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# Surface wave propagation on highly viscous liquid jet
高粘性液体ジェットの波動伝搬

Tomoki Ishiwata[1‡] and Keiji Sakai[1] ([1]Inst. Indust. Sci., Univ. of Tokyo)
石綿 友樹 [1‡], 酒井 啓司 [1] ([1]東大 生研)

## 1. Introduction

The properties of liquids, such as, the surface tension and the viscosity, play an important role in the fluid process under huge deformation rates, over ~$10^4$ $s^{-1}$, in, such as, the spin-coating, offset printing and inkjet technology. It has been difficult, however, to measure these properties directly under such extra-ordinal conditions.

A few methods has been reported; Kutsuna et al. observed the oscillation of a fluid particle generated by collision of two same-sized droplets emitted with two face-to-face inkjet devices[1]. With this method, we can obtain the surface tension and the viscosity of the droplets from the frequency and the decay of the oscillation, respectively. On the other hand, it remains still difficult to measure high viscosity, over ~10 cP because of overdamping of the droplet oscillation.

In this paper, we introduce the simultaneous measurement technique of the surface tension and the viscosity for the highly viscous liquid (~50 cP) using the liquid jet breakup. The jet breakup is caused by the capillary force of the surface tension, and the viscosity and the inertia resist it. In addition, the jet is pulled back to the inkjet nozzle by the capillary force. Therefore, if density of liquid is known, we can obtain the properties by analyzing the behavior of the liquid jet.

## 2. Theory

Generally, the liquid jet is unstable because of the fluctuation on the jet and spontaneously breaks into several particles. In the continuous-mode inkjet, this instability of the jet is preferably applied to high speed droplet generation; a liquid jet is fountained from a nozzle with constant pressure, to which perturbation of the pressure is applied by a piezoelectric transducer. In this case, the jet velocity $v$ is represented by $v = v_j + v_s \sin(2\pi f t)$ where $v_j$ is the mean jet velocity and $v_s$ and $f$ are the amplitude and the frequency of the modulation caused by the transducer, respectively. The wave generated with the modulation spontaneously grows up and divides the jet into droplets.

The jet spouted from the nozzle is pulled back to the nozzle by the capillary force. Therefore, we can obtain the value of the surface tension from the measurement of the jet and droplet velocity. Because of difficulty in the direct measurement of the jet velocity, we use the conservation law of the mass and the momentum. The conservation law relates the initial velocity to the droplets velocity as

$$\pi a^2 v_j = 4/3\,\pi r_d^3 v_d f \tag{1}$$

and

$$\rho(v_j^2 + v_s^2/2) r_j^2 - r_j \sigma = 4/3\,\rho r_d^3 v_d f\ , \tag{2}$$

where $a$ is the initial radius of the jet, $r_d$ a radius of the droplets, $\rho$ and $\sigma$ are the density and the surface tension, respectively, and $v_d$ the velocity of droplets[2]. At the limit of $v_s \ll v_j$, we can obtain the surface tension, according to Eq. (1) and Eq. (2).

The analysis of the experimental results was carried out along the theory3) describing the temporal evolution of the fluctuation in the thickness of the liquid cylinder.

## 3. Experiment

A schematic view of our equipment of the jet emission is shown in **Fig.1**. The equipment is composed of a glass nozzle, two piezoelectric actuators, a liquid tank and a pressure source. As the nozzle, we employ a glass capillary with a squeezed edge and an aperture diameter of 8-30 μm. We use an air compressed up to ~0.7 MPa for the lowly viscous liquid and a $N_2$ gas with ~14.7 MPa for highly viscous liquid as the pressure source. The pressure of about 50 kPa is required to generate the jet of 1 mPa・s with the initial velocity of a few m/s. The required pressure is found to be proportional to the viscosity of the jet. The glass capillary is sandwiched between two piezoelectric actuators, that generate the sinusoidal modulations of the liquid pressure to induce the perturbation on the jet

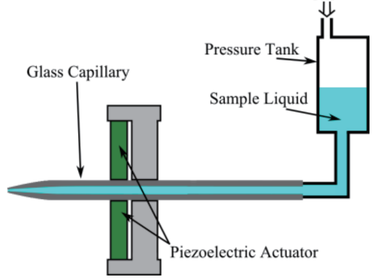

Fig. 1 Schematic view of our continuous-mode

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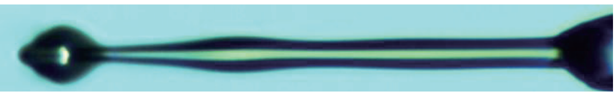
ishiwata@iis.u-tokyo.ac.jp

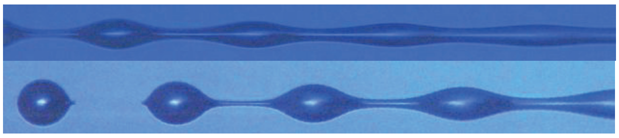
surface. The frequency of pressure modulation $f$ is about 10 kHz. We used silicone oil as a sample liquid in this experiment.

In order to observe the jet and droplets, a microscope with a stroboscopic observation system is employed. The Strobe light with the duration of 40-180 ns illuminates the particles synchronizing with the piezoelectric driver and the delay circuit.



a) 1cSt silicone oil

b) 10 cSt silicone oil



c) 50 cSt silicone oil

Fig. 2 Microphotograph of the emission of silicone oil

## 4. Results and Discussion

**Figure 2** shows the emission of silicone oils of 1, 10 and 50 cSt. The droplets fly with the velocity of 3.9, 1.4 and 1.9 m/s, respectively. The radii of the jets are 5.6, 17.1, 17.3 μm, and those of droplets are 11.8, 31.0, 38.8 μm, respectively. With these values and Eqs. (1) and (2), we calculated the velocities of the jets and the surface tensions. The obtained velocities are 4.8, 2.0, 2.3 m/s and the surface tensions are 19.2, 17.4, 16.3 mN/m, respectively.

We also measured the viscosity from the wave on the jet. Because of the shrinkage of the jet due to the surface tension, the wave is deformed from the harmonic oscillation. Therefore, only the form of the restricted portion of the jet is used for the fitting. The growth rates of the jets are 6.7, 6.1, 1.3 mm$^{-1}$ for the wave numbers of 23, 29, 26 mm$^{-1}$, respectively, and the viscosities are determined to 1.7, 6.5, 41 m Pa･s.

The experimentally obtained surface tension and the viscosity roughly agree with the literature values. Some reasons are considered to explain the discrepancy; the microscopic measurement may give an error as large as 1 μm. Besides, the velocity of the jet is given by the cubic of the radius of the droplets and the square of the radius of the jet. Error of 1 μm in determining them would lead to the discrepancy of 30 % in velocities. Accuracy in determining the jet velocity can be improved easily, however, by measuring the consumed amount of the liquid, for example.

In any way, we succeeded in measuring the surface tension and the viscosity under the huge deformation rate as

$$\dot{\varepsilon} \sim \frac{k}{2\pi}\frac{dr_j}{dt} \sim \frac{k\omega r_j}{2\pi} \qquad (5)$$

,which is in the order of 100-1000 s$^{-1}$.

Table I The values of the surface tension and viscosity obtained with the catalog[4] and measurement

| | **$\sigma_{ref}$ (mN/m)** | **$\sigma_{exp}$ (mN/m)** | **$\eta_{ref}$ (mPa･s)** | **$\eta_{exp}$ (mPa･s)** |
|---|---|---|---|---|
| 1cSt | 16.9 | 19.2 | 0.818 | 1.7 |
| 10cSt | 20.1 | 17.4 | 9.35 | 6.5 |
| 50cSt | 20.8 | 16.3 | 48 | 41 |

## 5. Conclusion

We developed the measurement method of the surface tension and the viscosity under the huge deformation rate (~1000 s$^{-1}$) with the jet break method. The dynamic properties were roughly agreed with the static properties for silicone oil of 1-50 cSt. We need to devise the technique for the measurement of the radius of the jet and droplets in order to obtain the accurate properties.

## 6. Refference

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