets array becomes larger with ***Lx***. ***SMD*** increases with ***Lx***. The increase of ***SMD*** decreases with increase of ***Lx***. ***SMD*** decreases with increase of ***Pi***. These phenomena are similar to the sprays with thin plate nozzle with single circular hole. ***SMD*** with circular holes increases with ***Dn***. ***SMD*** with thin plate nozzles with 0.04mm x 0.1mm slit agree with those with circular holes. ***SMD*** with thin plate nozzles with 0.02mm x 0.1mm slit are larger than those with circular holes. Therefore large aspect ratio of slit may decelerate disintegration of liquid jet and may disturb the coalescence of neighbor droplets. ***SMD*** with thin plate nozzles with circular holes increase with ***Dn*** and circular equivalent diameter is available for estimation of ***SMD*** slit nozzle except 0.02mm x 0.1mm slit.

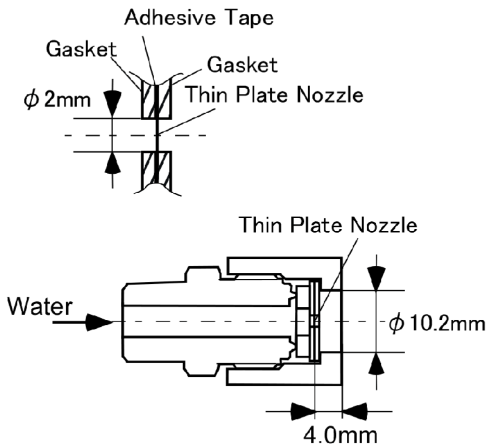
## Introduction

MEMS (Microelectromechanical System) technologies reduce the cost of nozzle with small holes under 0.1mm of diameter. MEMS technologies are applied to produce nozzles of ink-jet printer head and nebulizers with low costs. The nozzles of ink-jet printer employ small holes with piezoelectric vibrator. Flow rates of these applications are small. On the other hand, fuel injector nozzles for automobile require lager flow rates. Multi-holes fuel injector for automobiles is fabricated by press working with very low costs. Multi-holes fuel injector enables suitable design of spray pattern to combustor. However the diameter of the nozzle hole is not as small as ink-jet printer head. Fuel injector nozzles fabricated by MEMS technologies are study stage. LIGA process technology applied to the micro-nozzle for Diesel engine [1]. “Silicon Plate Nozzle” has been researched for automobile engines [2] [3]. Micro nozzle array with PZT is applied to ultrasonic atomization technique [4]. So, a plate nozzle with pinholes can be used for nozzles with larger flow rate such as fuel injectors for internal combustion engines in the future.

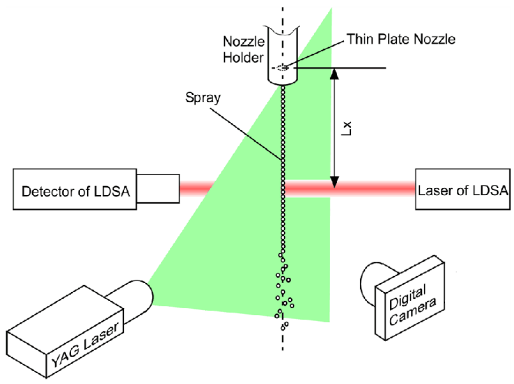
AIST tries demonstration of small gas turbine with ceramic rotor. The fuel flow rate of the nozzle is below 0.2g/s at the ignition condition. The micro nozzle is one of the candidates of the fuel injector of such a small gas turbine. Therefore, we consider possibility to adopt a planar plate nozzle with small holes to an internal combustion engine such as gas turbines. There are many variable design parameters such as number of holes, size of holes, shape of a hole, intervals of holes, patterns of holes, etc. These parameters effect on atomization phenomena. We have begun to study thin plate nozzles fabricated by electroforming as the first step. Disintegration phenomena of thin liquid jet were investigated with optical instruments and thin planar nickel plate nozzles fabricated by electro-

*Corresponding author

forming process. We have already report Sauter Mean Diameters ***SMD*** from 0.01mm to 0.07mm single hole nozzle, 0.01mm 16-holes nozzle and 0.02mm 91-holes nozzle [5-8]. Sauter Mean Diameter ***SMD*** with a single hole nozzle mainly increase gradually with ***Lx***. However suspended fine droplets are observed and ***SMD*** varies complicatedly with ***Lx***. On the other hand, in the case of a multi-hole nozzle, ***SMD*** increases monotonously with ***Lx***. The modal diameter based on volume monotonously increases with ***Lx***. However various shapes of holes are available for electroforming process. Surface area of circular long column is smaller than those of the columns with same cross-section area and the same length. Therefore interfacial area of a circular liquid jet with circumference air is smaller than those of the other shape liquid jets with the same cross-section area. Non-circular hole may accelerate disintegration of liquid jet due to the differences of surface tension and shear stress. This paper reported the comparison of atomization with rectangular slits and circular holes [5-8].



(a) Planar thin plate nozzle



(b) Setting of apparatus

**Figure 1.** Experimental apparatus

## Experimental set up

Disintegration phenomena of thin liquid jet were investigated with optical instruments and thin planar nickel plate nozzles. The thin plate nozzles are fabricated by electroforming process by Optnics Precision Co., ltd. The thickness of the nozzle is 0.02mm. The sizes of the rectangular slits are 0.02mm x 0.05mm, 0.02mm x 0.1mm and 0.04mm x 0.1mm. Each circle equivalent diameter of the slit is 0.036mm, 0.050mm and 0.071mm. Each aspect ratio is 2.5, 0.5 and 2.5. The inner diameters of the circular holes ***Dn*** are from 0.01, 0.02, 0.03, 0.05 and 0.07mm. These are already tested [5-8]. The edges of holes are sharp. But hole is tapered because of the limitation of UV methods. The angle of the tapered wall to the axis is 4-5 degree in design. The accurate side is set as the inlet side of the nozzle. The hole on the accurate side of the nozzle is smaller than the opposite side. Fluorine coating is processed on the both sides of the nozzle. Since the thickness of the electroforming nozzle is too thin to use alone, it is mounted between two thick nickel gaskets for experiments.

Ion exchanged water is sprayed vertically downward into static atmospheric air from small holes of thin plate nozzle. Injection pressure ***Pi*** from 0.1 to 2.0MPa. The water jet was illuminated by light sheet of YAG laser (New Wave solo 120). Photographs of disintegration phenomena of the water jets are taken by digital camera (Nikon D1X; 5.3Mpixels) and laser sheet of YAG laser. The Sauter mean diameters ***SMD*** were measured by laser diffraction method by using LDSA1500A (Tohnichi computer applications co. ltd.). We use the histogram mode. The Sauter mean diameters SMD are measured at 20 - 200mm from nozzle hole exit.

## Results and Discussion

As shown in fig.2, mass flows rate of thin plate nozzles with slits are larger than those with circular hole. The coefficient of contraction of the slit of is roughly around 0.8 although the coefficient of contraction of the circular several tens micrometers hole is roughly around 0.6-0.7. Therefore the slit is effective to increase mass flow rate of thin plate nozzle.

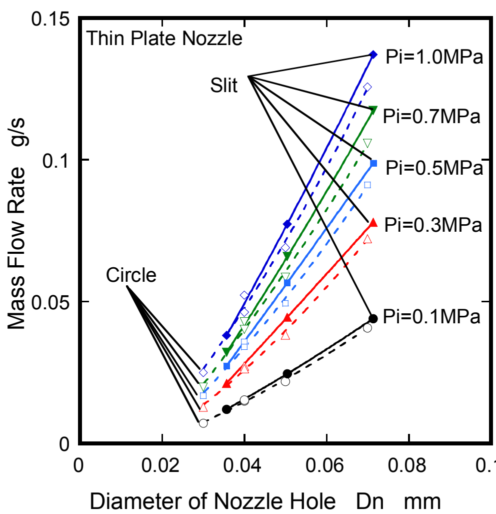


**Figure 2.** Mass Flow rate

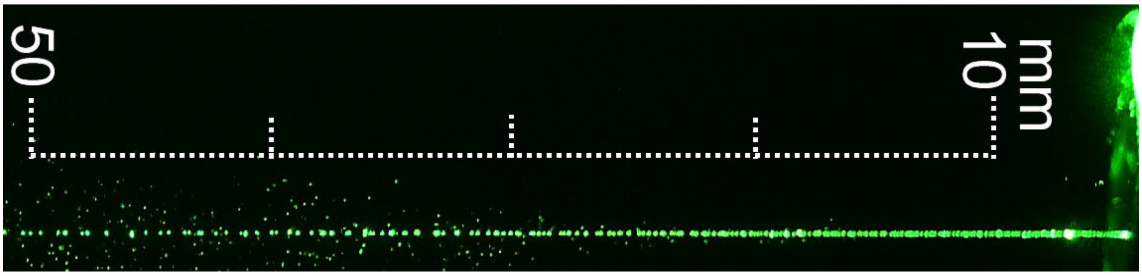



**Figure 3.** Spray from the 0.02mm x 0.05mm Slit at ***Pi*** =1MPa

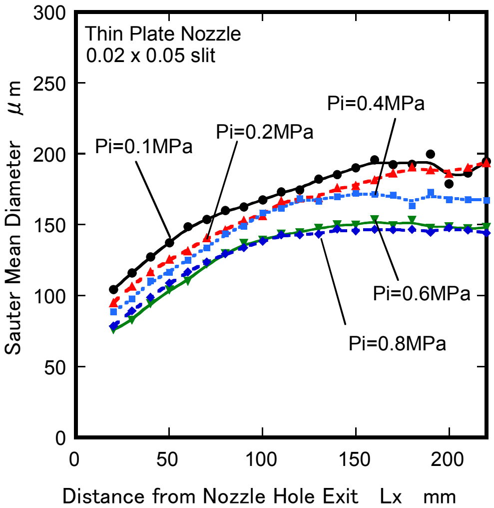



**Figure 4.** Sauter mean diameter of spray with the thin plate nozzle with 0.02mm x 0.05mm Slit

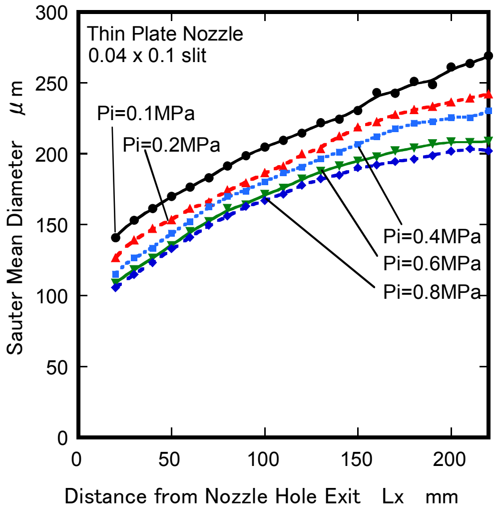



**Figure 5.** Sauter mean diameter of spray with the thin plate nozzle with 0.04mm x 0.1mm Slit

As shown in fig. 3, at 6mm of ***Lx*** (distance from the nozzle hole exit), water jet is already disintegrated into droplets. The droplets move inline. The interval of the droplets array becomes larger with ***Lx***. These phenomena agree with the phenomena of previous results with the circular single hole nozzle. At ***Lx***=20mm, fine droplets are observed. At lower injection pressure such fine droplets are not observed near nozzle exit. 0.02mm x 0.1mm slit and 0.04mm x 0.1mm slit show similar disintegration phenomena.

***SMD*** of spray with the thin plate nozzle with 0.02mm x 0.05mm are shown in fig. 4. ***SMD*** increases with ***Lx***. The increase of ***SMD*** decreases with increase of ***Lx***. ***SMD*** decreases with increase of ***Pi***. These phenomena are similar to the sprays with thin plate nozzle with single circular hole. Therefore it has been estimated that the coalescence of neighbor droplets occurs at larger ***Lx***. Figure 5 shows ***SMD*** of spray with the thin plate nozzle with 0.04mm x 0.1mm. The aspect ratio of the slit is the same as fig. 4 but the size is twice. ***SMD*** is smaller than twice of fig.4. ***SMD*** increases with ***Lx*** similar to fig. 4.

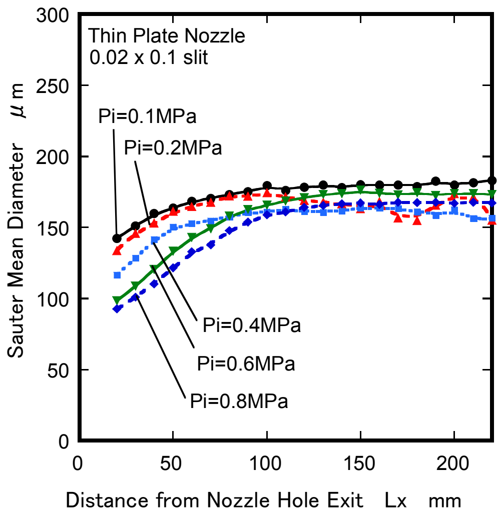
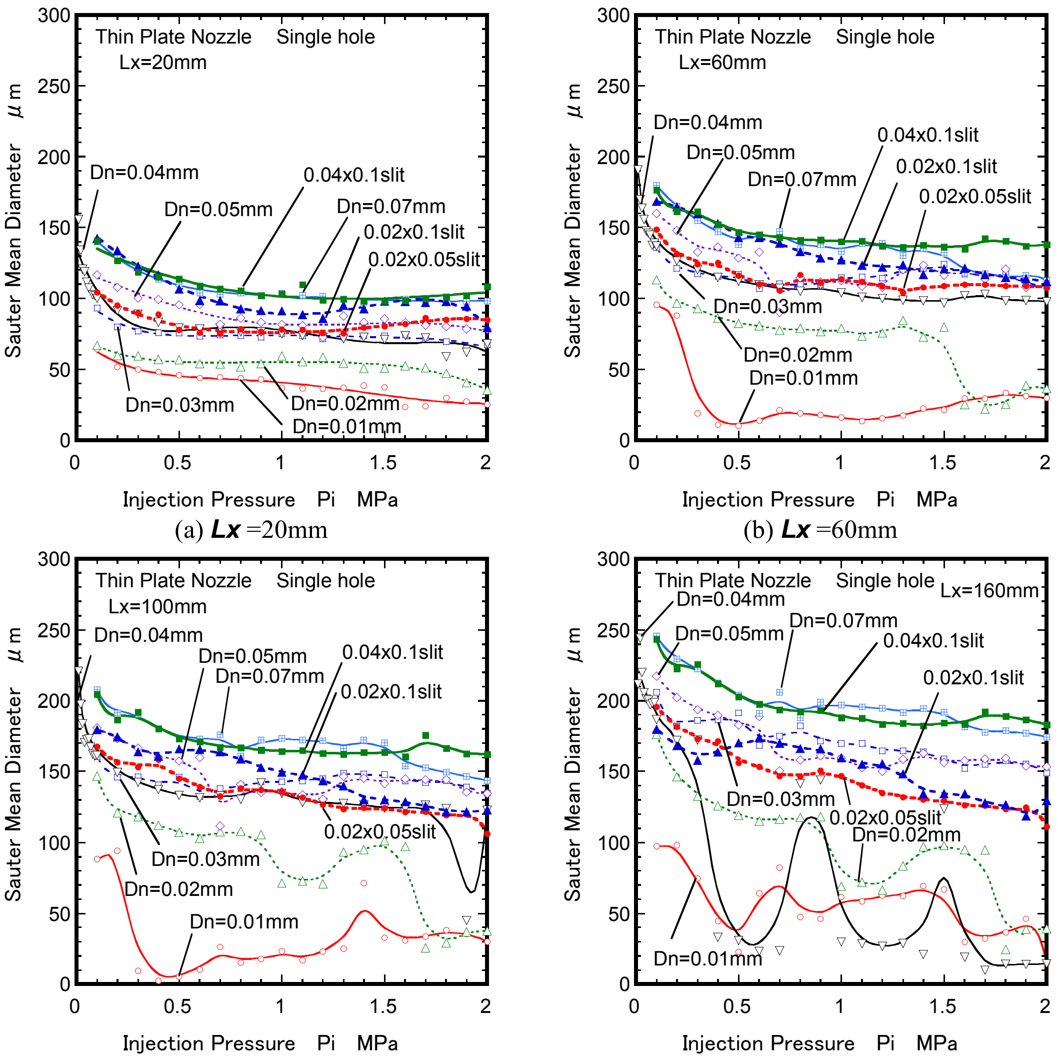



**Figure 6.** Sauter mean diameter of spray with the thin plate nozzle with 0.02mm x 0.1mm Slit

On the other hand ***SMD*** of spray with the thin plate nozzle with 0.02mm x 0.1mm is almost constant at ***Lx*** > 100mm. ***SMD*** increases with ***Lx*** at Lx <100mm. At low ***Pi*** below 0.2MPa, ***SMD*** near nozzle exit are larger than that in fig. 5. The aspect ratio of the slit is twice of the slit of fig.5 and the area of the slit is half of the slit of fig. 5. Therefore large aspect ratio of slit may decelerate disintegration of liquid jet.

Figure 7 shows ***SMD*** with the various thin plate nozzles versus injection pressure ***Pi***. ***SMD*** decrease with increase of ***Pi*** near nozzle hole exit at ***Pi*** <0.6MPa as shown fig. 7 (a). ***SMD*** with slit is almost constant at ***Pi*** >0.8MPa. At larger ***Lx*** =20mm ***SMD*** of spray with small circular holes of ***Dn*** is from 0.01mm to 0.04mm vary complicatedly due to suspended fine droplets. These suspended fine droplets reduce the spatial average value of ***SMD*** measured by laser diffraction method. The time averaged volume ratio of these suspended fine droplets to liquid jet is negligible. Although ***SMD*** with 0.02mm x 0.1mm slit is almost same as ***SMD*** with 0.04mm x 0.1mm slit at nozzle hole exit as shown fig. 7 (a). ***SMD*** with 0.02mm x 0.1mm slit is almost same as ***SMD*** with 0.02mm x 0.05mm slit at far from nozzle exit as shown fig. 7 (d). Therefore large aspect ratio of slit may disturb the coalescence of neighbor droplets. Figure 8 shows ***SMD*** with the various thin plate nozzles near nozzle hole exit versus the circle equivalent diameter of nozzle holes. ***SMD*** with thin plate nozzles with circular holes increase with ***Dn***. ***SMD*** with thin plate nozzles with 0.04mm x 0.1mm slit agree with those with circular holes. ***SMD*** with thin plate nozzles with 0.02mm x 0.1mm slit are larger than those with circular holes. Therefore circular equivalent diameter is available for estimation of ***SMD*** slit nozzle except 0.02mm x 0.1mm slit. In order to evaluate the performance of the slit nozzles the other measure than circular equivalent diameter is necessary. Then mass flow rate at same ***Pi*** is selected. Figure 9 shows ***SMD*** with the various thin plate nozzles versus mass flow rates. However ***SMD*** with thin plate nozzle 0.02mm x 0.1mm slit is larger than the other thin plate nozzle.




(a) ***Lx*** =20mm (b) ***Lx*** =60mm

(c) ***Lx*** =100mm (d) ***Lx*** =160mm

**Figure 7.** Sauter mean diameter with the various thin plate nozzles versus injection pressure ***Pi***

**Conclusion**

Disintegration phenomena of water jet were investigated with thin plate nozzles with the slit of 0.02mm x 0.05mm, 0.02mm x 0.1mm and 0.04mm x0.1mm. The coefficient of contraction of the slit of is roughly around 0.8 although the coefficient of contraction of the circular several tens micrometers hole is roughly around 0.6-0.7. The disintegration phenomena are similar to those with thin plate nozzle with single circular hole. ***SMD*** with 0.02mm x 0.1mm slit are larger than those with circular holes.

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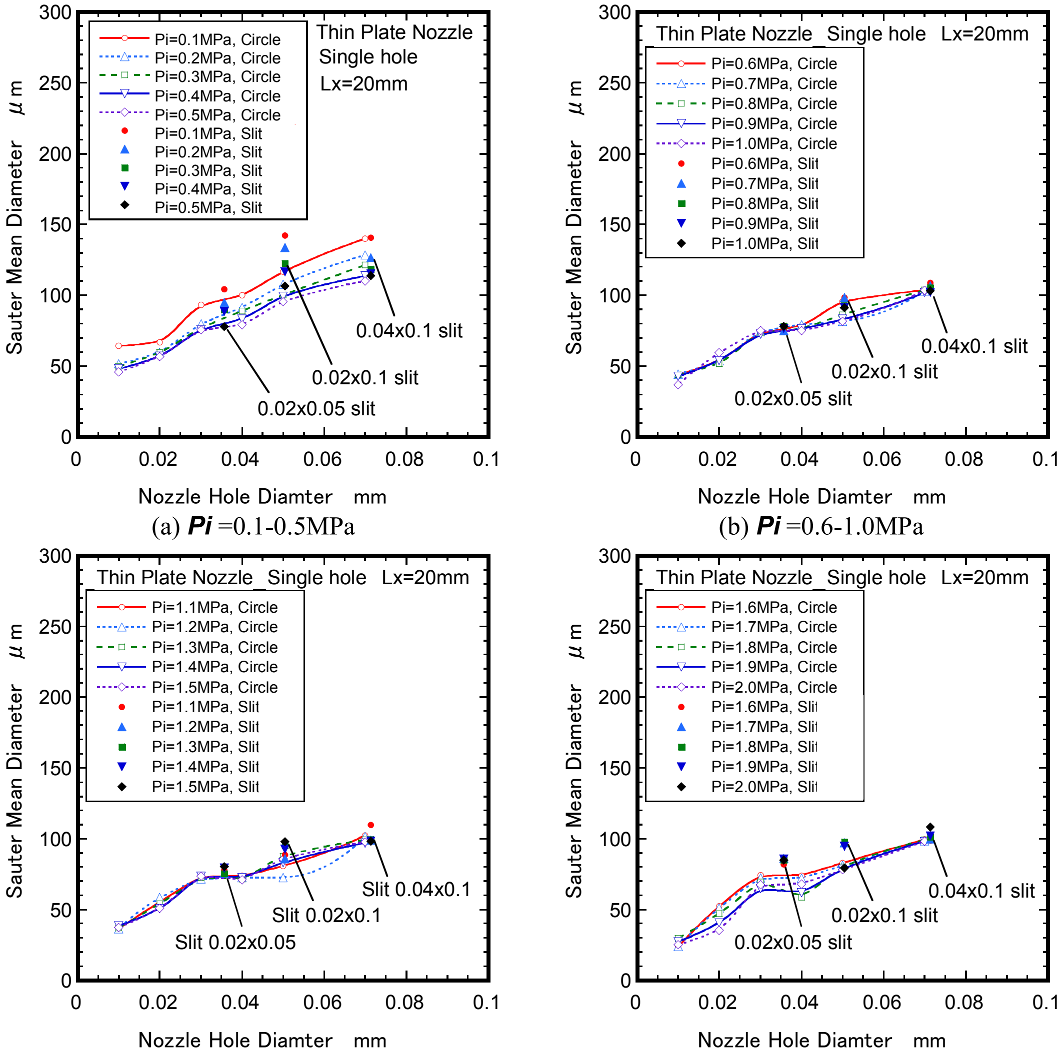
**Nomenclature**

***Dn*** Nozzle hole diameter
***Lx*** Distance from the nozzle hole exit
***Pi*** Injection pressure
***SMD*** Sauter Mean Diameter




(a) ***Pi*** =0.1-0.5MPa (b) ***Pi*** =0.6-1.0MPa

(c) ***Pi*** =1.1-1.5MPa (d) ***Pi*** =1.6-2.0MPa

**Figure 8.** Sauter mean diameter with the various thin plate nozzles near nozzle hole exit versus circle equivalent diameter of nozzle holes

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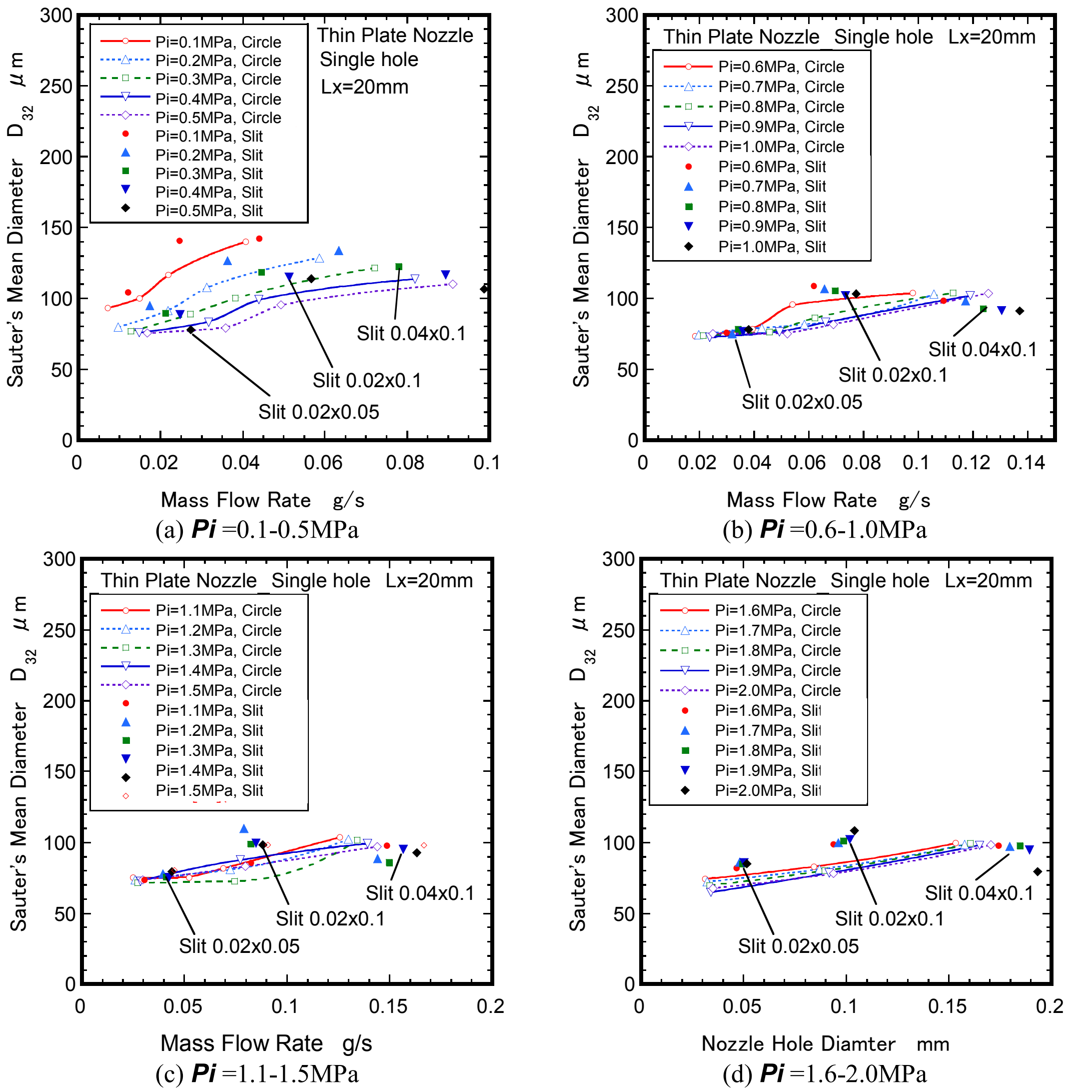


**Figure 9.** Sauter mean diameter with the various thin plate nozzles versus mass flow rates