A New Ejector for Highly Viscous Liquid Using Inertia of Beam Buckling Deformation

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Abstract

This paper describes a newly developed ejector that uses the inertia of beam buckling deformation, which can eject highly viscous liquids of over 30mPas at room temperature, to be used for fabrication of uniform spherical particles. The ejector is simply a beam consisting of a fluid path and a nozzle located at the approximate center in the longitudinal direction. By applying compression and rotation, the concave bend of the beam gradually changes its shape in the ejecting direction, starting from both longitudinal ends. When this change approaches the center, a sudden reversal buckling occurs and the droplet is separated from the meniscus by the force of the inertia. Adequate conditions for ejecting small droplets of highly viscous liquids were estimated both from the results of experiments and fluid simulations. Requisite inertia was lowered with ease by forming rear-side openings in the fluid path. The authors also demonstrated case examples with the use of an ejector that was experimentally created.

1. Introduction

Active endeavors are being made to make use of the strengths of inkjets in application and development toward the industrial/medical fields (Digital Fabrication). In general, inkjets of a piezoelectric or thermal type are often used in DF. In such cases, the fluid viscosity that can be ejected in a stable manner at room temperature is limited to approximately 20 mPas. In DF, an inkjet that can eject highly viscous fluid is desired, for the purposes of providing broad latitude in the design of fluids, and in increasing high-functionality from the use of various additives.

The method of heating inkjet printheads is restricted to ejection of fluids that do not undergo thermal deterioration, although their viscosity can be temporarily lowered. Although there have been reports that ejection of highly viscous fluids of several hundred to several thousand mPas was performed with electrostatic attraction [1] and the acoustic wave interferometry [2], there were challenges in their application to the fabrication as such in requiring a high-voltage/high-frequency power supply, and the structure of multi-nozzle inkjets being complex.

Consequently, the authors have been progressing with the development of an ejector with a simplified structure that can eject highly viscous fluid exceeding 30 mPas at room temperature [3]. The ejector is to be used such as for the fabrication of uniform spherical particles, using the characteristics where a uniform volume of small droplets can be ejected numerously. Figure 1 represents a conceptual diagram of a method for fabricating particles where, after droplets are ejected into a receiver bath, the particles are cured in a state where their spherical shape is maintained by supplying external energy.

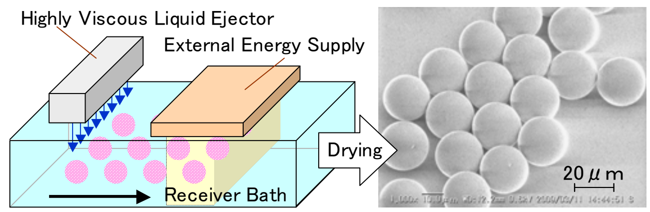


***Figure 1**. Fabrication for Uniform Particles with Inkjet*

This paper reports the results that were obtained upon investigating the inertia conditions required for forming a small drop volume of highly viscous fluid with newly developed ejector and introduces case examples of ejection, through both ejection experiments and fluid analyses.

2. Principle of Inertial Ejection

Figure 2 shows a droplet ejection method in which the energy of “motion to sudden halt” that created in association with a buckling reversal of the beam is applied to the fluid [4]. A nozzle and fluid path was built into a beam that is clamped at both ends by a beam holder. Either one or both of the ends of the beam were driven by a rotating drive-unit. By fixing the beam at a position where it is offset from the center of rotation, compression and rotation are applied simultaneously to the beam.

The beam is driven from an initial concave state in relation with the ejection direction (right direction in Fig. 2). When rotation of the drive-unit progresses, the beam changes from a concave to a convex shape, starting both ends then moving towards the center. In the end, a large-scale buckling reversal occurs from the center of the beam, and ends with a sudden stop. As a result, the fluid near the nozzle separates from the meniscus by force of the inertia in the ejection direction.

By increasing the amount of concave bending in the initial state by compressing the beam in the longitudinal direction in advance (vertical direction in Fig. 2), and by simultaneously increasing the rotational angle applied by the drive-unit, the displacement and the moving speed at the center of the beam caused by the buckling reversal, that is, the inertia applied on the fluid can be increased. In addition, the moving speed of the beam depends on the bending rigidity of the beam; for example, when compared to using simple bending of a cantilevered beam [5], greater inertia can be obtained with a lower rigidity.

There is no need to use a high-rigidity chamber or to narrow the fluid path in order to maintain pressure efficiency. A multi-nozzle ejector with multiple fluid paths arranged in a line (in front to back direction in Fig. 2) can be manufactured easily, and collective ejection is possible with the drive-unit.

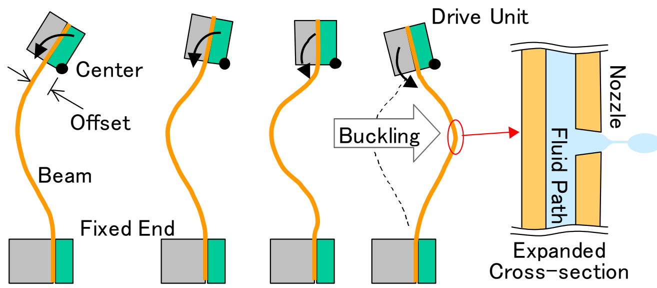


***Figure 2**. Principle of Inertial Ejection Utilizing Beam Buckling*

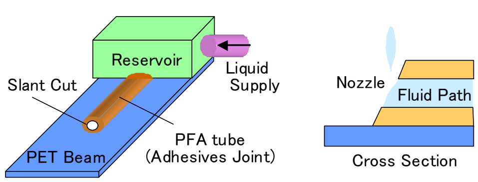
3. Experiments

Figure 3 (a) and (b) respectively represent ejectors that were experimentally created for the main purpose of behavior research of inertial ejection. Fig. 3 (a) is an ejector with a single fluid path, that was jointed a transparent PFA (Perfluoroalikoxy) tube with an inner diameter of 100 µm to a PET (Polyethylene terephthalate) beam with a thickness of 100 µm.

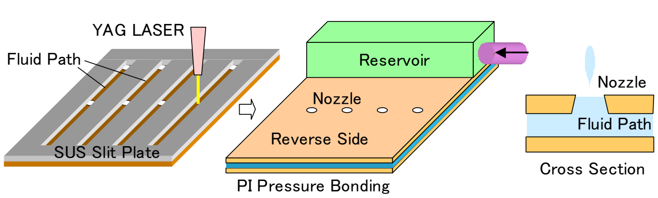
Fig. 3 (b) is a multi-nozzle ejector on which PI (Polyimide) resin of a thickness of 25 µm was laminated by thermo-compression bonding onto both sides of a 20 µm thick SUS (Stainless steel) etched with slits of 70 µm width. The nozzle of the tubular fluid path was formed by cutting the end of the tube at the longitudinal center of the beam at a 45-degree angle. For the multiple fluid paths, a YAG laser was used to bore the nozzles and the opening at the rear side that will be described hereinafter.

In addition to using purified water and 4 mPas water-based ink and as ejection fluid, diethylene glycol (DEG) of 30 mPas and glycerin water of which the viscosity was modified from several mPas to 100 mPas by the mixture ratio were used as highly viscous model fluids.

For the drive-unit used to apply compression and rotation on the beam, a mechanism where a rotational reciprocating movement can be obtained by a solenoid and cam were adopted. The movements of the droplets and the beam were observed using the stroboscopic method and a high-speed camera. In measuring the drop volume, a method for measuring the diameter of the droplets ejected into the medium was used.



***(a)** Single Nozzle Ejector with PFA Tube*



***(b)** Multi Nozzle Ejector by Stacking SUS and PI*

***Figure 3**. Schematic Views of Ejector's Structure*

Flow3D was used for fluid analysis, and a 2-dimensional polar coordinate model where nozzles were set on a cylindrical chamber with a diameter of 200 µm and height of 100 µm was developed. The chamber was moved and halted after having been filled with liquid. The deceleration/braking time (hereinafter called "braking time") is defined as the time from when, an initial moving speed of 10 m/s starts to decelerate at a certain time and becomes 0. In addition, inertia was changed by moving speeds and travel distances, and fluid behavior was compared.

4. Results and Discussion

4.1 Basic Experiment with Hollow Tube Ejector

Figure 4 shows the relationship between fluid viscosity and drop volume when, using a tubular fluid path, the travel distance of the beam was changed, to 2, 3 and 4 mm during buckling reversal at a drive of 2 Hz. For several results, the state of the meniscus and the droplets that were observed immediately after ejection through the fluid path were described together.

Based on Fig. 4, it is evident that the drop volume, of which had been roughly 250 pl per 1 mPas fluid, decreases suddenly in accordance with an increase in viscosity. There was no ejection of the 100 mPas fluid in an area with small travel distance. However, ejection occurred when the travel distance was increased, and the small drop volume of 50 pl tested at a travel distance of 3 mm, increased to approximately 70 pl at a travel distance of 4 mm. In the scope of this experiment, the drop speed was approximately 5 m/s in relation to a beam moving speed of 5 m/s when immediately before the braking happened.

Based on the observations, a refill delay is inferred as being the direct cause of the decrease in drop volume that is associated with an increase in viscosity. In other words, when inertia is small and the meniscus retreats once due to an ejection, the restoration of the highly viscous fluid is delayed due to friction in the fluid path, and the fluid remains in a retreated state. Under the conditions of this experiment, the fluid volume of the nozzle itself decreased, and the drop volume also decreased or became 0.

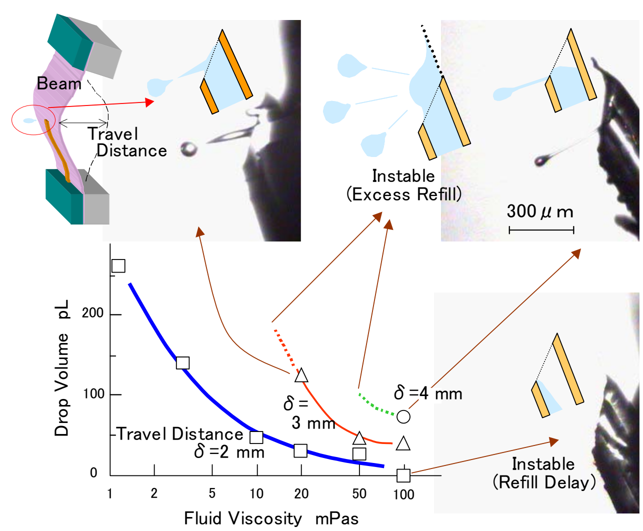


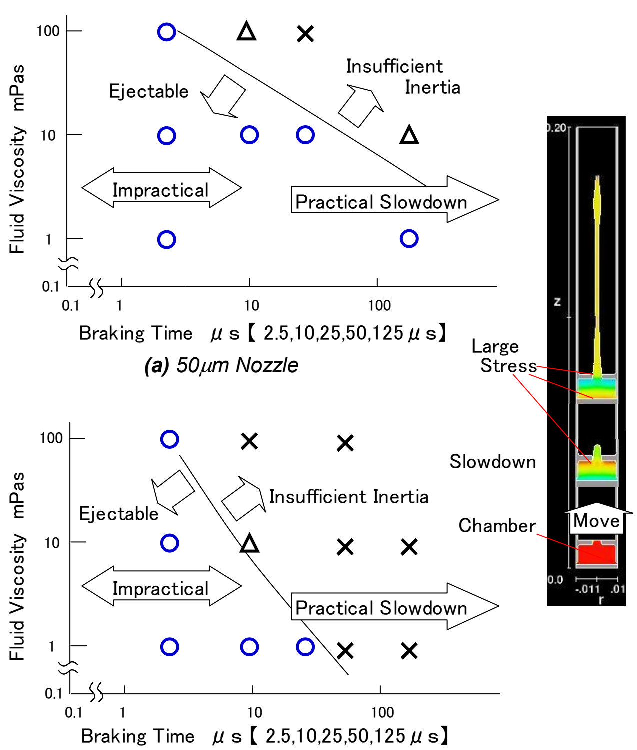
***Figure 4**. Relation between Fluid Viscosity and Droplet Volume under Different Inertia*

Conversely, when inertia is large, refill is sufficient or in excess due to the “centrifugal force directed toward the nozzle” that acts on the fluid in accordance with buckling reversal. For example, as indicated on Fig. 4, there is excess refill, resulting in an overflow of fluid and instable ejection (observations difficult), for the 10 mPas fluid at a travel distance of 3 mm and the 50 mPas fluid at a travel distance of 4 mm.

In relation to the refill delay of highly viscous fluid that occurred in the experiment, when high back pressure is applied to move the meniscus forward for ejecting small droplets, the balance of the nozzle fluid level is disrupted, an overflow occurs, and ejection becomes difficult. In order to eject small droplets, structural discipline of the small diameter nozzles is needed. However, there was insufficient inertia and stable ejection was not possible with ejectors that had been bored with 25 µm and 50 µm nozzles, even with low-viscosity fluids. As a result, the conditions necessary for ejection of small drop volumes of highly viscous fluids were subsequently analyzed and examined.

4.2 Adequate Condition by Fluid Simulation

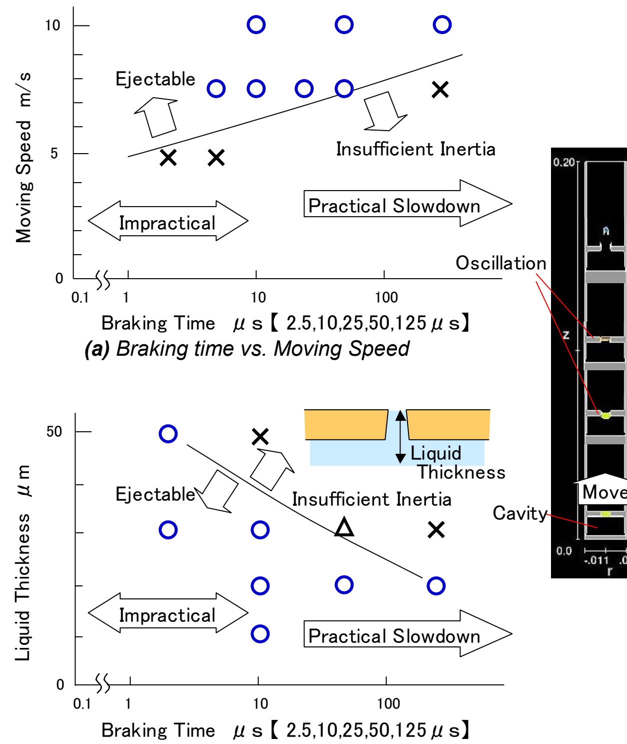
Figure 5 (a) and (b) respectively show whether ejection is possible for 25 µm and 50 µm diameters nozzles, at an initial moving speed of 10m/s. The fluid viscosity is set at 1 mPas, 10 mPas and 100 mPas, and the braking time is changed from 2.5 µs to 125 µs. In the figures, ○ represents cases where the droplets were separated and ejected. △ represents cases where a liquid column formed but separation was insufficient. × represents cases where only a slight liquid level elevation formed.



(a) 50µm Nozzle

(b) 25µm Nozzle

***Figure 5**. Requisite Conditions for Inertial Ejection*



(a) Braking time vs. Moving Speed

(b) Braking time vs. Liquid Thickness

***Figure 6**. Decrease in Inertia by Rear Opening*

The behavioral diagram of the fluid that is also included with these figures is of a time when 100 mPas fluid was decelerated and stopped for 2.5 µs with a 50 µm nozzle. The state of inertial separation was observed, and it is inferable that the factors inhibiting inertial separation can be generally classified into resistance that occurs when the fluid passes through the nozzle and separates, and the resistance that occurs when the fluid attempts to break away at the bottom surface of the chamber.

From Fig. 5 (a) and (b), it is evident that an increase in the fluid viscosity and the braking time (decrease in inertia) causes ejection difficulty. Although a 50 µm nozzle enables ejection with smaller inertia than a 25 µm nozzle, in order to eject fluids of over 10 mPas, it was necessary to apply strong inertia for both nozzles by sudden and unrealistic braking in an order of several to 10 µs. Therefore, as a measure to decrease the inertia required for ejection, the structure was changed to one where the chamber was opened by adding a cavity in order to reduce the resistance.

Figure 6 (a) and (b) show whether ejection was possible using a nozzle with a diameter of 50 µm and fluid with a viscosity of 100 mPas, when the braking time and moving speed, and the braking time and liquid film thickness were changed, respectively. Liquid film thickness was defined as the distance from the nozzle surface to the upper end of the cavity that was added. The behavioral diagram of the fluid that is also included with these figures is of a time when 100 mPas fluid was decelerated and stopped for 50 µs with a 50 µm nozzle.

From the behavioral diagram, it can be seen that the fluid, which was initially in form of a membrane near the nozzle, temporarily retreats due to the force in the reverse direction acting on the fluid as a result of the chamber ascent. Afterwards, when deceleration and braking begins, the fluid level is oscillated and restored, and a phenomenon, where the fluid separates in the upward direction when chamber stops moving, is also observed.

Firstly, Fig. 6 (a) shows that when moving speed is decreased, ejection is not possible unless the braking is made more sudden, and that ejection is made easier when making the bottom surface of the chamber into a free surface. In this analysis, when the moving speed is less than 5 m/s, ejection was difficult even if a sudden and unrealistic braking was performed. Next, based on Fig. 6 (b), as it was perceived that the thinner the liquid film thickness, the easier ejection becomes. Furthermore, shear resistance with the nozzle inner wall is significantly reduced when the film thickness is 20 µm, inertial separation of droplets was possible even at a braking time exceeding 100 µs.

There is a tradeoff in determining the moving speed, the travel distance and the braking time, because excess inertia tends to cause lost motion of the beam buckling. From the above analysis, the small adequate inertia necessary for ejection, with an ejector where the bottom surface of the chamber was opened has been found. Since it was also confirmed that maintaining a thin liquid film is necessary in order to reduce the inertia necessary for ejection, a multi-nozzle ejector with a large opening at the rear side of the fluid path was then experimentally created and the state of ejection was examined.

4.3 Demonstration of Multi Nozzle Ejection

Figure 7 is SEM images of nozzles. One image shows a bored square nozzle of a 50 µm, observed from the surface side. The next image shows the nozzle rear surface observed from the opposite side of ejection area through a large opening.

Figure 8 (a) and (b) respectively show results that were obtained from stroboscopic observation when DEG was ejected, and from when a medium was set up at a distance of approximately 5 mm, and water-based ink was ejected, using the 30-nozzle ejector with the above mentioned configuration. In the experiment, the ejection frequency was 10 Hz and fluid was supplied from the upstream side of the fluid path with a backpressure of 0.5 kPa. In addition, negative pressure was applied on the downstream side in order to enable for both the overflow of fluid from the rear opening to be prevented and for the nozzle liquid film to be maintained at an optimum level.

In contrast to ejection being difficult due to insufficient inertia when there is no large opening on the rear surface, it is evident based on Fig. 8 that a small drop ejection is now seen. The drop volume as calculated from observations was approximately 110 pl with the 50 µm square nozzle and 25 pl with the 25 µm square nozzle, for both DEG and ink.

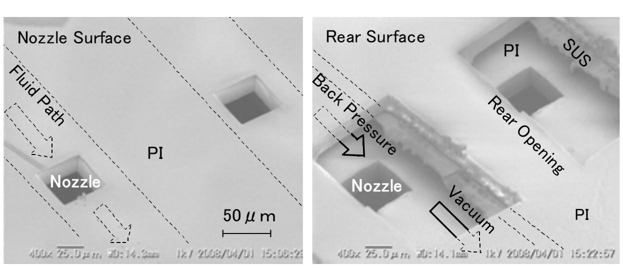
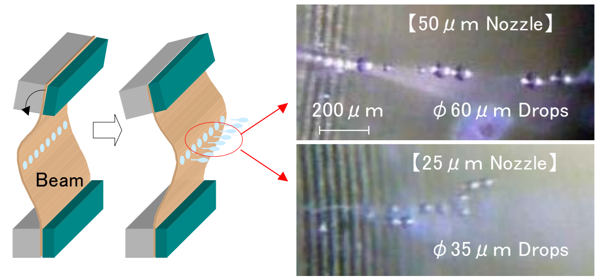
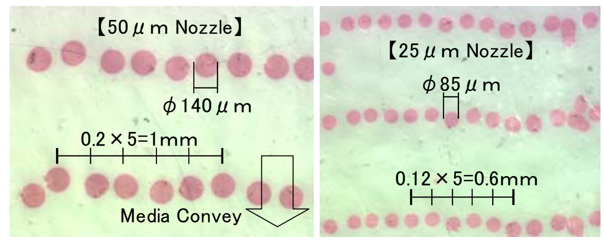


***Figure 7**. SEM views of Rear-opening Ejector*



***(a)** Stroboscopic Drop View of 30mPas DEG*



***(b)** Media Impact Shape of 4mPas Ink*

***Figure 8**. Demonstrations of Multi-nozzle Ejector*

5. Conclusion

Using buckling reversal of beams, an ejector that enables inertial separation of highly viscous fluid was developed. Based on ejection experiments and fluid analyses, it was demonstrated that ejection could be facilitated by the use of a structure where a large opening is made on the rear surface of the fluid path. As conditions for ejection of a small drop volume of highly viscous fluid, the braking time of the beam, the moving speed and other necessary inertial forces were estimated and case examples were also presented for 2 Hz single nozzle ejection of 50 pl drops for 100 mPas fluid and 10 Hz multi nozzle ejection of 25 pl drops for 30 mPas with an ejector that was experimentally created.

Droplet ejection in the order of several to 10 pl of 100 mPas fluid and an increase in the ejection frequency will become a challenge in the future.

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Author Biography

Torahiko KANDA received his B.E. and M.S. degrees in mechanical engineering from Yokohama National University in 1986 and 1988, respectively. He joined Fuji Xerox Company Limited in 2004, and is now Research Leader of the Ink Jet Technology Laboratory, Research & Technology Group. He has been engaged in research and development of precision machining for ink jet printhead.