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# Precise measurement of liquid viscosity and surface tension with an improved oscillating drop method

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An improved oscillating drop method was developed to measure the surface tension and viscosity of a liquid without any external forces under microgravity conditions. The combination of a drop levitation system, a laser backlight system, and a line sensor enables the properties to be measured precisely. The surface tension value from 68.9±4.3 mN/m to 71.8±4.5 mN/m and the viscosity value of $0.92\times10^{-3}$ Pa s were obtained at 23.5 °C for pure water. These values agreed quite well with the reported value.

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The oscillating drop method is an attractive method for measuring thermophysical properties of a liquid. Using this method, the properties can be measured without contamination because the sample does not come into contact with any substrates or crucibles. In addition, the properties can be measured over a wider temperature range, because an undercooled state can be easily achieved and no reaction occurs with the crucible at higher temperatures. The basic theory of this method was established by Rayleigh [1] and Lamb [2], and the following equations were given for the calculation of these properties. Surface tension can be calculated using

$$\gamma=\frac{3\pi M\nu^2}{n(n-1)(n+2)}, \tag{1}$$

where $\gamma$ is the surface tension, $M$ is the mass of the droplet, $n$ is the label for oscillation mode, and $\nu$ is the oscillation frequency. Viscosity can be calculated using

$$\eta=\frac{3}{20\pi}\frac{1}{\tau}\frac{M}{R}, \tag{2}$$

where $\eta$ is the viscosity, $\tau$ is the modules of decay, and $R$ is the droplet radius in the stable state. In practice, some difficulties occur when applying the theories, because the droplet is usually under conditions different from the ideal ones. For example, the droplet can be distorted or rotated [3] by a given force field [4]. Some correction formulas have been proposed [5,6] and some technical efforts have been made [4]. However, the best way is obviously to measure without any external forces and use the simple basic equations. In this study, the drop-shaft type microgravity facilities of the JAMIC (Japan Microgravity Center) and the MGLAB (Microgravity Laboratory of Japan) were used to remove all forces acting on the droplet. In addition, the positioning forces such as an electromagnetic force, electrostatic force, and acoustic force, were also removed. For this purpose, apparatus equipped with a line sensor and a laser backlight system was developed.

Figure 1 shows a schematic diagram of the droplet formation system. At first, a droplet is placed between two needles facing each other. Next, the needles are moved backward very quickly. In this case, the reduction of the initial speed of the droplet is required because the droplet is significantly magnified for the precise detection of its small oscillations. When the initial speed is high, the droplet moves to the outside of the observation area in an instant. The experimental apparatus was designed to overcome these difficulties through the following trial.

The geometry of the needle is one of the important factors. The tip of the needle was sharpened like a circular cone. While the needle with this geometry is pulled out from the droplet, the total interfacial free energy between the needle and the droplet decreases gradually. This gradual decrease in the free energy gives a smaller force to the droplet and enables the needle to be smoothly pulled out of the droplet. When needles with a flat tip are used, the interfacial free energy suddenly decreases at the tip and a strong force is applied to the needle.

The wettability of the needle by the droplet is also an important factor for the stable levitation of the droplet. The better the wettability is, the stronger the force is generated

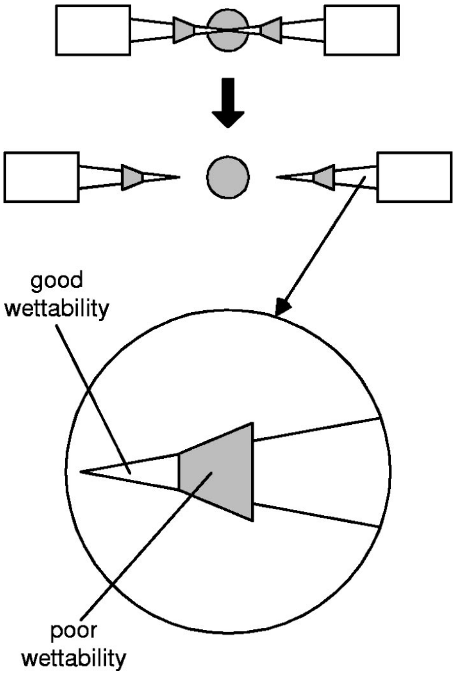

FIG. 1. Schematic diagram of the droplet formation system.

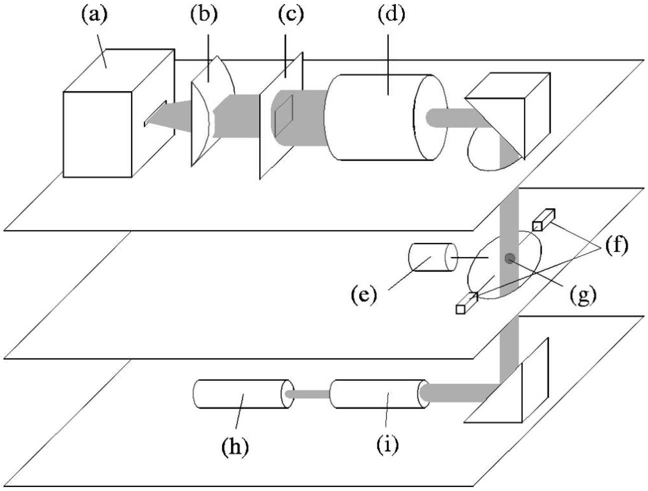

FIG. 2. Schematic diagram of the measurement system (a) line sensor, (b) cylindrical lens, (c) square slit, (d) beam expander, (e) liquid supplier, (f) needle, (g) levitated droplet, (h) laser, (i) beam expander.

between the droplet and the needle. In this case, it seems better to use a material with poor wettability. However, when a poor-wetting material is used for the needles, the droplet cannot surround the needle, and consequently it adheres to a part of the needle. When the needles are pulled away under these conditions, the droplet is pulled toward the other side of the adhering position. When a material with good wettability is used for the needles, the wettability of the two needles must be controlled to be exactly equal. A slight difference in the wettability generates unbalanced wetting of the two needles. Based on these considerations, good-wetting needles partially covered with a poor-wetting film have been adopted. The areas of the good-wetting surface of the two needles can be controlled to be same by the film. Using these types of needles, the initial speed is controlled at almost zero.

Figure 2 shows a schematic diagram of the experimental apparatus. A small droplet of approximately 18 mg was used in this study. For a smaller droplet, the resonance oscillation frequency is larger and its damping rate is also higher. In this case, the observation can be finished in a short time. A line sensor is suitable for recording such fast and small oscillations. The line sensor (DALSA Co. Ltd.) used in this study can record 7200 lines per second with 2048 pixels. The number of pixels is much larger than that of the one line in an area charge-coupled device (CCD) used for an ordinary high-speed video camera. The recording rate is also higher than that of an area CCD with the same pixels for one line.

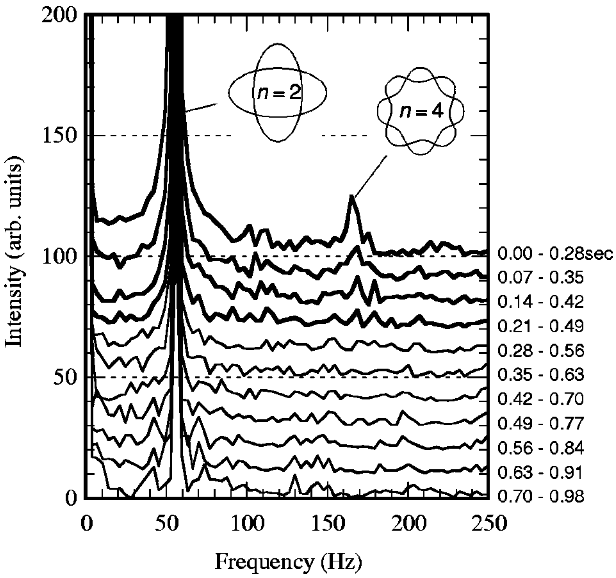

FIG. 4. Fourier spectrums of the change in the maximum diameter for the initial period.

In order to measure the amplitude precisely, the diameter should be measured at its maximum, that is, when the phase of the oscillation is $\pi/2$ rad. Under the conditions of this study, the period of the surface oscillation is approximately 0.018 s. For this frequency, the line sensor can record 128 lines per period, and this recording rate corresponds to the phase resolution of 0.05 rad. Accordingly, the sensor can measure the diameter at the oscillation phase of $\pi/2 \pm 0.025$ rad. This means that the sensor can measure the diameter with an error of 0.1%. The shadow of a 3-mm-diameter droplet occupies about 850 pixels and the error of the measured diameter is also nearly 0.1%.

A laser backlight system alleviates away complicated focusing problems. It is generally difficult to observe a moving object with keeping it in focus. Even when an autofocusing mechanism or a lens with a wide depth of field is used, the observed size of the object changes as it moves. In this system, the laser is focused on the line sensor by a cylindrical lens. The shadow of the droplet can be observed as a dark line on the sensor, and using this method, the maximum diameter of the droplet can be recorded for any position of the droplet. When the droplet moves inside the laser column, the precise maximum diameter can be measured because a laser is a parallel ray. In particular, the droplet can move for a long distance in the direction of the laser axis because the laser column is long in that direction.

Figure 3 shows data recorded by the line sensor. One line is recorded over a period of 1/7200 s, and the next line is added to the right-hand side. This indicates that time passes from the left to the right in this image. It is found that the droplet moved about 3 mm in about 1 s and that the oscilla-

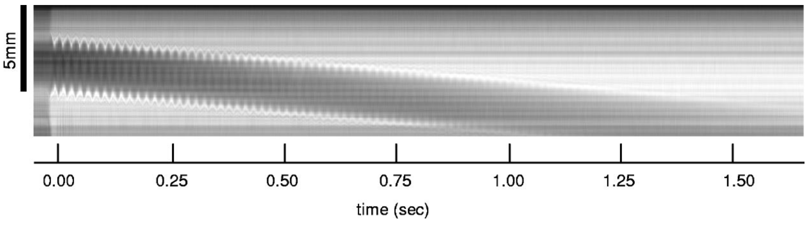

FIG. 3. Data recorded by the line sensor.

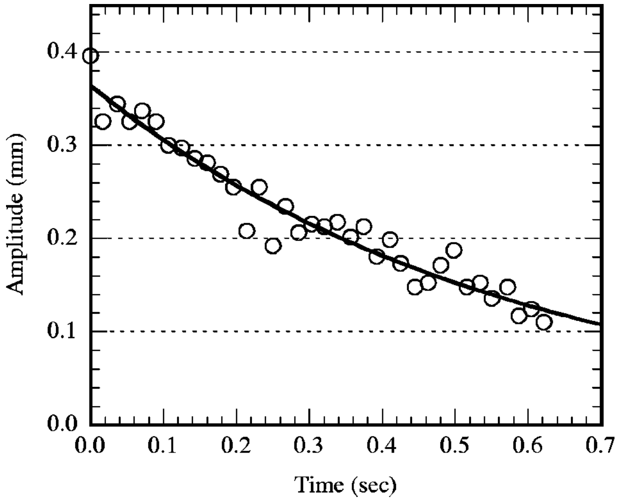

FIG. 5. Damping of the surface oscillation.

tion was observed during this period. The change in the maximum diameter is measured from both edges of the droplet and converted into the real length using scales, which were determined by using three steel ball bearing spheres of different sizes. In order to remove the effect of any initial deviations, the initial change in the oscillation was investigated in detail using Fourier spectrums of the change in the maximum diameter for the initial period. In this levitation method, odd-order oscillations are not easily generated because the initial oscillation is generated by the two straight needles. In Fig. 4, only the oscillations of the $n=2$ mode and the $n=4$ mode are recognized. However, oscillation of higher $n$ mode is generally damped very quickly. In this case too, the oscillation of the $n=4$ mode is damped within 0.28 s. Accordingly, only the data after 0.28 s are used to calculate $\tau$. Figure 5 shows the change in the amplitude and the fitted damping line. The calculated value of $\tau$ is 0.525 s, and the calculated viscosity is $0.92\times10^{-3}$ Pa s. This value is very close to the reported value of $0.924\times10^{-3}$ Pa s at 23.5 °C [7].

In this method, no external force acts on the droplet after the levitation, and consequently, the measured oscillations show only single peak for the oscillation of the $n=2$ mode in the Fourier spectrum. This fact guarantees that the shape of the droplet is spherical and Eq. (1) can be used to calculate the surface tension without any corrections. Surface tension values of $68.9\pm4.3$ mN/m, $71.8\pm4.5$ mN/m, and $70.0\pm4.0$ mN/m are calculated from three different experimental runs. These values are very close to the reported value of 72.4 mN/m at 23.5 °C [8]. The scatter of these results come from the slight difference in the droplet mass, and the measured frequencies were the same for the three runs. The accuracies are calculated from the resolution of the Fourier spectrums. As the oscillation frequency is higher, the resolution is higher relatively, and the higher resolution of Fourier spectrum is also obtained for the longer observation time.

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