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Numerical investigation on frequency shift of an electromagnetically levitated molten droplet

Lin Feng [a], Wan-Yuan Shi [a,b,*]

[a] College of Power Engineering, Chongqing University, Chongqing 400044, China
[b] Key Laboratory of Low-grade Energy Utilization Technologies and Systems, Ministry of Education, Chongqing 400044, China

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ABSTRACT

The oscillating droplet method using electromagnetic levitation is a superior way for measuring the surface tension of molten materials, especially for reactive and refractory melts. Through frequency analysis of droplet motions, oscillation frequency is obtained and Rayleigh's theory is applied to determine the surface tension. However, the Rayleigh's theory presumes that the droplet is spherical with small deformation in Legendre's expressions and oscillates freely. Such prerequisites are hard to realize in reality and frequency shifts are introduced inevitably. In this work, a series of axisymmetric simulations are performed to investigate the frequency shift due to irregular deformation and positioning force exerted on an electromagnetically levitated droplet. The arbitrary Lagrange-Euler method is adopted for tracing the free surface of the droplet. The results found that the droplet deformation increases with increasing heating current and droplet radius, which leads to a negative frequency shift. On the contrary, the positioning current induces a positive frequency shift. The frequency shift caused by irregular deformation can be balanced by that induced by positioning current and a rather accurate oscillation frequency can be achieved when an appropriate positioning current is imposed, which is determined to be 121.5–146.0 A for deformation rate of $\xi = 1.101$ to $\xi = 1.875$ for silver droplet. With this work, it is expected to provide guidelines for better arranging operating parameters of EML device and improving the measurement accuracy of surface tension when the frequency shift caused by irregular deformation and external electromagnetic force are taken into account.

1. Introduction

The precise knowledge of the surface tension coefficient of the molten metals and the alloys is technologically important and scientifically interesting in some metallurgical progresses, such as casting [1], welding [2] and crystal growth [3]. Conventional methods for measuring the surface tension are the sessile-drop method, the pendant-drop method, and the maximum bubble pressure method [4]. Although these techniques are adequate for ordinary liquids like water, oil and alcohol, they are not for reactive and refractory metals. The oscillating droplet method using electromagnetic levitation (hereafter denoted as EML) technology provides an available way for measuring the surface tension of such class of materials. This method enables the materials to be levitated in inert gas, thus any contacts and reactions with containers are fully avoided. Due to the noncontact nature, materials are prone to achieve either superheated or undercooled state and the surface tension can be measured over a wide range of temperature. The oscillating droplet method is based on Rayleigh's theory for the measurement of surface tension of a spherical, force-free liquid droplet with small deformation in forms of Legendre's functions, which is expressed as [5],

$$f = \frac{1}{2\pi}\sqrt{\gamma l(l-1)(l+2)/\left(\rho R_0^2\right)}; \quad l = 2,3,4\ldots. \tag{1}$$

where f is the oscillation frequency measured by high-speed camera for recording the surface oscillations, γ is the surface tension, R_0 is the radius, ρ is density and $l = 2$ is the known Rayleigh oscillation mode. In EML system for surface tension measurements on the ground, the droplet tends to be tear-shaped rather than spherical due to gravity and magnetic pressure induced by alternating currents. The oscillating mode ($l = 2$) of the tear-shaped droplet splits into three peaks ($m = 0, \pm1, \pm2$) [6–9], thus the Rayleigh's theory cannot be applied directly. In addition to translational oscillations, rotations may also occur and the oscillating frequency $m = \pm2$ further splits into two peaks [8,10]. Although a sum rule was derived

* Corresponding author at: College of Power Engineering, Chongqing University, Chongqing 400044, China.
E-mail address: shiwy@cqu.edu.cn (W.-Y. Shi).

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Nomenclature

a	horizontal diameters of droplet [m]
b	vertical diameters of droplet [m]
$\boldsymbol{B}$	magnetic flux intensity [T]
c_p	specific heat [J/kg·K]
$\boldsymbol{E}$	electric field vector [V/m]
f	frequency [Hz]
$\boldsymbol{F}$	electromagnetic force [N/m^3]
$\boldsymbol{H}$	magnetic field intensity [A/m]
$\boldsymbol{I}$	current [A]
$\boldsymbol{J}$	current density vector [A/m^2]
T	temperature [K]
$\boldsymbol{u}$	velocity vector [m/s]
β	temperature coefficient of surface tension [N/m·K]
ε	emissivity [–]
Φ_v	power absorption [W/m^3]
λ	thermal conductivity [W/m·K]
ρ	density [kg/m^3]
μ	dynamic viscosity [Pa·s]
γ	surface tension [N/m]
σ	electric conductivity [S/m]
σ_{sb}	Stefan-Boltzmann constant [W/m^2·K^4]
ξ	deformation rate, $\xi = b/a$ [–]
ζ	deformation coefficient of Legendre polynomials [–]
Γ	local mean curvature [1/m]

subscript

a	ambient
h	heating
m	molten material, mesh, melting temperature
$\boldsymbol{n}$	unit normal vector
p	positioning
T	at temperature of T
$\boldsymbol{\tau}$	unit tangential vector

superscript

*	conjugate complex

by Cummings and Blackburn [9,11] to determine the surface tension by measuring the complex frequency spectrum of all five peaks, it is advantageous to perform such experiments in microgravity where the droplet shape remains spherical naturally.

In order to perform microgravity experiments, TEMPUS device was designed and experiments were conducted to measure the surface tension of molten melts. The TEMPUS system concludes of positioning coils and heating coils. The former one produces an axially symmetric quadrupole field to hold the materials in certain space while the latter one generates a dipole field to heat and deforms it. When heating coils are shut down, the deformed molten droplet starts to oscillate and the oscillations are recorded by cameras. In this way, plenty of microgravity experiments were conducted by Egry and coworkers [7,12] during International Microgravity Laboratory (IML) flights. These results were compared with those in terrestrial experiments and the spectrum shown only one clear peak. The corresponding surface tension measured in microgravity was in satisfying agreement with those in literatures. Numerical simulations were conducted by Zong et al. [13,14] to predict the steady shape of levitated droplet, in which an external magnetic pressure was introduced into the surface of droplet while the Lorentz force acted on internal flow was neglected. Dynamic simulations of droplet oscillations were presented by Berry and Bojarevics [15–17] using VOF and Lagrange method respectively.

In addition to the effects of asphericity, the irregular deformation of droplet also affects the oscillation frequency apparently. Plenty of works have been conducted to investigate the effect of given amplitude on droplet oscillation. The oscillation frequency was found to decrease with the increase of amplitude experimentally by Trinh and Wang [18]. Azuma and Yoshihara [19] performed theoretically discussions about the effect of amplitude on oscillation frequency and second order deviations were taken into account. Recently a three-dimensional simulation was conducted by Watanabe [20] using level set method to investigate the effect of initial amplitude and droplet rotation on oscillation frequency of free droplet. The results indicated that the oscillation frequency decreases as increasing amplitude, while it increases as the rotational rate, which was overestimated by theoretical predictions.

In previous works, the effect of amplitude on oscillation frequency was investigated based on a given shape in forms of the Legendre polynomials. In reality, the shape of deformed droplet is affected by plenty of factors such as material properties and operating conditions, leading to an irregular and non-Legendre polynomial shape. Besides it is hard to accomplish free oscillations of droplet because positioning forces are essential to limit the active region during experiments. Due to the limits of Rayleigh's theory in which a spherical droplet oscillates freely with initial outline of Legendre polynomial is presumed, errors are introduced inevitably. However the influence of deformation and external positioning forces on oscillation frequency of droplet in EML system still remains unknown as far as the author's knowledge. In this work, a series of numerical simulations are performed to investigate the influencing factors on oscillation frequency of an electromagnetically levitated droplet. To trace the surface of droplet precisely, the arbitrary Lagrange-Euler (hereafter denoted as ALE) method is adopted, which showed great performance in many deformable problems [21–23]. Dynamic oscillations of droplet are obtained and the influences of heating current, droplet radius as well as Marangoni effect on deformation of silver droplet are investigated. Then the effect of irregular deformation on oscillation frequency of a free droplet is explored throughly. Finally, positioning forces are introduced and the results are compared with those in free oscillations. With this work, we hope to provide a useful way to improve the measurement accuracy of surface tension through appropriate configuration of system parameters when irregular deformation and external force are taken into account.

2. Physical model

The schematic of TEMPUS device is shown in Fig. 1. There are two types of coaxial coils, eight for positioning with opposite current directions to generate a quadrupole field and prevent the materials from drifting while four symmetrically arranged coils with same current direction for heating and generating a dipole field to melt and squeeze efficiently. In microgravity experiments, firstly the materials are levitated and melt under combined action of quadrupole and dipole fields. Then heating coils switch off, allowing materials to oscillate under quadrupole field rather than free oscillations. High-speed cameras are used to record the deformations and oscillations of droplets to employ digital image processing for frequency analysis. Rayleigh's theory is then applied