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A New Variant for Measuring the Surface Tension of Liquid Metals and Alloys by the Oscillating Drop Method[1]

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The theoretical background of the oscillating drop technique for measuring surface tension is briefly presented and the different analysis procedures are cited. A new method is described for obtaining oscillation frequencies by fast fourier transformation (FFT) of the pyrometer voltage signals from temperature measurements at the top of the levitated sample. The results on the first experiments on liquid nickel are in a good agreement with the literature data.

KEY WORDS: electromagnetic levitation; oscillating drop technique; surface tension.

1. INTRODUCTION

The main experimental difficulty in measuring the surface tension of liquid metals is due to contamination of the samples, mostly by oxygen arising from the surrounding gas atmosphere or the refractories. It has been shown that the presence of surface active elements, such as oxygen and sulfur, in metallic melts drastically decrease the surface tension [1–7]. Therefore, surface tension values given in the literature scatter widely, especially for high-melting metals. To overcome these problems, the electromagnetic levitation technique for determining the surface tension of molten metals was first introduced by Lu and co-workers [8–10]. The principle of the electromagnetic oscillation droplet technique is based on the general theory

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for an oscillating falling drop proposed by Rayleigh [11]. The droplet oscillation, which is caused by the restoring force of the surface tension, is excited in the electromagnetic field and could be used to calculate surface tension from the oscillation frequency.

2. THEORETICAL BACKGROUND

The theoretical treatment of the relationship between the surface tension and the oscillation frequency of a free-falling (or levitated) liquid drop has been derived by Rayleigh, equating the change in the surface energy with the kinetic energy of motion as the consequence of the surface oscillation [11]. Doing this, the surface tension of a levitating droplet in an electromagnetic field can be expressed by the mass of the droplet and the oscillation frequency of the fundamental mode $\ell = 2$. Rayleigh's equation is given as follows:

$$\sigma = \tfrac{3}{8}\pi m \nu_{l=2}^2 \tag{1}$$

Under real experimental conditions, however, the Rayleigh frequency is split into either three or five unequally spaced peaks, called split modes. This effect is caused by an aspherical equilibrium shape of the oscillating droplet. Therefore, Rayleigh's equation, based on the perfect shape of the droplet, has to be modified. Theoretical work to solve this problem has been performed by Cummings and Blackburn [12]. They interpreted the influence of the electromagnetic field as a magnetic pressure on the surface and derived a frequency sum rule to obtain the oscillation frequency from the split modes, m:

$$\nu_{l=2}^2 = \left(\tfrac{1}{5} \sum_{m=-2}^{m=+2} \nu_{l=2,m}^2\right) - 2\nu_{\mathrm{t}}^2 \tag{2}$$

where ν_{t} is the translation frequency. A rotating nonaxisymmetric droplet shows five unequally spaced peaks in its spectrum. In the case of a nonrotating axisymmetric droplet, only three peaks occur. Two pairs of the five peaks are doubly degenerate and Eq. (2) can be rewritten as

$$\nu_{l=2}^2 = \tfrac{1}{5}(\nu_{l=2,m=0}^2 + 2\nu_{l=2,m=\pm 1}^2 + 2\nu_{l=2,m=\pm 2}^2) - 2\nu_{\mathrm{t}}^2 \tag{3}$$

The validity of this theory was shown by Egry et al. [13]. Their comparison of surface tension data under terrestrial conditions (high magnetic field strength) considering the magnetic pressure with those from microgravity [approximate force-free and use of Eq. (1)] obtained during the

IML-2 Spacelab flight using the containerless electromagnetic processing facility TEMPUS shows a very good agreement.

3. EXPERIMENTS

The analysis procedures of the oscillation frequency can be classified as

- high-speed photography [8–10, 14],
- use of a photodetector and oscilloscopic observation of the signal [15–19],
- use of a photocell in combination with an on-line Fourier wave analyzer [20–25],
- use of a photodetector and off-line fast fourier transformation (FFT) [26],
- digital image processing and FFT afterward [13, 27–32], and
- use of a pyrometer in combination with an on-line Fourier wave analyzer [33–35].

A schematic diagram of our levitation apparatus is shown in Fig. 1. For the power supply a high-frequency generator, operating at 400 kHz, is used. A silica tube (outer diameter, 16 mm) is placed within a levitation coil and is connected with a small vacuum chamber below. The chamber contains six quartz glass sample holders and six copper molds on a rotating table. The experimental unit is capable of being evacuated to 1 mPa. The upper end of the silica tube is closed by an optical quarz plate. The motion and the temperature of the levitated sample are observed via a prism placed above this quartz plate. Temperature regulation of the sample is achieved by varying the composition of the gas mixture and its flow rate, using a circulating-gas cooling system. The gas used is argon or helium, with the addition of 10% hydrogen to prevent the formation of oxide on the samples during the experiments. In earlier works [33–35] on the determination of oscillation frequencies, the target of a quotient pyrometer was focused onto the edge of the oscillating sample and the change in the incoming radiation intensity was recorded. The output signals were then transmitted to an analog/digital oscilloscope, where they were monitored, controlled, and stored. Simultaneously, a Fourier transformation of the pyrometer output signal was performed by a Fourier wave analyzer to obtain the frequency spectrum. In the present work, the pyrometer target is focused directly on the upper pole of the sample. Via an analog/digital converter (maximum speed, 4 kHz), the output signal of the pyrometer passes through a special antialiasing filter (low pass) and is sent to a computer. A function generator is used as a timer to assure that the converter and the software are in synchronization. Finally, the recorded signal is analyzed by Fourier transformation. In contrast to the old method [33–35], the new method has the following advantages:

- measurements can be made at various sampling rates,
- much longer time periods can be stored than before (maximum, $4 \cdot 10^6$ points),
- the recorded data can be divided into several time periods, and
- a clearer spectrum is obtained.

A typical time-versus-pyrometer voltage signal is shown in Fig. 2 for a pure liquid undercooled nickel sample at 1717 K. The mass of the drop was

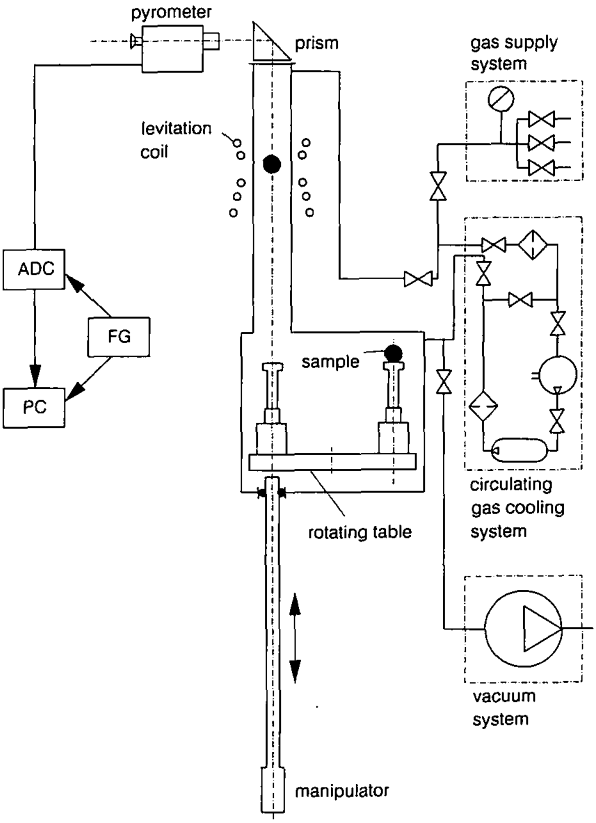

Fig. 1. Schematic diagram of the experimental system.

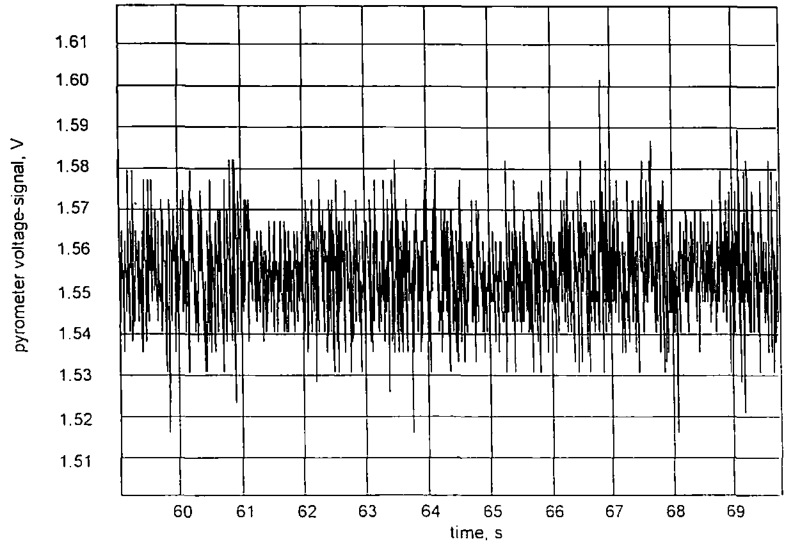

Fig. 2. Time versus pyrometer voltage signal; recorded at 128 Hz.

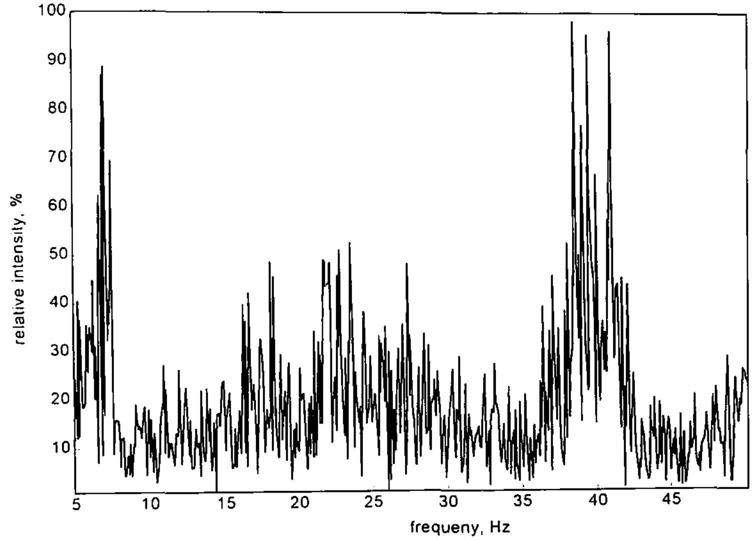

Fig. 3. Oscillation spectrum obtained by Fourier transformation of the data presented in Fig. 2.

$m = 1.06491$ g. The signal was recorded at a sampling rate of 128 Hz; 1024 values of this signal were Fourier transformed. The resulting spectrum is shown in Fig. 3. The translation frequency is located at about 7 Hz and the split modes are represented by the five highest peaks in the range 38–42 Hz. Using Eqs. (1) and (2), we obtain a value of $\sigma = 1807$ $\mathrm{mN \cdot m^{-2}}$ for the surface tension. This value is in a good agreement with the measurements of Lee et al. [33], 1829 $\mathrm{mN \cdot m^{-2}}$, and Sauerland [32], 1773 $\mathrm{mN \cdot m^{-2}}$.

4. CONCLUSIONS

The method presented combines optical temperature measurement with the oscillation drop technique and yields a clear frequency spectrum of the surface oscillations of levitated droplets. A temperature signal from a pyrometer is nearly always available during levitation experiments and mathematical treatments for analyzing oscillating signals are part of nearly every computer program for the presentation and mathematical treatment of the experimental data. From that point of view, the method is an easy way to obtain the surface tension. Finally, more systematic investigations have to be done to obtain information on the uncertainty of the results.

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