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ISS搭載ELFによる溶融鉄・酸化物融体によるコア・シェル液滴の表面振動計測
Analysis of Surface Oscillation of Core-Shell Droplet by Liquid Iron and Molten Oxide measured by using Electrostatic Levitation Furnace (ELF) in ISS

佐藤令奈[1,†]，松本彩里[1]，高橋圭太[1]，渡邉匡人[1]，石川毅彦[2]，小山千尋[2]織田裕久[2]，伊藤剛[2]
Reina SATO [1], Irori MATSUMOTO [1], Keita TAKAHASHI [1], Masahito WATANABE [1], Takehiko ISHIKAWA [2], Chiro KOYAMA [2], Hirohisa ODA [2] and Tsuyoshi ITO [2]

1 学習院大学理学部，Department of Physics, Gakushuin University, Tokyo, Japan
2 宇宙航空研究開発機構, JAXA, Tsukuba, Japan
* Correspondence: 23141013@gakushuin.ac.jp

1. Introduction

Under microgravity conditions, droplets made of immiscible liquids form core-shell droplets caused by the relationship between interfacial tension and surface tension. By applying the oscillating drop method to these core-shell droplets, the interfacial tension can be obtained by measuring the eigenfrequencies of the normal mode of the surface oscillation of the droplet1). We have successfully measured the surface oscillation of core-shell droplets to obtain two eigenfrequencies by liquid Fe and molten SiO_2-CaO-Mn_3O_4-TiO_2-Fe_2O_3 oxide using the electrostatic levitation furnace (ELF) on board the ISS2). In order to calculate the interfacial tension from these two eigenfrequencies, the density and surface tension values of the molten oxide and liquid Fe are required. Thermophysical property values for liquid Fe can be used from literature values since many measurements have been performed previously. However, for molten oxide new measurements are required because thermopysical property data for the same composition of molten oxides is necessary. However, it is difficult to obtain accurate surface oscillation measurements of multi-component oxide melts containing Fe even in ELF due to their electrification behavior. Therefore, we investigate a method to determine the interfacial tension value from the eigenfrequencies of the core-shell droplet surface oscillation obtained by the measurement, without direct measurements of the physical properties of the oxide melt from focusing on the behavior of eigenfrequencies of normal mode oscillation of core-shell droplets depending on its radius ratio.

2. Analysis of eigenfrequencies of surface oscillation of core-shell droplet

Under microgravity conditions, immiscible liquids form a core-shell droplet. The surface oscillation of the core-shell droplet is analyzed from the equations of motionusing velocity potential in spherical coordinates. From the analytical solution of the equations, we obtained the following eigenfrequencies of the normal mode of surface oscillation of core-shell drop with the mode number of $l = 2$.

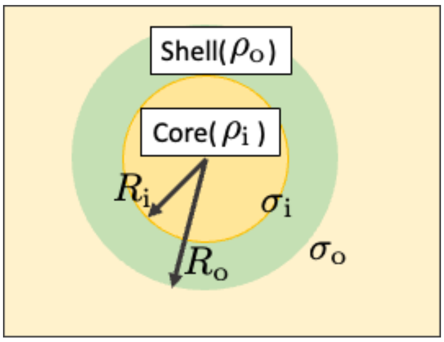

Figure 1. Core-shell droplet configuration used in eqs.(1) and (2).

$$\omega_{\pm}^2 = \frac{W}{J} K_{\pm} \tag{1}$$

$$K_{\pm} = \frac{1}{2}\left(\frac{\sigma m_{\rm i}}{\tau^3} + \frac{m_{\rm o}\tau^3}{\sigma}\right) \pm \sqrt{\frac{1}{4}\left(\frac{\sigma m_{\rm i}}{\tau^3} - \frac{m_{\rm o}\tau^3}{\sigma}\right) + 1}, \;\; W = \sqrt{\frac{\sigma_{\rm o}\sigma_{\rm i}}{(R_{\rm o}R_{\rm i})^3}\frac{24}{5\rho_{\rm o}}}, \;\; J = \frac{3}{5}(1+\Delta\rho_{\rm i})\tau^5 - \frac{2}{5}\Delta\rho_{\rm i}\tau^{-5}. \tag{2}$$

where, $\sigma_{\rm o}$ is the surface tension of molten oxide, $\sigma_{\rm i}$ is the interfacial tension between liquid Fe and molten oxide, $R_{\rm i}$ is the radius of the core part (liquid Fe), and $R_{\rm o}$ is the radius from center of drop to outside of shell part (molten oxides). Also, in (1) and (2) symbols are shown as follows using the densities of the core (liquid Fe) $\rho_{\rm i}$ and the shell (molten oxide) $\rho_{\rm o}$.

$$\sigma = \sqrt{\sigma_{\rm o}/\sigma_{\rm i}}, \;\; \tau = \sqrt{R_{\rm o}/R_{\rm i}}, \;\; \Delta\rho_{\rm i} = \frac{(l+1)(\rho_{\rm i}-\rho_{\rm o})}{(2l+1)\rho_{\rm o}}, \tag{3}$$
$$m_{\rm i} = (1+\Delta\rho_{\rm i})\tau^5 - \Delta\rho_{\rm i}\tau^{-5}, \;\; m_{\rm o} = \frac{3}{5}\tau^5 + \frac{2}{5}\tau^{-5}.$$

These symbols are shown in **Fig. 1**.

If we obtain ω_+ and ω_- from the oscillating drop experiments, we can calculate the interfacial tension $\sigma_{\rm i}$ from the following equations.

$$\sigma_{\rm i} = \omega_-^2\omega_+^2 \frac{J^2}{m_{\rm i}m_{\rm o}-1}\frac{R_{\rm i}^3R_{\rm o}^3}{\sigma_{\rm o}}\left(\frac{5\rho_{\rm o}}{24}\right)^2. \tag{4}$$

To caluculate the interfacial tension using (4), we need thermophysical properties of $\rho_{\rm i}$ (density of liquid Fe), $\rho_{\rm o}$ (density of molten oxides), $\sigma_{\rm o}$ (surface tension of molten oxides). For density of liquid Fe can be used from literature values since many measurements have been performed previously. However, it is difficult to obtain accurate surface tension of multi-component molten oxides containing Fe even in ELF due to their electrification behavior.

Therefore, we make an approximation for $K_{\pm}$ in eq.(2) with the assumption that the surface tension of molten oxide $\sigma_{\rm o}$ is larger than the interfacial tension between liquid Fe and molten oxide $\sigma_{\rm i}$3). This assumption is caused by the core-shell drop formation by these two liquids. For the assumption, we find $\sigma m_{\rm i}/\tau^3 > m_{\rm o}\tau^3/\sigma$ and also that $K_{\pm}$ is simplified. On the assumtion, ω_+ and ω_- are described as follows;

$$\omega_+^2 = \omega_o\left(1 - \frac{5}{3}\Delta\rho_{\rm i}\tau^{-10}\right), \;\; \omega_- = \omega_{\rm o}\frac{3}{5}\frac{\tau^6}{\sigma^2}\left(1-\tau^{-10}\right), \tag{5}$$

where, $\omega_{\rm o}$ is obtained from W in eq.(2) as $\omega_{\rm o}^2 = 8\sigma_{\rm o}^2/(\rho_{\rm o}R_{\rm o}^3)$which corresponds to the Rayleigh frequency of eigenfrequency of the normal mode of single-liquid surface oscillation by molten oxides. ω_+ and ω_- are shown in **Fig. 2** with exact solutions of eigenfrequencies described in eqs.(1)and (2). For $\sigma > 3$ regions, the approximated solution of ω_+ is asymptotic to the exact solution of ω_-. On the basis of the features of eigenfrequencies of surface oscillation of core-shell droplet, thus ω_- only includes σ, and then we find that the interfacial tension $\sigma_{\rm i}$ is described only by ω_- as following;

$$\sigma_{\rm i} = \omega_-\frac{5\rho_{\rm o}R_{\rm o}}{24}\frac{1}{\tau^6(1-\tau^{-10})}. \tag{6}$$

To obtain $\sigma_{\rm i}$ using eq.(6), we need $\rho_{\rm o}$ of molten oxide density,$R_{\rm o}$ of radius of molten oxide and τ including $R_{\rm i}$ of liquid Fe radius. We can obtain these values from the inside observation of the core-shell droplet by for instance an X-ray radiograph technique.

We perform only on the ground the X-ray radiograph observation for the solidified sample processed by ELF in ISS, therefore we must estimate the radius of core and shell parts during levitation in ELF. During core-shell droplet levitation using ELF, we obtained the shadow image of the molten core-shell droplet and its temperature. The mass of core-shell drop processed by ELF can be known when the solidified sample returns to the ground as $M_{\rm to}^{\rm s}$.

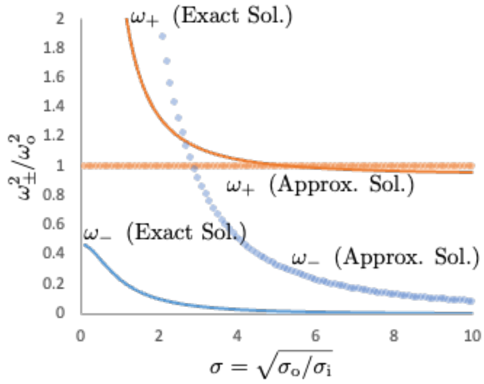

Figure 2. ω_+ and ω_- as a function of $\sigma = \sqrt{\sigma_o/\sigma_i}$ of exact solutions by eqs.(1) and (2), and of approximated solution by eq.(5).

From these results, we can estimate ρ_o, R_o and R_i because the density of Fe is known well in solid and liquid states with temperature dependence. If we are able to perform the inside observation of the solidified sample processed by ELF and to obtain both radius core and shell R_i^s and R_o^s shown in **Fig. 3**. Using M_{to}^s, R_i^s and R_o^s, we can obtain the density of molten oxide ρ_o during levitated by ELF as,

$$\rho_o = \frac{M_{to}^s - \rho_{Fe}^s V_{Fe}^s}{(4\pi/3)R_o^3 - \rho_{Fe}^s \rho_{Fe}^L V_{Fe}^s}, \quad V_{Fe}^s = \frac{4\pi}{3} R_{Fe}^{s\,3}. \tag{7}$$

From these procedures, we can calculate the interfacial tension from eq.(6) without new measurements of molten oxide surface tension and density.

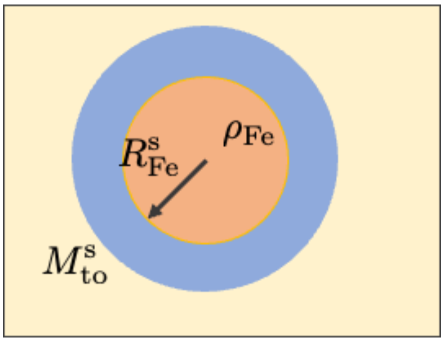

Figure 3. Solidified core-shell droplet configuration used in eq.(7).

3. Conclusion

We analyzed the eigenfrequencies of the surface oscillation of core-shell droplets to obtain the interfacial tension without measurements of the surface tension of molten oxides. On the assumption of larger surface tension of molten oxide rather than interfacial tension between molten oxide liquid Fe, approximation of eigenfrequencies of ω_+ and ω_- was derivated. Using the approximated ω_+ and ω_-, we obtained the equation of interfacial tension without the surface tension of molten oxides. In the presentation, experimental results will be applied to the procedure and the obtained interfacial tension value will be discussed with the previous literature values.

References

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