Disintegration of Thin Liquid Jet Injected from Several Tens Micrometer Hole

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Abstract

Disintegration phenomena of thin liquid jet were investigated with optical instruments and thin planar nickel plate nozzles or pinhole nozzle made by press working. A plate nozzle is made by electroforming process and punching for basic research of development of the multi-holes fuel injectors fabricated by Micro-Electro-Mechanical-Systems (MEMS) technologies. A thin plate nozzle is made by electroforming process. Its thickness is 0.02mm; hole diameter ***Dn*** is from 0.01mm to 0.07 mm. Fluorine coating is processed on both sides of plate. Slit holes are also tested to know the effect of the holes shape. The shadowgraph of droplets from thin plate nozzle is investigated. Micro Laser Diode Module with focusing lens is used for measurement of time interval of shadowgraphs of droplets. The beam size is 0.07mm. The autocorrelation function of light intensity shows that the coalescence of droplets occurs extremely near nozzle exit.

Introduction

There are several methods to make a small hole, such as drilling, electric discharging machining, punching etc. Micro-Electro-Mechanical–Systems (MEMS) reduce the cost of manufacturing the nozzle with many micron-scale holes. For example, small holes fabricated by electroforming process are used for ink-jet printer head and a nebulizer nozzle with low cost by mass production. Flow rates of these applications are small. These nozzles have a piezoelectric vibrator in order to supply constant sized droplets. On the other hand, fuel injector nozzles fabricated by MEMS technologies are researched and developed. For example, electroforming nozzles for diesel injectors are investigated [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 planar plate nozzle with pinholes can be used for nozzles with larger flow rate such as fuel injectors for internal combustion engines in the future.

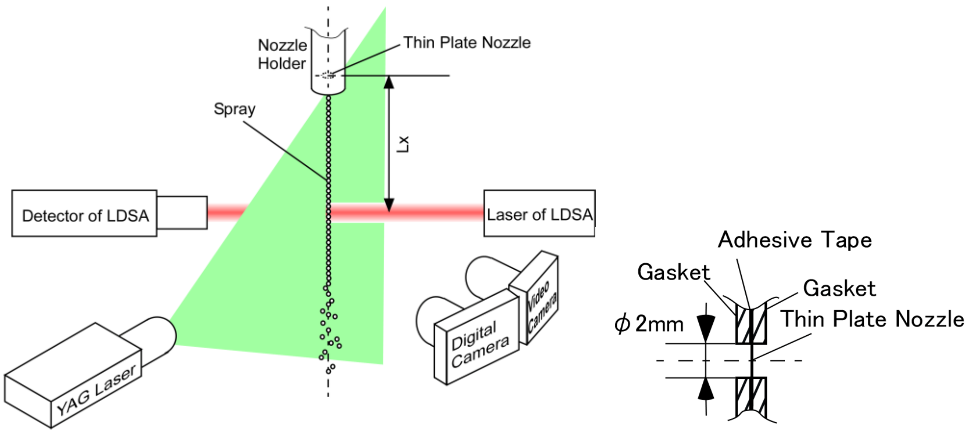
There are many design parameters of multi holes nozzle such as hole size, hole length, hole shape, hole pitch, injection pressure etc., but experimental data are not organized enough to design nozzle efficiently. We have begun to study thin plate nozzles fabricated by electroforming as the first step. Disintegration phenomena of thin liquid jet were investigated with optical instruments and thin planar nickel plate nozzles fabricated by electroforming 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]. The comparison of atomization with rectangular slits and circular holes were reported [9]. Therefore our experimental data of single-hole nozzle and multi-holes nozzle [5-9] are tried to be organized. Empirical formula of Sauter’s Mean Diameter near the nozzle hole is obtained [10]. However the available condition of the empirical formula is limited. Hence the disintegration phenomena are investigated by measuring the time interval of the droplet array.

Experimental Methods

Disintegration phenomena of thin liquid jet were investigated with optical instruments and thin planar nickel plate nozzles or pinhole nozzle made by press working. The thin plate nozzles are fabricated by electroforming process by Optnics Precision Co., ltd. The thickness of the nozzle is 0.02mm.. 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. Slit holes are also tested to know the effect of the holes shape. Fluorine coating is not processed. Experimental data of these nozzles are reported in previous papers [5-10].

Ion exchanged water is sprayed vertically downward into static atmospheric air from small holes of thin plate nozzle as shown in Fig. 1. Injection pressure Pi is from 0.1 to 1.0MPa. The water jet was illuminated by light sheet of YAG laser. Photographs of disintegration phenomena of the water jets are taken by digital camera and laser sheet of YAG laser (New Wave solo 120).

Micro Laser Diode Module with focusing lens (Edmund NT57-100) is used for measurement of time interval of shadowgraphs of droplets in spray. Its wavelength is 655nm. Focus range is from 50mm to infinity. Its beam size at nearest focus is below 50µm. The focus length is set to 100mm from the module. The measured beam size is 0.07mm. The light intensity of the shadowgraph of droplets is recorded by pin photo diode sensor and digital storage oscilloscope (Yokogawa DL-716, input modle:701855, 10M sample/s). Obtained data are processed by FFT program..



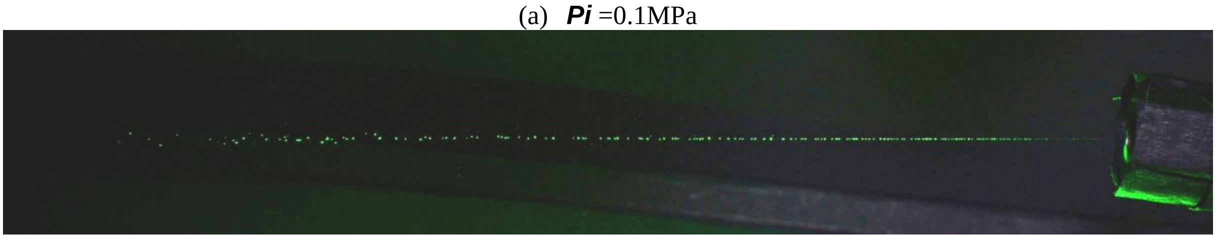
(a) Experimental nozzle (b) Thin Plate Nozzle

Figure 1 Experimental apparatus

Results and Discussion

Water jet from the thin plate nozzle is already disintegrated into droplets array at 10mm of ***Lx*** (distance from the nozzle hole exit) as shown in fig. 2. The droplets move inline. The interval of the droplets array becomes larger with ***Lx***. The number density of droplets is estimated to decrease with increase of ***Lx*** and ***SMD*** increases with ***Lx***.

(a) ***Pi*** =0.1MPa



(b) ***Pi*** =1.0MPa

Figure 2 Droplets array from thin plate nozzle (***Dn*** = 0.03mm)

Sauter mean diameter ***SMD*** with a single hole nozzle mainly increase gradually with ***Lx*** as shown in fig.3 [8]. The increase of ***SMD*** decreases with increase of ***Lx***. ***SMD*** decreases with increase of ***Pi***. ***SMD*** near nozzle hole exit increase almost linearly with ***Dn*** at low ***Pi***. At far from nozzle hole exit, The empirical formula for ***Dn***=0.03-0.06 mm, ***Pi***=0.1-2.0MPa and ***Dn***=0.07, ***Pi***=0.1-1.5MPa is obtained as the following [10].

$$SMD = ((-15.59Dn + 2.84)(Pi/Pi_0)^{-0.164} + (0.000000342Dn^{-3.19} + 0.011)Lx)Dn \quad (1)$$

here, ***SMD***, ***Dn*** in mm $Pi_0 = 0.1$ MPa

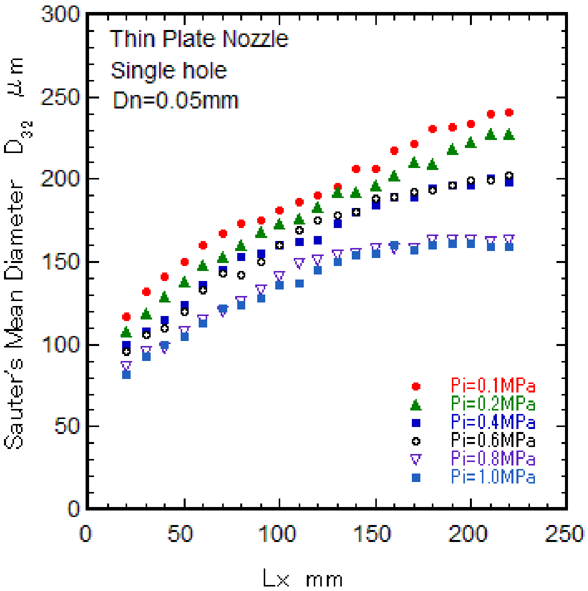


Figure 3 Variation of ***SMD*** with ***Lx*** [8]

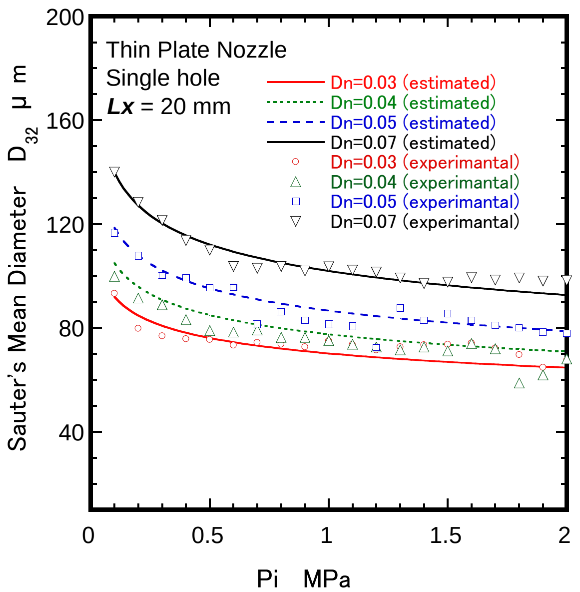
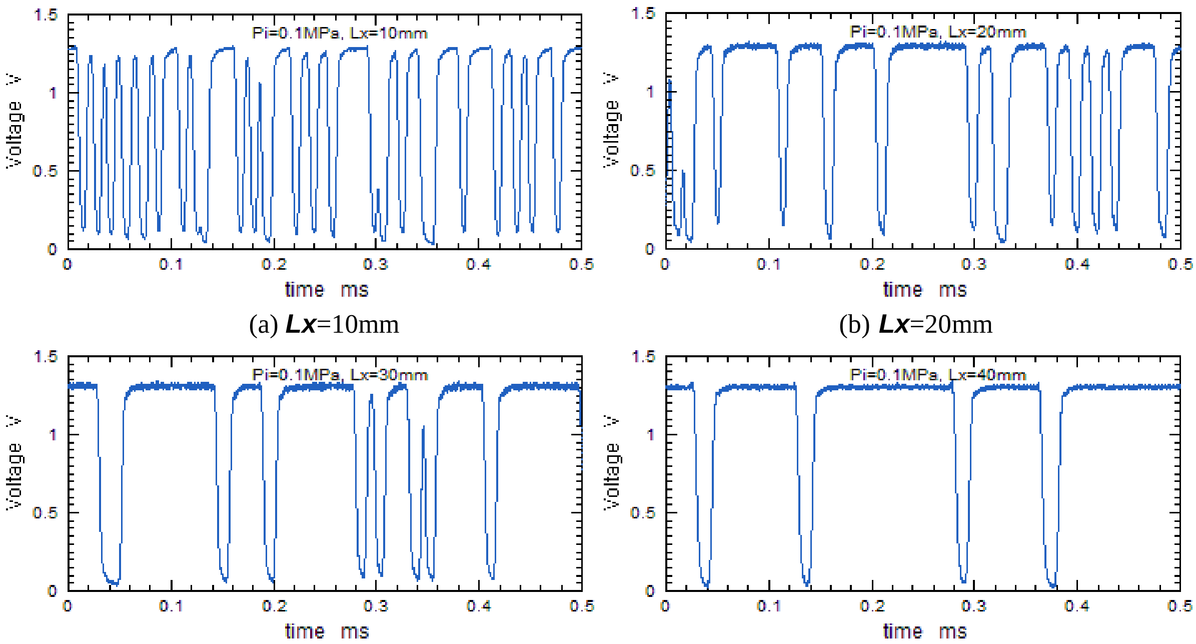


Figure 4 Estimated ***SMD*** with ***Pi*** [10].

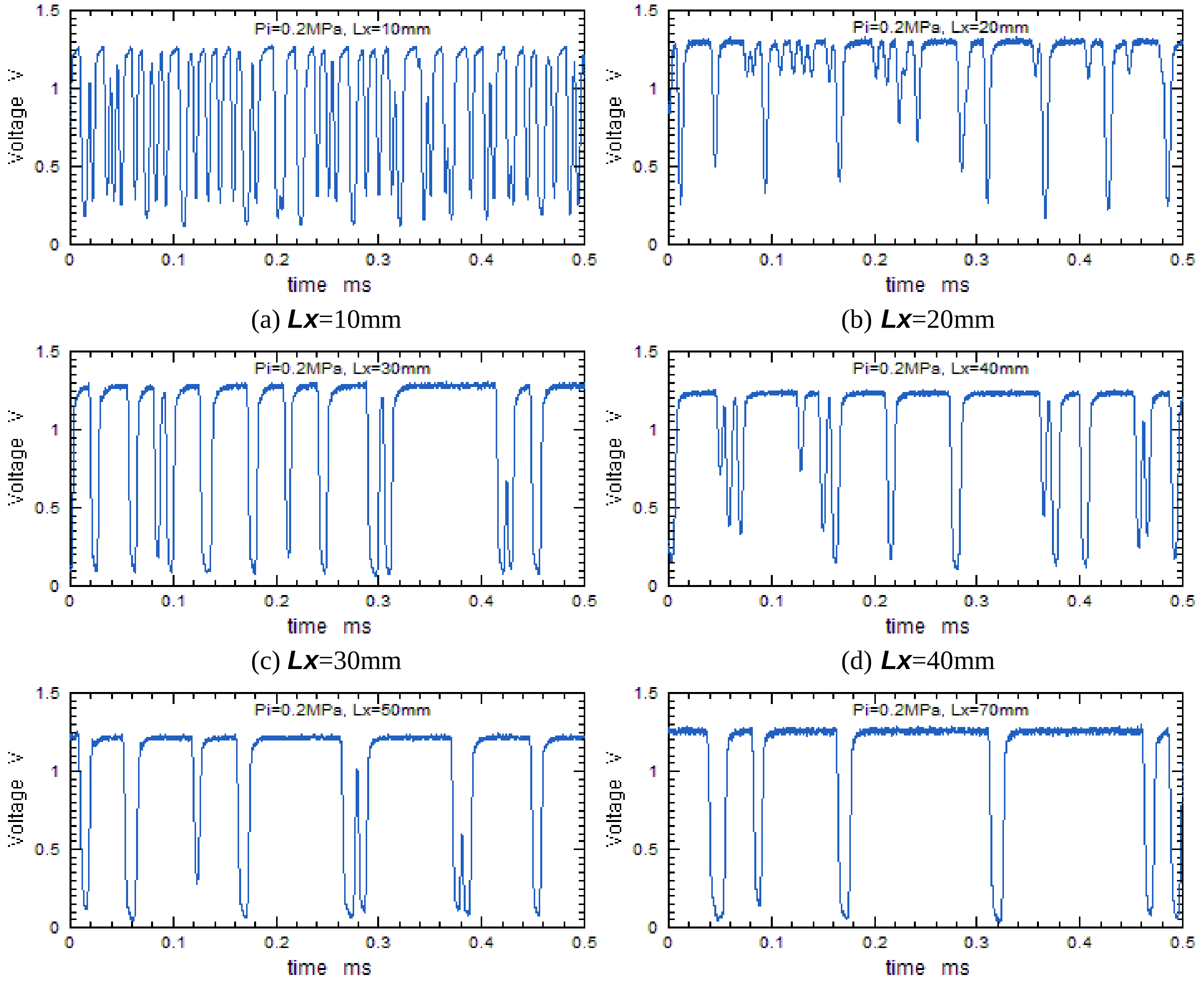
Therefore, some droplets combine into one because the relative velocity of droplets is small [5]. Since ***SMD*** at far from nozzle exit depends on the droplets collapse, ***SMD*** at far from nozzle exit can be influenced by various disturbances caused by share force with circumstance air, complicated hole shape, etc. Although breakup length should be discussed with initial diameter of a droplet, there are not enough data to evaluate quantitatively. Therefore time changes of the light intensity caused by the shadowgraph of moving droplets are measured as shown in fig 5-1 to 5. Since laser beam size at focus point is 0.07mm, the measurement volume is not so larger than droplets. The shadow of the droplet decreases light intensity extremely when the droplet passes through the central axis of the laser beam. When the distance of droplets is larger than the laser beam size, light intensity reaches the maximum. In the case of ***Pi***=0.1MPa, at ***Lx***=10mm, the shadows of droplets sometimes are not separated. And each droplet size is not constant. At ***Lx***=20mm, number of the droplet decrease extremely. At larger ***Lx***, droplets combine into one or some droplets might not pass the measurement volume.



(a) ***Lx***=10mm (b) ***Lx***=20mm

(c) ***Lx***=30mm (d) ***Lx***=40mm

Figure 5-1 Variation of light intensity caused by shadows of droplets (***Dn***=0.03mm, ***Pi***=0.1MPa)



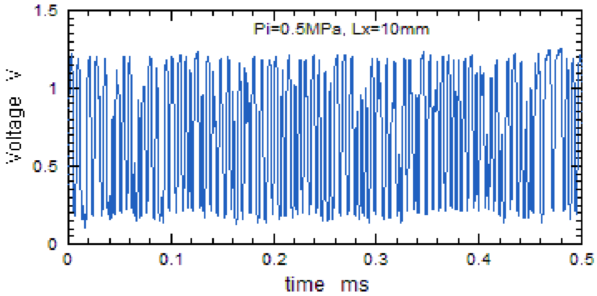
(a) ***Lx***=10mm (b) ***Lx***=20mm

(c) ***Lx***=30mm (d) ***Lx***=40mm

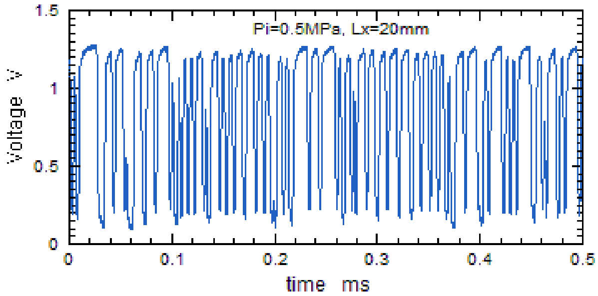
(e) ***Lx***=50mm (f) ***Lx***=70mm

Figure 5-2 Variation of light intensity caused by shadows of droplets (***Dn***=0.03mm, ***Pi***=0.2MPa)

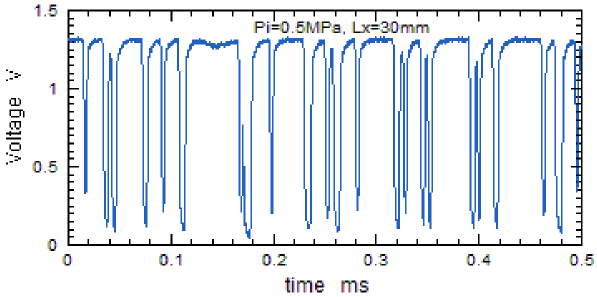
In the case of ***Pi***=0.2MPa, number of shadows of droplets increases. The time interval of shadows passing through the measurement volume increases with ***Lx***. In the case of ***Pi***=0.5MPa, number of shadows of droplets increases and the time interval of shadows passing through the measurement volume is shorter than that in the case of ***Pi***=0.2MPa. These phenomena agree with the decrease of the sizes of droplets and the increase of the velocity of droplets. Data at lager ***Lx*** are obtained since the droplets moves stably. When ***Pi*** increases to 0.7MPa, each shadow of a droplet is hard to be separated at ***Lx***=10mm. The movement of droplet is not as stable as that in the case of ***Pi***=0.5MPa. In the case of ***Pi***=1.0MPa, shadow of a droplet cannot be separated well to the other shadows.



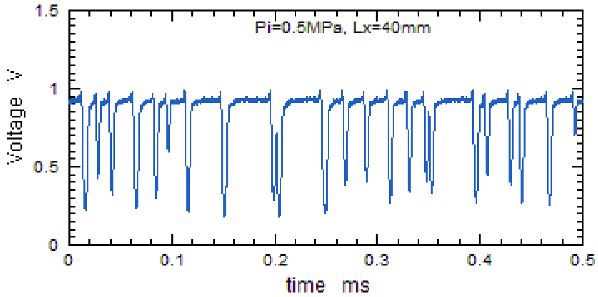
(a) ***Lx***=10mm



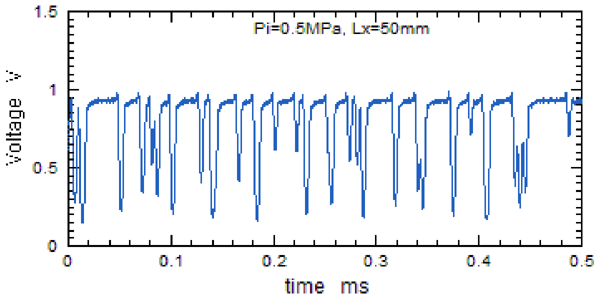
(b) ***Lx***=20mm



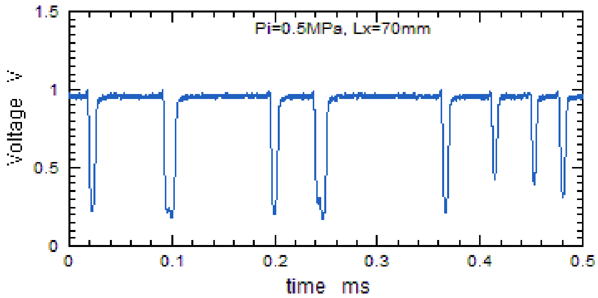
(c) ***Lx***=30mm



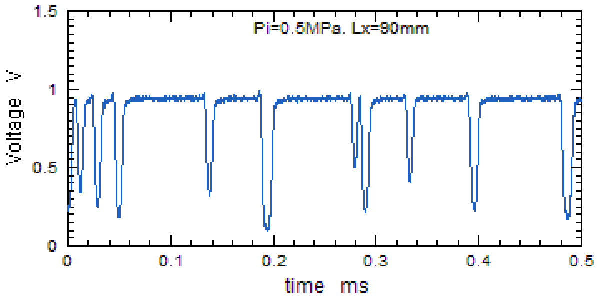
(d) ***Lx***=40mm



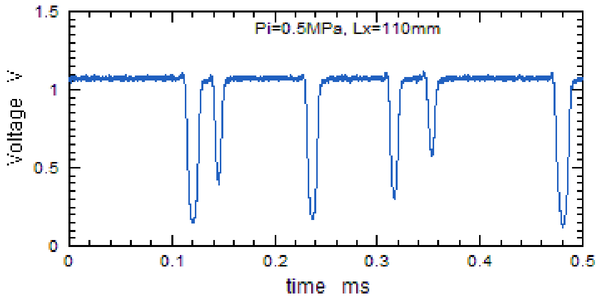
(e) ***Lx***=50mm



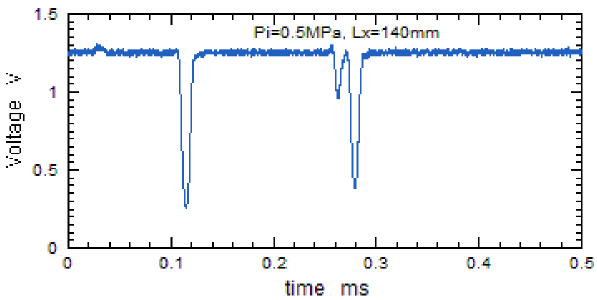
(f) ***Lx***=70mm



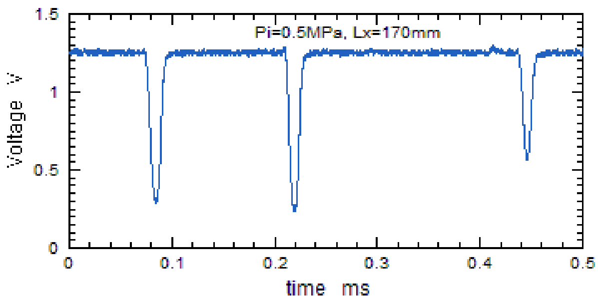
(g) ***Lx***=90mm



(h) ***Lx***=110mm

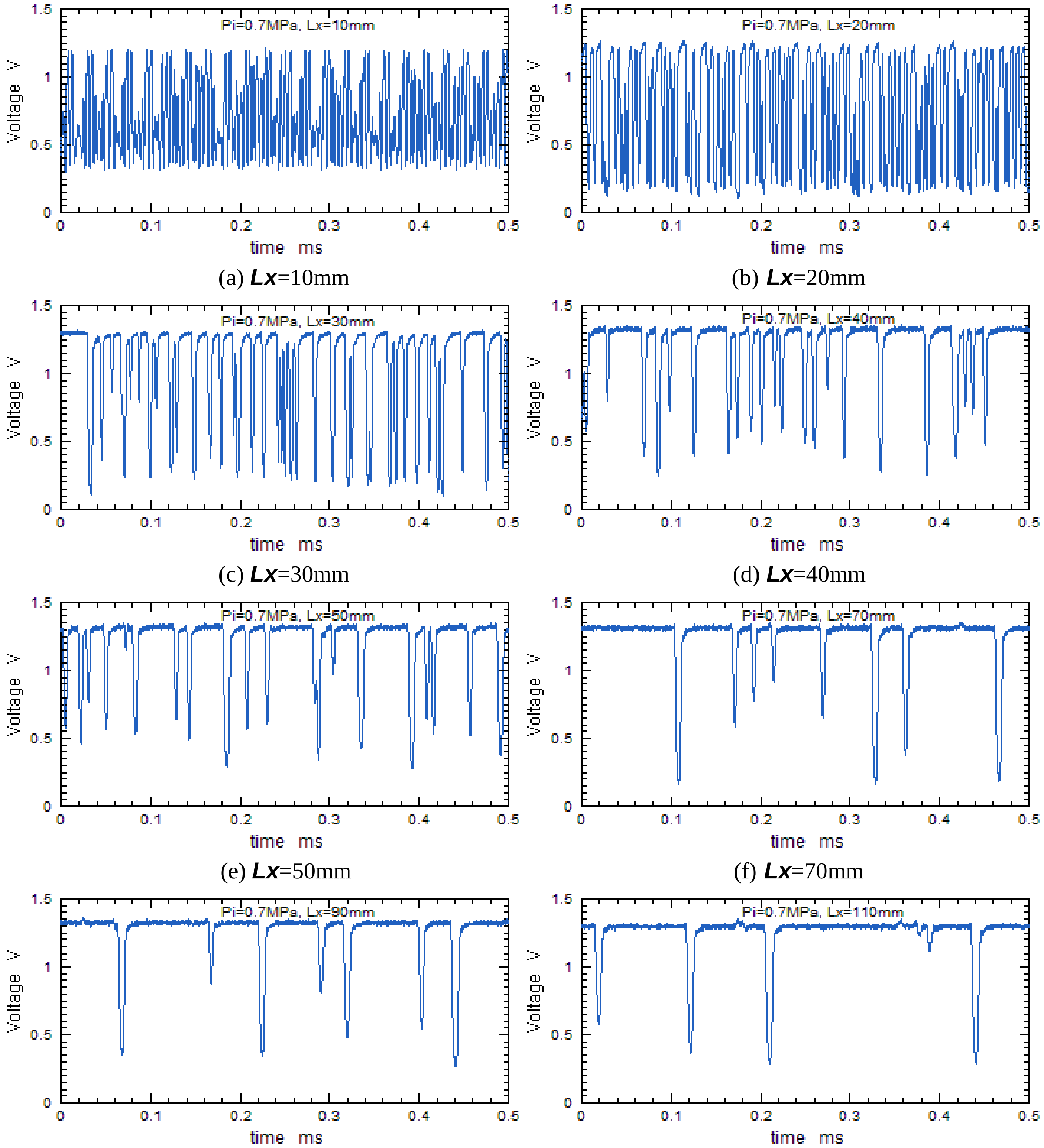


(i) ***Lx***=140mm



(j) ***Lx***=170mm

Figure 5-3 Variation of light intensity caused by shadows of droplets (***Dn***=0.03mm, ***Pi***=0.5MPa)



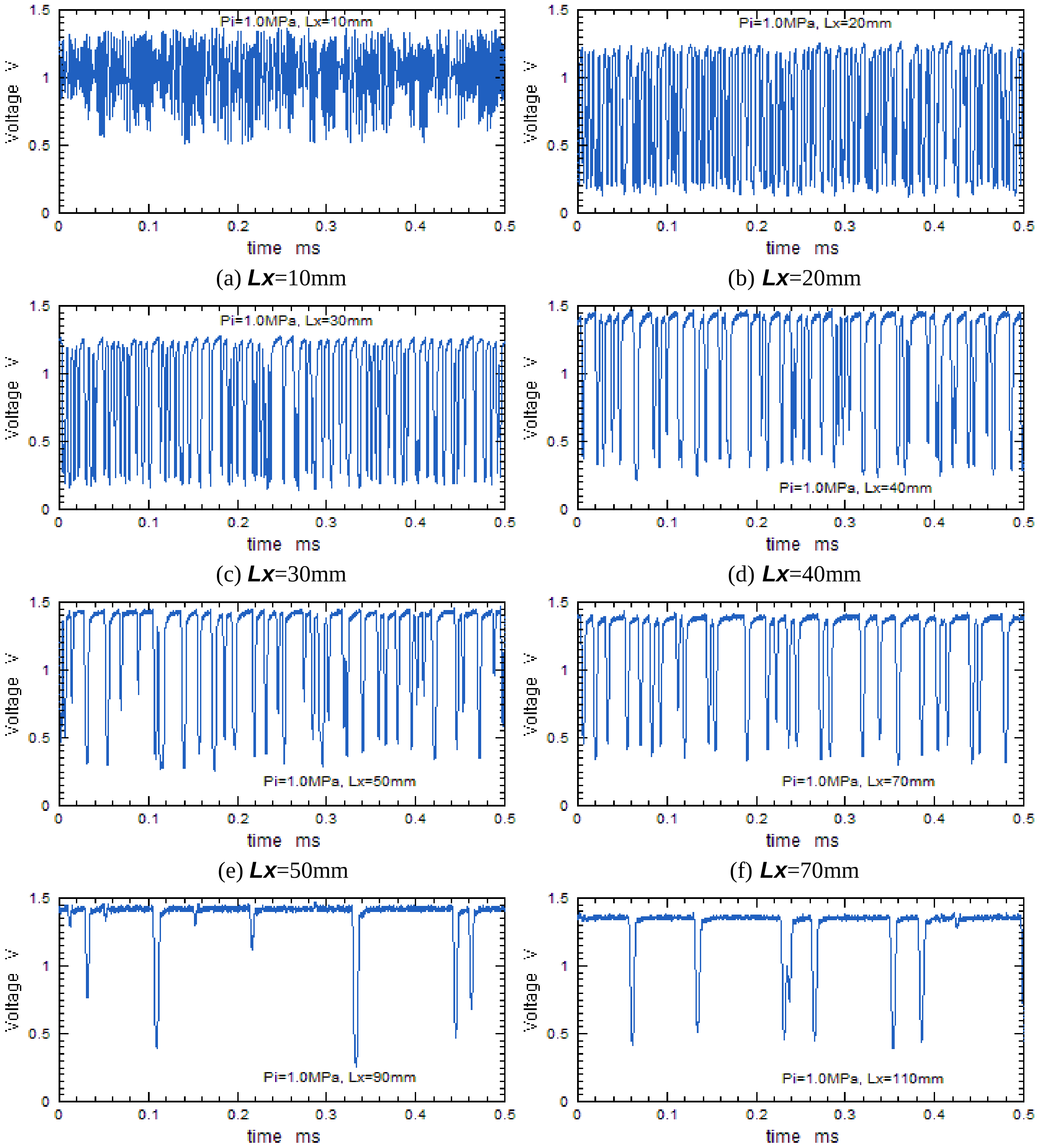
(a) ***Lx***=10mm (b) ***Lx***=20mm

(c) ***Lx***=30mm (d) ***Lx***=40mm

(e) ***Lx***=50mm (f) ***Lx***=70mm

(g) ***Lx***=90mm (h) ***Lx***=110mm

Figure 5-4 Variation of light intensity caused by shadows of droplets (***Dn***=0.03mm, ***Pi***=0.7MPa)



(a) ***Lx***=10mm (b) ***Lx***=20mm

(c) ***Lx***=30mm (d) ***Lx***=40mm

(e) ***Lx***=50mm (f) ***Lx***=70mm

(g) ***Lx***=90mm (h) ***Lx***=110mm

Figure 5-5 Variation of light intensity caused by shadows of droplets (***Dn***=0.03mm, ***Pi***=1.0MPa)

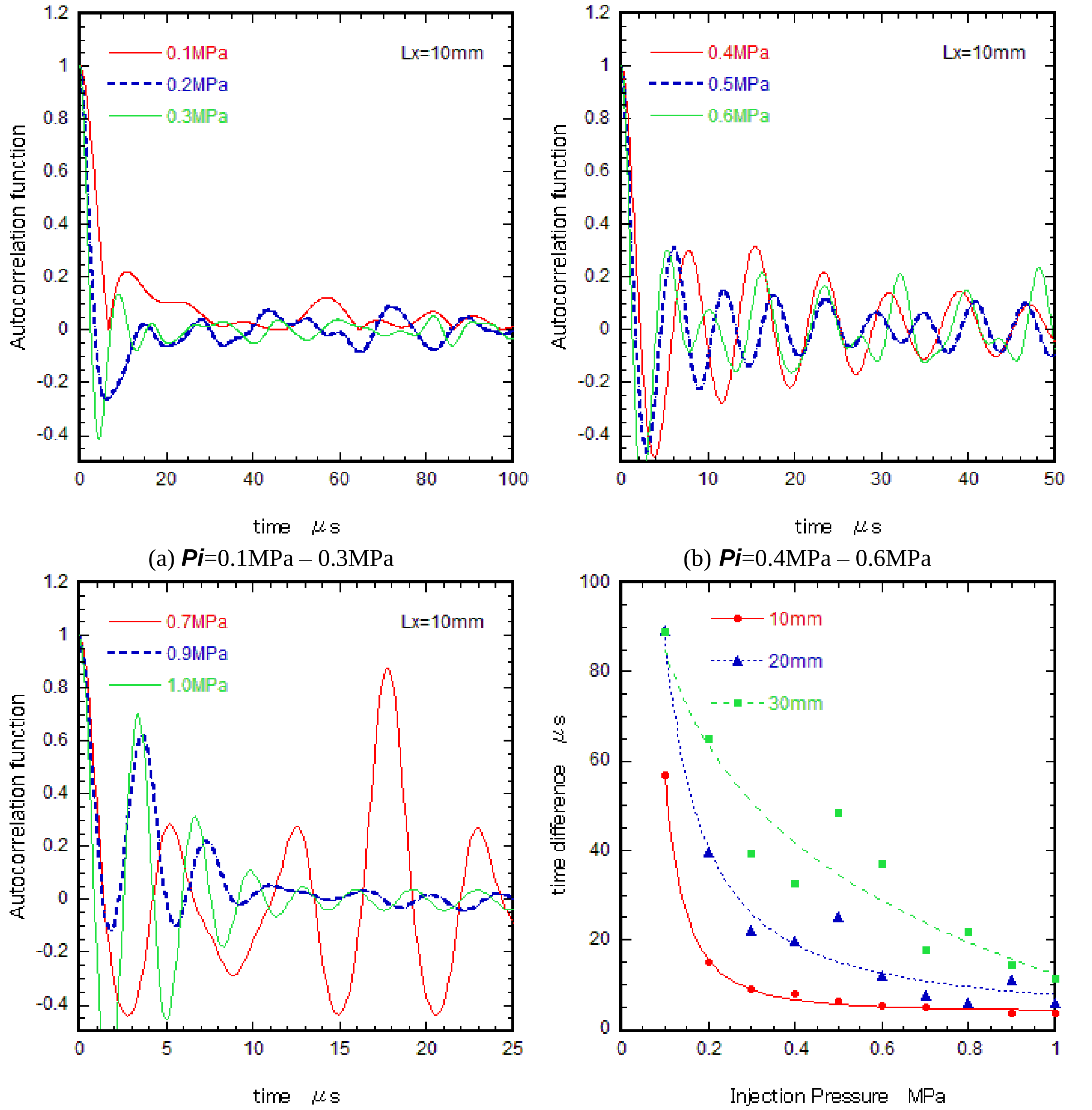
The autocorrelation function related with the frequency of the droplet passing through the measurement volume. Figure 6 shows the autocorrelation function. The first peak point corresponds to the time difference of the next droplets if the interval of the droplets are constant and droplet size is constant. The first peak point shift to zero with increase of ***Pi***. The first peak point increase extremely with ***Lx*** as shown in (d). This means that the number of droplets decrease with ***Lx***. That is the coalescence of droplets occurs extremely near nozzle exit.

Summary and Conclusions

The shadowgraph of droplets from thin plate nozzle is investigated. The autocorrelation function of light intensity shows that the coalescence of droplets occurs extremely near nozzle exit.

Acknowledgements

The experimental works are supported by Dr. Ebara, Mr. Shimizu, Mr. Hayashi and Mr. Okada.



(a) ***Pi***=0.1MPa – 0.3MPa (b) ***Pi***=0.4MPa – 0.6MPa

(c) ***Pi***=0.7MPa – 1.0MPa (d) first peak point of autocorrelation function

Figure 6 Autocorrelation of light intensity caused by shadows of droplets (***Dn***=0.03mm)

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