Title	Oscillation analysis of an electromagnetic levitated droplet for determination of its surface tension(Physics, Processes, Instruments & Measurements)
Author(s)	Matsumoto, Taihei; Fuji, Hidetoshi; Nogi, Kiyoshi
Citation	Transactions of JWRI. 2001, 30(2), p. 11-15
Version Type	VoR
URL	https://doi.org/10.18910/9878
rights	
Note	

Oscillation analysis of an electromagnetic levitated droplet for determination of its surface tension†

Taihei MATSUMOTO*, Hidetoshi FUJII and Kiyoshi NOGI*****

Abstract

Shape changes in a levitated droplet dominate the surface oscillation mode, and affect the apparent surface tension value of the droplet. The effect of those changes was investigated using the electromagnetic levitation method under microgravity conditions. The microgravity conditions were produced with a drop shaft system at JAMIC (Japan Microgravity Center). All experiments were carried out in an atmosphere of purified Ar-3%H_2 gas. The sample temperature was measured with a two-color pyrometer, and all samples were weighed before and after the experiments. Surface oscillations of a droplet were recorded with two high-speed video cameras. Measured images were analyzed by digital image processing. The coil system consists of a positioning coil and heating coil, which generate quadru -poles and di-poles respectively. The equilibrium shape of the droplet can be controlled by changing the current ratio for the coils. Consequently, it has become clear that even a small change in the equilibrium shape affects the distribution of oscillation frequencies.

KEY WORDS: (Microgravity) (Surface Tension) (Droplet) (Surface Oscillation) (Silicon) (Electromagnetic Levitation)

1. Introduction

The surface tension of liquid materials is one of the most important parameters in many industrial processes involving the molten state. For example, in casting and welding, the surface tension has a great effect on the shape and microstructure of the products and the resultant strength. Although numbers of surface tension data have been obtained for molten silicon, there is a large difference between the reported values.[1-11] This is mainly because the surface tension of molten silicon is quite sensitive to surface contamination, in particular to oxygen. Oxygen is easily taken in from the equipment and environment in conventional techniques such as the sessile drop method. For example, in the sessile drop method, the oxide substrate is one of the sources of contamination and the hot wall of the ceramic tube for a resistance heater is another source. These sources of contamination are more important at higher temperatures. On the other hand, the electromagnetic levitation technique has many advantages in measuring thermophysical properties of undercooled, or highly reactive melts. Since in this technique, the sample does not come into contact with any crucible or substrate, which is usually the major source of heterogeneous nucleation sites and contamination.[12, 13]
However, under terrestrial conditions, the thermophysical properties cannot easily be measured with this technique because the shape of a molten semiconductor is distorted from a spherical shape due to gravity and the balanced magnetic force. Under microgravity conditions, on the other hand, the shape of a levitated drop is close to a sphere and can be controlled more easily. It is thought that the equilibrium shape of a liquid should greatly affect the oscillation condition. The relationship, however, has not been discussed in detail. In this study, the shape of a drop is controlled by changing the output ratio for two different coils and the effect of the shape on peak distribution is investigated.

2. Experiments

Figure 1 shows a schematic diagram of the electromagnetic levitation apparatus. The size of the apparatus is about $1m^3$. As shown in this figure, the apparatus is equipped with a radio frequency generator, batteries, a pyrometer, high-speed video cameras, and an infrared radiation heater. The radio frequency generator

† Received on February 1, 2002
* Research Associate
** Associate Professor
*** Professor

Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan.

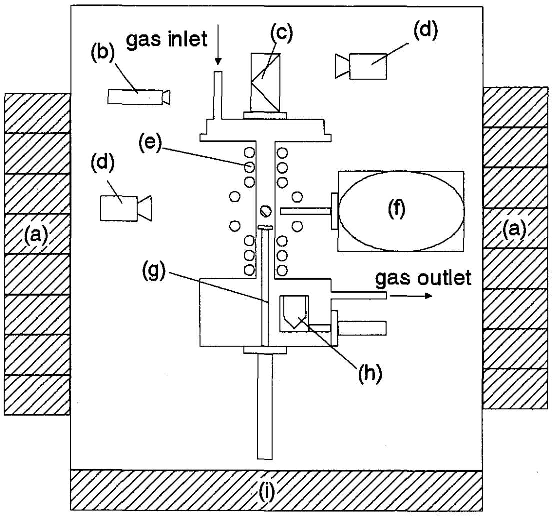

Fig. 1 Schematic diagram of the electromagnetic levitation system.
(a) Batteries, (b) Pyrometer, (c) Mirror, (d) High Speed Video Camera, (e) Coil, (f) Infrared Ray Furnace, (g) Sample Stage, (h) Copper Mold, (i) Water Tank

The atmosphere was Ar-3%H_2. It was purified by platinum asbestos and magnesium perchlorate. It was confirmed by an analysis of the output gas that the silicon was deoxidized in the purified gas at melting. Accordingly, the oxygen partial pressure was less than 1.1×10^{-14} Pa.[14] The silicon samples used were spherical and weighed approximately 0.7g. The sample was pre-heated with an infrared ray heater, and then was electromagnetically heated and levitated. After that, the whole levitation system was dropped to obtain a microgravity condition. The surface oscillation was recorded at a speed of 200 frame/sec. From the recorded

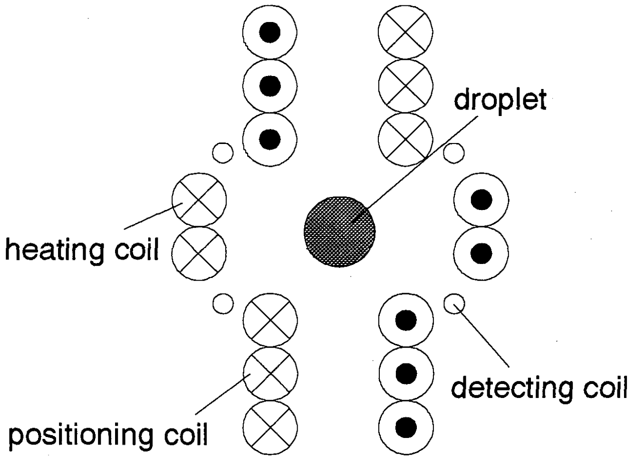

Fig. 2 Schematic diagram of the coil system.

data, the area and two droplet radii normal to each other on all frames were analyzed by digital image processing. The data were subsequently subjected to Fourier transformation, and surface oscillation was analyzed.

3. Coil system

Figure 2 shows the coil system used in this study. The coil system consists of three types of coil: a positioning coil, a heating coil and a detecting coil. The positioning coil is usually used in the electromagnetic method. The coil supplies a lifting force against gravity. The positioning force also acts as a force that makes the droplet oblate. In order to control the shape of the droplet, the heating coil is also accommodated in this study. The coil plays roles of heating and making the droplet prolate. Thus, the droplet shape can be controlled using these coils. A detecting coil is also accommodated to detect the translational motion of the levitated droplet.

4. Microgravity system

In order to produce a microgravity condition, a drop-shaft type experiment system (JAMIC) was used in this study. The shaft is 710m in depth and produces a 10 second microgravity condition. The microgravity level of the system is less than 10^{-4}G. While the drop capsule is falling, the capsule blows gas from the top in order to compensate for the air resistance. In addition, the drop capsule consists of an outer capsule and an inner capsule. The space between the inner capsule and the outer one is maintained in a vacuum so that the free fall velocity of the inner capsule will not be affected by the air resistance.

5. Measurement principle

A levitated sample oscillates around the equilibrium shape. When the equilibrium shape is spherical, the surface tension can be calculated with the following equation.[15)]

$$\omega_l^2 = \frac{4}{3}\pi l(l-1)(l+2)\frac{\gamma}{M} \qquad (1)$$

where ω is the angular frequency of surface oscillation and l is the label for oscillation modes. M is the droplet mass, and γ is the surface tension. The frequency of l=2 is called the Rayleigh frequency and can be written as follows:

$$\nu_R^2 = \frac{8}{3\pi}\frac{\gamma}{M} \qquad (2)$$

where $\omega = 2\pi\nu_R$

Thus, in this method only the values of the frequency and the mass are necessary for the calculation of the surface tension. Although the value of density is required for the sessile drop method and other methods, there is no need for the value to be used and this allows the surface tension to be calculated more precisely.

In practice, the equilibrium shape is not spherical and therefore, several peaks are usually observed. In this case, Cummings & Blackburn's correction formula is sometimes used to calculate the Rayleigh frequency.[16)]

$$\omega_R^2 = \frac{1}{5}\left(\omega_{l=2,m=0}^2 + 2\omega_{l=2,m=1}^2 + 2\omega_{l=2,m=2}^2\right) - \omega_{tr}^2\left\{1.90 + 1.20\left(\frac{z_0}{a}\right)^2\right\}$$

$$z_0 = \frac{g}{2\omega_{tr}^2} \qquad (3)$$

where ω_{tr} is the mean translational frequency of drop's center of mass, g is the gravitational acceleration, and a is the radius of the droplet. l and m are the labels for oscillation modes.

6. Results and discussion

Throughout each drop experiment, the data are recorded for sample position, sample temperature, sample images obtained from above and side, each coil current as a function of time. As an example, the change in the positioning coil current and the translation of a sample were shown in Fig. 3. As shown in the figure, the translation of a drop was damped in the early stage of falling. In other words, the positioning coil current was adjusted to maintain the drop in the middle of the coils using the detecting coil data.

Figure 4 shows the relationship between the shape of a levitated drop and the current ratio of two coils: the positioning coil and the heating coil. W is defined as the radius of droplet in the horizontal direction and L is that in the vertical direction. The axial ratio changes with the coil current ratio, in other words, the shape of a drop can be controlled by changing the coil current ratio.

Figure 5 shows variations in the recorded area

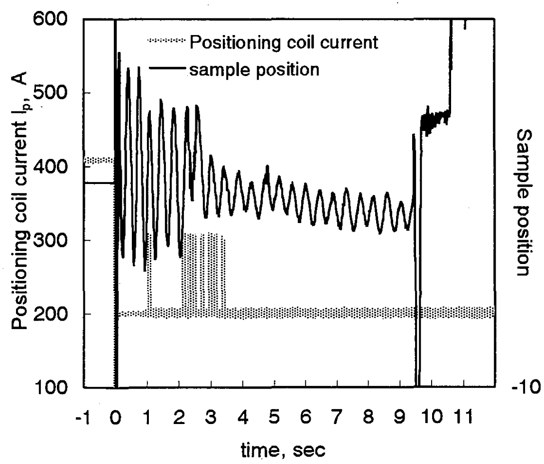

Fig. 3 Feedback control of sample oscillation in early stage of falling.

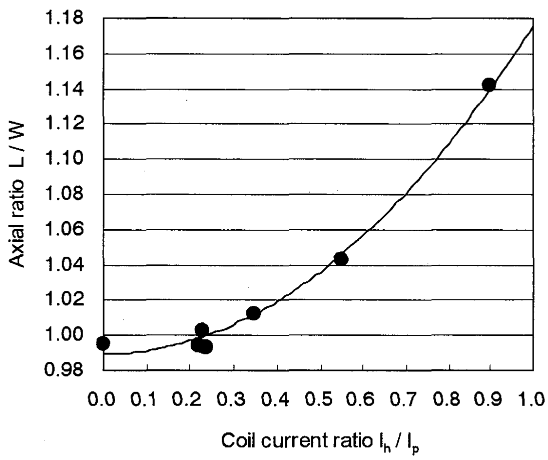

Fig. 4 Relationship between the axial ratio and coil current ratio.
L: radius in the vertical direction, W: radius in the horizontal direction, I_h: current in the heating coil, I_p: current in the positioning coil

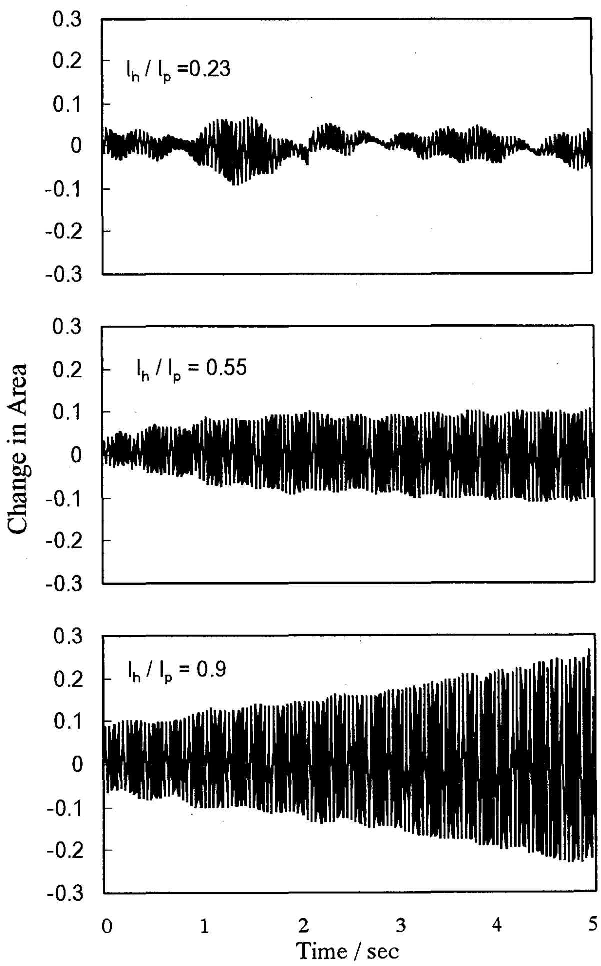

Fig. 5 Time dependence of surface oscillation with each coil current ratio.

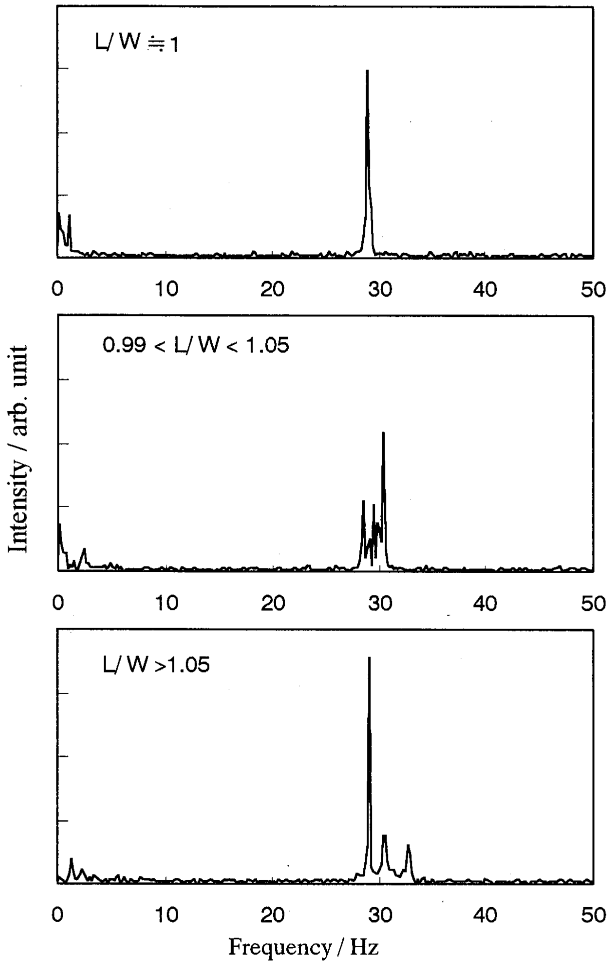

Fig. 6 Variation of frequency spectra with equilibrium shape of droplet.

change with different coil current ratios obtained by digital image processing. As can be seen in the figure, the amplitude of oscillations became larger as the coil current ratio became higher. This means that the heating coil changes the liquid drop shape and also affects on its oscillations.

Figure 6 shows typical frequency spectra calculated by Fourier transformation. The pattern of peak distribution can be classified into three cases. 1) when the droplet is almost spherical, that is L/W ≒ 1; the frequencies of the five oscillations are almost the same, and hence there looks only one peak in the spectrum. 2) When the droplet is near spherical, that is 0.99 < L/W < 1.05; all the five fundamental oscillations are detected. 3) when the droplet is distorted from a sphere, that is L/W > 1.05; a strong peak of l=2, m=0 mode and two peaks of l=2, m= ± 2 mode are excited, and the m= ± 1 peaks are very weak.

The surface tension was calculated from the data when the shape of the droplet was a sphere or almost spherical. When only one peak was obtained in the Fourier transform, the surface tension was calculated

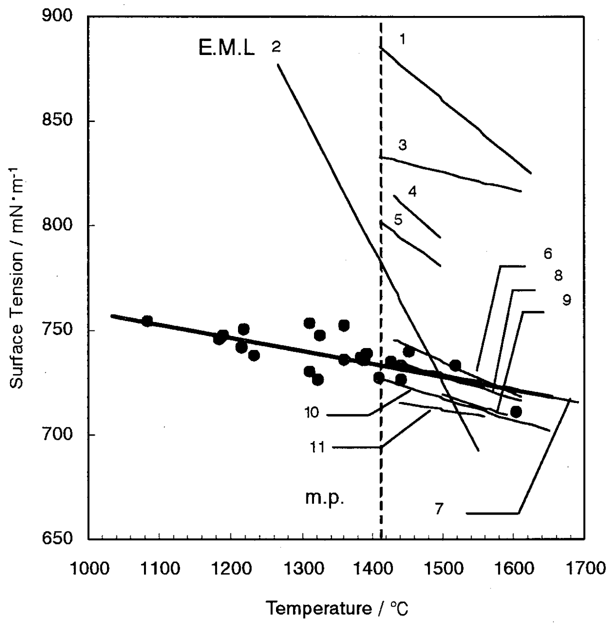

Fig. 7 Surface tension of molten silicon.
●: this work, 1-11: previous work,
2: electromagnetic levitation method

using the Rayleigh equation. When five peaks were obtained, Cummings & Blackburn's correction formula (eq. (3)) was used to calculate the Rayleigh frequency. Figure 7 shows the result of this calculation. All points are in good agreement with the results measured with the sessile drop method or other previous method. However, when Cummings' equation is applied to the result obtained in a terrestrial condition [2], the calculated values of surface tension, in particular, of the temperature coefficient are quite different from the values measured with the other methods, as shown in Fig. 7. This is probably because the droplet is too much distorted from a sphere in a terrestrial condition. It is concluded from the results that Cummings' correction formula can be used only when the distortion of a drop is small.

7. Conclusion

(1) When a droplet is close to a sphere, the axial ratio of the droplet is between 0.99 to 1.05, all oscillation modes are easily detected in the frequency spectrum. The values of surface tension obtained by Cummings' equation are in good agreement with reported values.

(2) Cummings' equation can be used only when the distortion of a droplet is small.

Acknowledgments

This work is the result of "Technology for production of High Quality Crystal" which is supported by the New Energy and Industrial Technology Development Organization (NEDO) through the Japan Space Utilization Promotion Center (JSUP) in the program of the Ministry of Economy, Trade and Industry (METI), and also Industrial Technology Research Grant Program from NEDO, and is carried out as a part of "Ground Research Announcement for Space Utilization" Promoted by Japan Space Forum.

References

1) S. C. Hardy, *J. Crystal. Growth* **69**, (1984), 456
2) M.Przyborowski, T.Hibiya, M.Eguchi and I.Egry, *J. Cryst. Growth*, **151**, (1995),)60
3) V. N. Bobkovskii, V. I. Kostikov, V. I. Levin, and A. S. Tarabanov, *Konstr. Mater. Osn. Grafita*, **5**, (1970), 138
4) S. I. Chung, K. Izunome, A. Yokotani, and S. Kimura, *Jpn. J. Appl. Phys.*, **34(5b)**, (1995), 631
5) N. Kawasaki, K. Watanabe, and Y. Nagasaka, *High Temperatures – High Pressures*, **30**, (1998), 91
6) Y. V. Naidich, V. M. Perevertailo and L. P. Obushchak, *Russ. J. Phys. Chem* **49**, (1975), 917
7) H. Sasaki, Y. Anzai, X, Huang, K. Terashita, and S. Kimura, *Jpn. J. Appl. Phys.* **34**, (1995), 414
8) E. S. Levin, P. V. Gel'd and B.V.Tsarevskii *Russ. J. Phys. Chem.* **40**, (1966), 1455
9) P. H. Keck and W. van Horn, *Phys. Rev.* **91**, (1953), 512
10) S. V. Lukin, V. I. Zhuchkov, N. A. Vatlin an d Y. S. Kozlov, *J. Less-Common Metals*, **67**, (1979), 407
11) S. I. Popel, L. M. Shergin and B. V. Tsarevskii, *Russ. J. Phys. Chem.* **44**, (1970), 144
12) B. J. Keene, K. C. Mills, A. Kasama, A. McLean, and W. A. Miller, *Metall. Trans.* **17B**, (1986), 159
13) K. Nogi, K. Ogino, A. McLean, and W. A. Miller,, Metals,*Metall. Trans.* **17B**, (1986), 163
14) Fuwa et al., *Hitetsu Kinzoku Seiren*, Jpn. Inst. Met. (1980), 320
15) Lord Rayleigh,On the Capillary Phenomina of Jets, *Proc. Roy. Soc. London* **29**, (1879), 71
16) D. Cummings and D. Blackburn, *J. Fluid Mech.*, **224**, (1991), 395