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FORMATION OF UNIFORMLY-SIZED DROPLETS FROM CAPILLARY JET BY ELECTROMAGNETIC FORCE

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ABSTRACT

A new method to fabricate uniformly sized metal droplets is proposed. In the method, intermittent electromagnetic pinch force is applied to a capillary jet of liquid metal in order to generate fluctuations of equal interval on the surface of the jet. As the fluctuations grow, the liquid metal jet is broken up into small droplets according to a frequency of the intermittent electromagnetic pinch force. Numerical simulation of the breakup of the capillary jet is carried out by a multiphase fluid flow analysis with surface tracking (volume of fluid method) and electromagnetic force analysis. The simulation results are compared with model experiments and the agreement between the two is good. It is found that the jet is broken up into uniformly sized droplets in the case of the frequency of the intermittent force imposition is equal to an optimal frequency, which corresponds to a natural disturbance wavelength of the capillary jet.

NOMENCLATURE

A_0 initial amplitude of perturbation
$\mathbf{B}$ magnetic flux density
d_0 nozzle diameter
f frequency
$\mathbf{F}$ Lorentz force
$\mathbf{J}$ current density
k turbulent energy
Oh Ohnesorge number
p pressure
r radius
Re Reynolds number
t time
$\mathbf{v}$ velocity
v_0 mean axial velocity at nozzle exit
We Weber number
z distance from nozzle exit

Greek letter
α volume fraction of fluid
γ surface tension
ϵ turbulent dissipation rate
κ mean surface curvature
λ wavelength
μ viscosity
ρ density
σ electrical conductivity

subscript
m mixture
1 gas
2 liquid

INTRODUCTION

Problems of breakup of capillary jet and formation of droplets are very fundamental topics in the field of fluid dynamics. For more than a century, a great number of studies have been devoted to understand the mechanism (reviewed by Eggers, 1997). According to the linear instability theory (Rayleigh, 1879; Weber, 1931), the breakup of capillary jet is mainly governed by surface tension. Small perturbations of an optimal wavelength grow fastest and the typical size of droplets is determined by the wavelength. Recently, many numerical simulations of breakup of capillary jet have been carried out with marked improvement in computational power and numerical techniques (for example, Pan and Suga, 2006; Yang *et al.*, 2006).

Droplet formation from a capillary jet has a broad range of industrial applications such as ink jet printers, solder spheres, fuel injection and so on. In the field of metal materials, many techniques have been developed to produce uniformly sized metal particles or small balls (for example, Acquaviva *et al.*, 1997; Minemoto *et al.*, 2005; Takagi *et al.*, 2006).

Minemoto *et al.* (2005) has proposed the jet-splitting method to fabricate uniformly sized spherical silicon particles of 1mm in diameter for spherical silicon solar cells. The method consists a dropping furnace and a free-fall tower. In the dropping furnace, molten silicon is issued from an orifice at the bottom of a crucible, and the jet is broken up into droplets due to natural disturbance of the surface of the jet. The silicon droplets are solidified in the free-fall tower and silicon particles are collected at the bottom of the tower. However, it is difficult to fabricate uniformly sized silicon particles consistently by means of this method.

Our group has proposed a new method to improve the production rate and yield of silicon particles for the spherical silicon solar cells (Bojarevics *et al.*, 2006; Imanishi *et al.*, 2008). In this method intermittent electromagnetic pinch force is applied to a molten metal jet. The electromagnetic force can be applied precisely to the jet without a direct contact.

In the present study, model experiments on the breakup of a capillary jet and the formation of droplets from the jet by use of the electromagnetic force are carried out. Gallium is used as a liquid metal because it is very easy to handle due to the low melting point. Then, the breakup of the capillary jet is calculated by a numerical simulation, which consists an electromagnetic force analysis and a multiphase flow analysis with surface tracking.

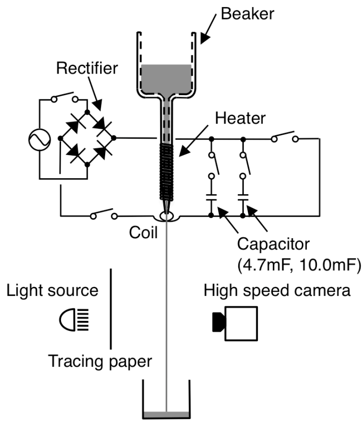

Figure 1: Experimental apparatus for the single pulse electromagnetic force experiment.

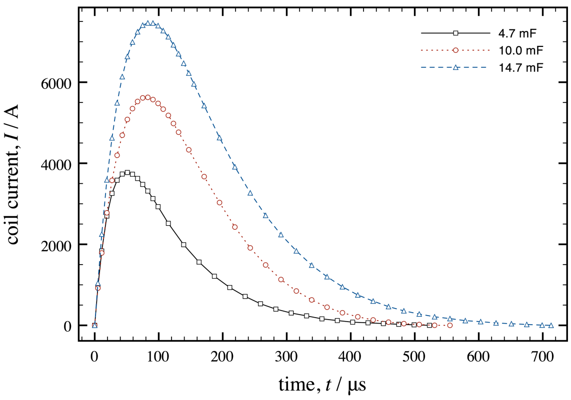

Figure 2: Change in the observed coil currents with time.

EXPERIMENTS

Our experiments consisted of two parts. The first one was single pulse electromagnetic force experiment to confirm that a liquid metal jet can be broken up by applying the electromagnetic force. The second one was intermittent electromagnetic force experiment to fabricate uniformly sized droplets from a capillary jet.

Single Pulse Electromagnetic Force

Experimental Setup

Fig.1 shows a schematic of an experimental setup. Molten gallium was heated and issued from the nozzle with mean axial jet velocity of 1.4m/s. The circuit including the capacitor, which was fully charged in advance, was shorted in order to apply a high current instantaneously to the single turn coil around the jet. Capacitance of the circuit could be selected from 4.7, 10.0, and 14.7mF, leading to a change of the coil current. To prevent oxidation of the metal surface, the experiment was run in argon atmosphere. Artem'ev and Kochetov (1991) pointed out that the breakup phenomena of a gallium jet was not affected by a surrounding gas of less than 0.2-0.3% in oxygen concentration. Shapes of the jet surface were captured by the high speed camera and the coil current was measured by a current probe. Fig.2 shows the change in the coil current with time. In the case of 14.7mF, the peak current of more than 7kA was applied to the coil.

The mechanism of the breakup by the electromagnetic force is as follows: Magnetic field around the coil and eddy current in the liquid metal jet are induced by the coil current. As a result of interaction of the magnetic field and the eddy current ($\mathbf{F} = \mathbf{J} \times \mathbf{B}$), Lorentz force is generated within the liquid metal. Fluid flow of the jet is disturbed and fluctuated by the force, and as the fluctuation grows, the liquid jet is going to be broken up.

Experimental Results

The serial photographs of the gallium jet are shown in Fig.3. The single pulse electromagnetic force was applied at 0ms. Firstly, surface fluctuation generated by the force was very small. After 10ms or more, small deformation of the surface can be observed on the photographs. As the fluctuation grew, the jet was broken up at the downstream position. The shape of the free surface seemed to be axisymmetric. The breakup length and time required to breakup of the capillary jet became shorter with the increase in capacitance. In this experiment, it was confirmed that the single pulse electromagnetic force could disturb and break up the molten metal jet effectively.

Intermittent electromagnetic force experiment

Experimental Setup

In order to fabricate uniformly sized droplets, an intermittent electromagnetic force was applied to a molten

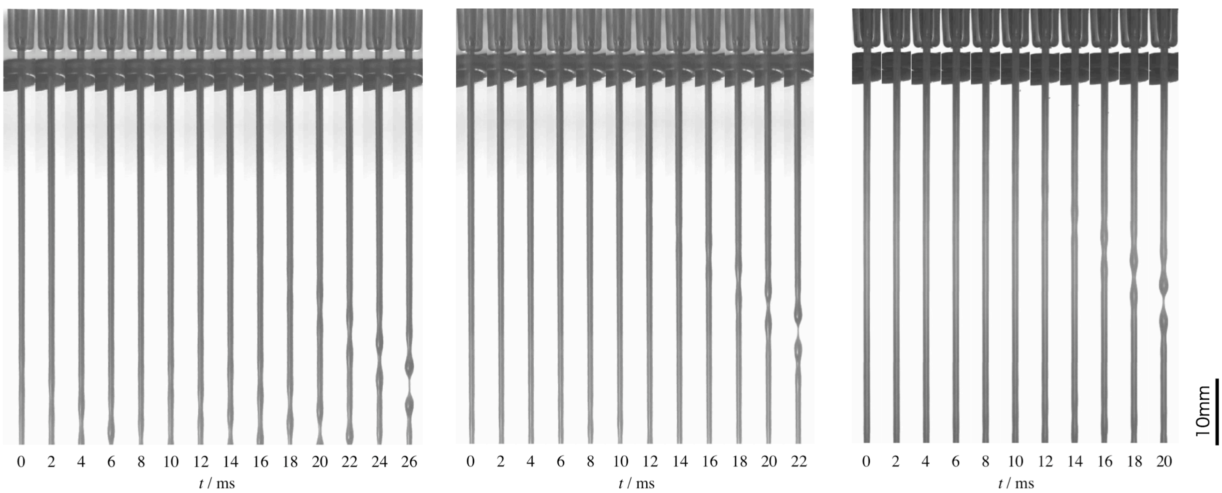

Figure 3: Serial photographs of the breakup of the gallium jet (left: 4.7mF, center: 10.0mF, right: 14.7mF).

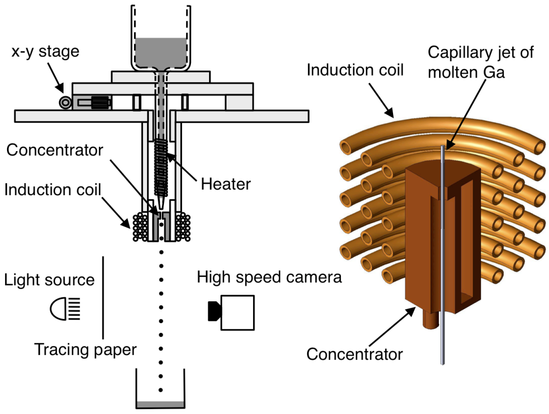

Figure 4: Schematic diagram of the droplet generator.

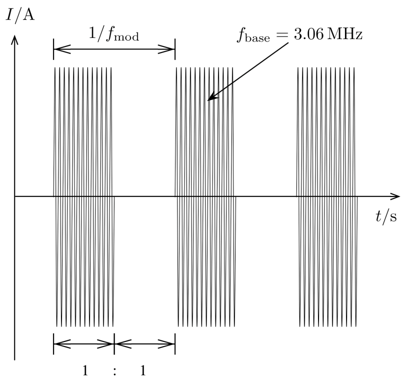

Figure 5: Schematic diagram of the modulated current.

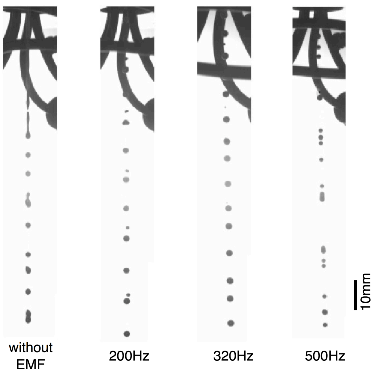

Figure 6: Photographs of the formation of the gallium droplets by the intermittent electromagnetic force.

metal jet. Fig. 4 shows schematic diagrams of the experimental setup. Same as before, molten gallium was used as a liquid metal and images of the jet were taken by the high speed camera. The droplet generator consisted of the induction coil and the concentrator. The concentrator, which was made of copper, had a tubular structure with an inward projection part on the inner surface. In addition, the concentrator was split longitudinally into two halves, which was insulated from each other. The concentrator was used to concentrate the electromagnetic force to a small region of the jet adjacent to the projection part. AC current of 51.3A$^{\mathrm{rms}}$ and 3.06MHz in base frequency, f_{base}, was applied to the coil. The current was modulated as square pulses intermittently and the modulating frequency, f_{mod}, could be changed from 200 to 1000Hz (see Fig. 5).

Experimental Results

Figure 6 shows photographs of experimental results. In the case 'without EMF', the jet didn't break up at equal interval. In the case that the modulating frequency was 200Hz, the jet broke up into droplets at equal interval; however, there were some small satellite droplets between the main droplets. The satellite droplets were formed at a neck part of the jet between the main droplets. It becomes a problem because the satellite droplets reduce the production yield of the uniformly sized particles. In the case of 320Hz, the jet broke up into uniformly sized droplets at equal interval, which corresponded directly to an optimal wavelength due to a natural instability of a liquid jet (Weber, 1931). The optimal wavelength λ is expressed as:

$$\lambda = \sqrt{2}\pi d_0 \sqrt{1 + \frac{3\mu_2}{\sqrt{\rho_2 \gamma d_0}}} \tag{1}$$

In this experiment, the optimal wavelength was 4.45mm, which corresponded to the modulating frequency of 309Hz. Thus, the jet could be broken up into uniformly sized droplets effectively, by adjusting the intermittent electromagnetic force interval close to optimal wavelength. In the case of 500 Hz, the jet didn't appear to break up at equal intervals because the frequency of droplet formation was too high, leading to coalescence.

NUMERICAL SIMULATION

Electromagnetic Force Analysis

In order to estimate the electromagnetic force generated by the single pulse experiments, the electromagnetic field analysis was conducted by use of a commercial code JMAG (JSOL Corp.). Fig.7 shows the calculation domain. Assumptions used in the calculation are as follows:

1. The system is axisymmetric.
2. Flow of the liquid metal does not affect the magnetic field.
3. The surface of the gallium jet near the coil is fixed, namely, the diameter of the jet is constant and equal to the nozzle diameter.

The second assumption is reasonable because the magnetic Reynolds number, Re_m, of the system is less than 10^{-2}. The first and third assumptions are not trivial at this stage, so they shall be reviewed later in the present paper.

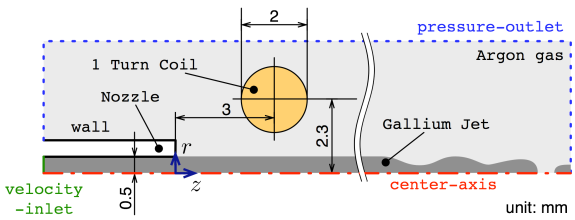

Figure 7: Schematic diagram of the calculation domain.

phase	liquid	gas
material	gallium	argon
density (kg m^{-3})	6.09×10^{3}	1.62
viscosity (Pa s)	2.04×10^{-3}	2.13×10^{-5}
surface tension (N m^{-1})	0.718	-
electrical conductivity (S m^{-1})	3.85×10^{6}	-

Table 1: Properties of materials.

Properties used in the numerical simulations are shown in Table 1. The observed coil currents (Fig.2) were used as current conditions in the calculation.

Fluid Flow Analysis

Numerical simulations on the breakup of the capillary jet is carried out by use of a commercial CFD code FLUENT (ANSYS, Inc.). In the calculations, the Volume Of Fluid (VOF) method proposed by Hirt and Nichols (1981) was used to track the free surface of the jet. The VOF is designed for two (or more) immiscible fluids where the position of the interface between the fluids is of interest. In this model, a single set of momentum equation is shared by the fluids. The properties of the mixed fluid are determined by the presence of the component phases in each control volume.

The scalar value of α_2 is defined as the ratio of the volume of the liquid over the total fluid volume. The transport equation of the volume of fraction α_2 is as follows:

$$(\partial \alpha_2 / \partial t) + \mathbf{v} \cdot \nabla \alpha_2 = 0 \tag{2}$$

where α_2 has the value 1 for liquid phase and 0 for gas phase. The scalar value α_2 is used to determine the properties of the mixed fluid in the following manner:

$$\begin{aligned} \rho_{\mathrm{m}} &= \rho_1 (1 - \alpha_2) + \rho_2 \alpha_2 \\ \mu_{\mathrm{m}} &= \mu_1 (1 - \alpha_2) + \mu_2 \alpha_2 \end{aligned} \tag{3}$$

A single momentum equation, which is dependent on the properties of the mixed fluid, is solved throughout the domain.

The surface tension model implemented in FLUENT is the continuum surface force (CSF) model proposed by Brackbill *et al.* (1992). With this model, an additional force due to surface tension is considered as a source term in the momentum equation. The pressure drop across the interface between the two fluids is

$$\Delta p = \gamma \kappa \tag{4}$$

The curvature κ is defined in terms of the gradient in the volume fraction α_2 as follows:

$$\kappa = \nabla \cdot (\nabla \alpha_2 / |\nabla \alpha_2|) \tag{5}$$

The Reynolds number of the jet was

$$\mathrm{Re} = \rho_2 d_0 v_0 / \mu_2 = 4.18 \times 10^3 \tag{6}$$

Therefore, the flow was turbulent and a realizable *k*-*ε* model was used in the simulation.

The time derivatives were discretized by an Euler implicit scheme and the convection terms are discretized by the quadratic upwind interpolation (QUICK) scheme. An Euler explicit with the geometric reconstruction scheme was used for the VOF calculation (Fluent Inc., 2006). The PISO algorithm was adopted for pressure–velocity coupling.

The electromagnetic force obtained by the electromagnetic field analysis was assigned as a source term of the Navier-Stokes equation in the fluid flow calculation.

RESULTS AND DISCUSSION

Breakup of Capillary Jet by Natural Disturbance

Firstly, a numerical simulation of breakup of capillary jet without the electromagnetic force was carried out in order to estimate an accuracy of the fluid flow analysis. Fig.8 shows the experimental result and the calculation results. The breakup length of the jet obtained by the simulation

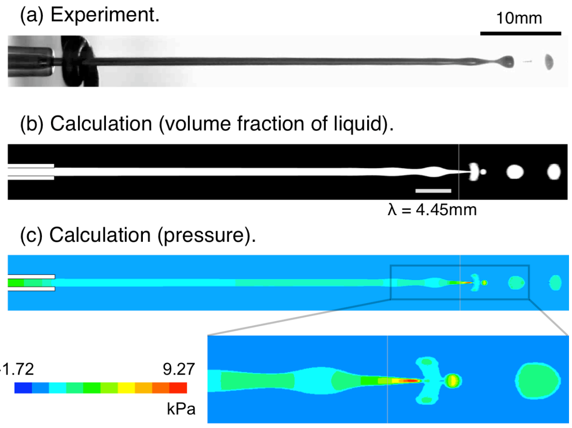

Figure 8: Breakup of the capillary jet by a growth of natural disturbance (without an electromagnetic force).

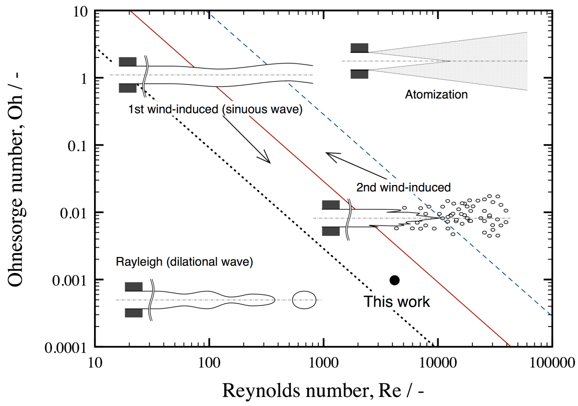

Figure 9: The Ohnesorge chart.

was shorter than the experiment (see Table 2), however the behaviour of the breakup was quite similar. As mentioned before, the optimal wavelength of perturbation on the capillary jet, which has the fastest growth rate, is 4.45mm in the present condition. The scale of the optimal wavelength is indicated in Fig.8(b). It can be seen from the figure that the wavelength of the capillary jet obtained by the numerical simulation coincides with the theoretical one. Pressure in the thinner part of the jet ('neck') was higher than the other part due to the Laplace equation (Eq.4).

Ohnesorge (1936) firstly pointed out that the breakup phenomena could be classified into several different regions on a graph of the Ohnesorge number versus the Reynolds number. The Ohnesorge number of the gallium jet were estimated as

$$\mathrm{Oh} = \mu_2 / \sqrt{\rho_2 \gamma d_0} = 9.76 \times 10^{-4} \tag{7}$$

According to the Ohnesorge chart (Fig.9; Lefebvre, 1989), the condition of the present study laid on the sinuous wave region. However, the shape of the free surface seemed to be axisymmetric from observation of the serial photographs taken by the high speed camera (Fig.3). Pan and Suga (2006) indicated that the dilational waves were still very dominant in the 1st wind-induced region although the small sinuous waves existed. This means that the jet was not axisymmetric in a precise sense. The discrepancy of the breakup length between the experiment and the simulation may arise from the assumption of axisymmetric used in the simulation.

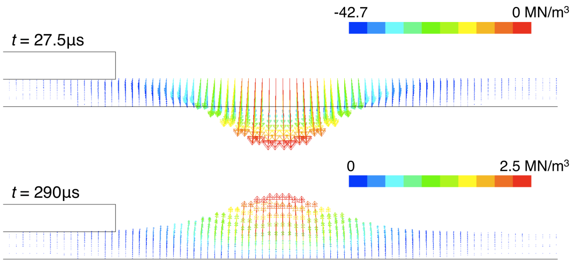

Figure 10: Electromagnetic force field (14.7mF).

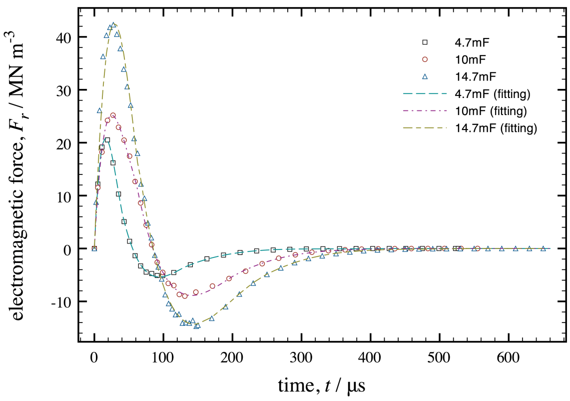

Figure 11: Change in the electromagnetic force with time.

Electromagnetic Force

Figure 10 shows the calculation results of electromagnetic force fields for the single pulse electromagnetic force experiment of 14.7mF in capacitance. At 27.5μs, the electromagnetic force pointed in a radially-inward direction, and at 290μs, the direction was changed into the opposite direction.

Figure 11 shows the temporal change in a radial component of the electromagnetic force on the free surface at the same z position of the coil. The maximum value of the force exceeded 40MN/m^{-3} in the case of 14.7mF in capacitance, which is much higher than the value of gravitational force, 60kN/m^{-3}.

Breakup of Capillary Jet by Electromagnetic Force

The calculation results of the breakup by the single pulse electromagnetic force were shown in Fig.12. By comparison with the experimental results (Fig.3), it can be said that the agreement between the two is good. The

	Exp.	Cal.
0mF (without EM force)	55-70mm	50-60mm
4.7mF	48.7mm	38.5mm
10.0mF	40.3mm	32.2mm
14.7mF	37.3mm	28.6mm

Table 2: Breakup length of the jet.

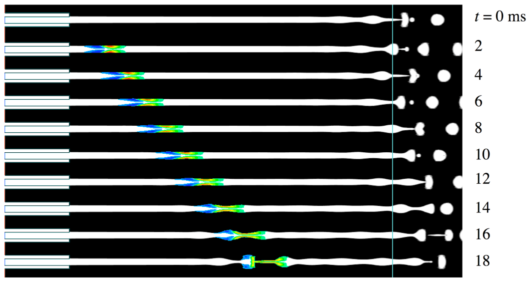

Figure 13: Region affected by the electromagnetic force (14.7mF).

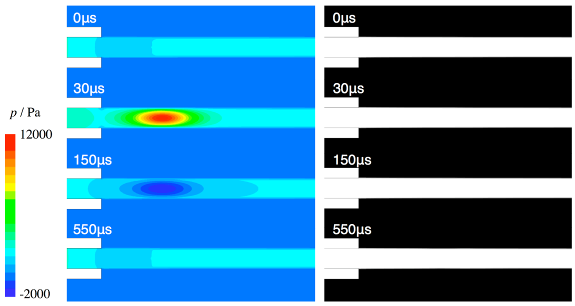

Figure 14: Pressure distribution (left) and the free surface of the jet (right) near the coil (14.7mF).

breakup lengths of the jet are summarized in Table 2. The simulations gave shorter breakup length than the experiments, however the dependency of the length on the electromagnetic force was similar.

Figure 13 shows a distribution of a passive scalar, which represents the region affected by the electromagnetic force. The jet was broken up just at the region. This indicated that the surface fluctuation was fixed on the surface, and transferred with the flow. Arai and Amagai (1999) also reported the same results of a fixed wave on the jet surface observed by their experiment.

Pressure distribution and the free surface of the jet near the coil are shown in Fig.14. The pressure in the jet was

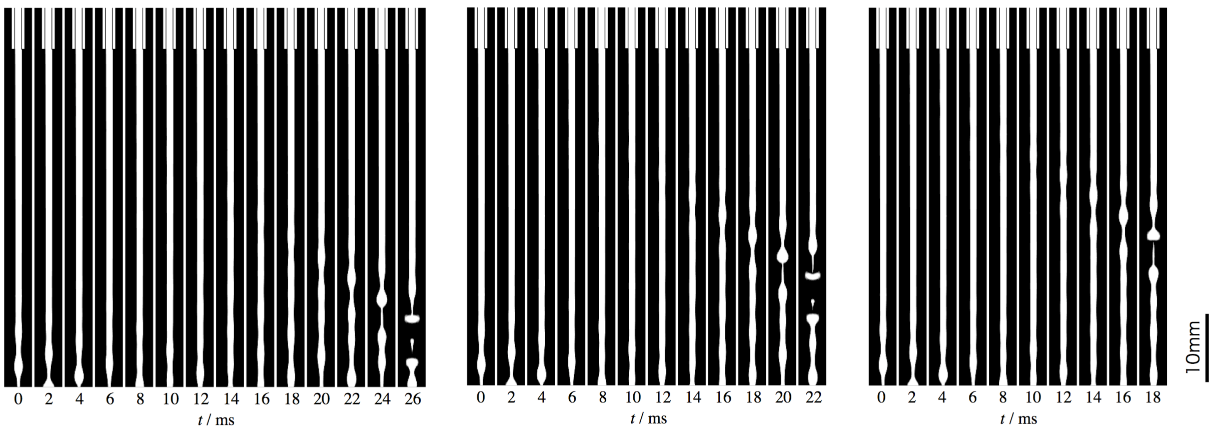

Figure 12: Numerical simulation of the breakup of the gallium jet (left: 4.7mF, center: 10.0mF, right: 14.7mF).

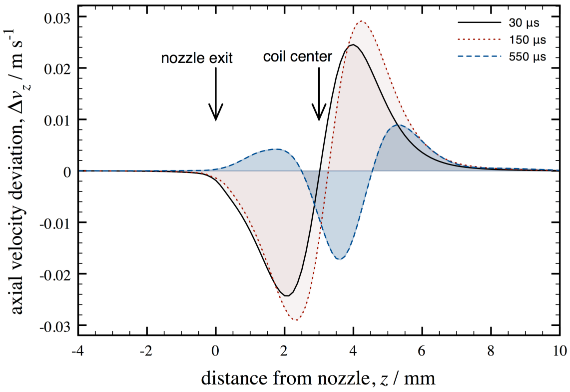

Figure 15: Axial velocity deviation from the initial velocity along the center axis.

increased by the electromagnetic pinch force, and then the pressure became negative as the force direction was changed into the opposite direction. In spite of the drastic change of the pressure, the shape of the free surface showed little change. The initial amplitude of the perturbation can be estimated by the following equation (Weber, 1931):

$$z = d_0 \ln \frac{r}{A_0} \left(\sqrt{\mathrm{We}} + \frac{3\mathrm{We}}{\mathrm{Re}} \right) \tag{8}$$

where z is the breakup position. By substitution of parameters into Eq.(8), the initial amplitude was estimated as A_0 = 0.8µm and it was very small compared to the jet diameter. So, the jet can be considered as 'a solid thin column' with the fixed surface in the electromagnetic analysis.

Figure 15 shows the axial velocity deviation from the velocity before applying the electromagnetic force. The negative value means that the axial velocity is slower than the velocity without electromagnetic force. At 30µs, the axial velocity in the upstream region above the coil ($z <$ 3mm) became slower and it became faster in the downstream region ($z >$ 3mm). The velocity deviation did not disappear after applying the electromagnetic force at 550µs and it was transferred with the flow to the downstream. This velocity deviation in the up and downstream results in the drainage of fluid from the center position and the diameter of the position becomes thinner slightly. The jet pressure at the position will be increased with decreasing in the diameter because of the Laplace pressure (Eq. 4); it will promote the fluid drainage more. This is the process of the jet breakup by the single pulse electromagnetic force.

CONCLUSION

In the single pulse electromagnetic force experiment, it was confirmed that the single pulse electromagnetic force could fluctuate the free surface of the jet and break up the jet. In the intermittent electromagnetic force experiment, it was found that the jet was broken up into mono-sized droplets when the modulation frequency of intermittent electromagnetic forces was adjusted to the optimal wavelength. The numerical simulation was carried out to simulate the breakup phenomenon of the jet by applying the single pulse electromagnetic force. The simulation results were compared with the experiments and the agreement between the two was good.

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