ADVANCED MEASUREMENT DEVICES FOR THE MICROGRAVITY ELECTROMAGNETIC LEVITATION FACILITY EML

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Keywords: Electromagnetic levitation, micro gravity, inductive measurement technique, electrical resistivity, surface tension, liquid metals, oxygen sensing and control

Abstract

This paper reports on two advanced measurement devices for the microgravity electromagnetic levitation facility (EML), which is currently under construction for the use onboard the "International Space Station (ISS)": the "Sample Coupling Electronics (SCE)" and the "Oxygen Sensing and Control Unit (OSC)".
The SCE measures by a contactless, inductive method the electrical resistivity and the diameter of a spherical levitated metallic droplet by evaluating the voltage and electrical current applied to the levitation coil. The necessity of the OSC comes from the insight that properties like surface tension or, eventually, viscosity cannot seriously be determined by the oscillating drop method in the EML facility without knowing the conditions of the surrounding atmosphere. In the following both measurement devices are explained and laboratory test results are presented.

Introduction

The study of liquid metals and alloys is often in company with major challenges and difficulties, which is due to the high temperatures and, consequently, high reactivity of these materials. An elegant way to bypass these problems is the use of containerless methods. Among these, electromagnetic levitation is a well established and robust technique for electrically conducting melts [1]. By application of alternating magnetic fields of high frequency (~375 kHz), metallic samples are heated and positioned in electromagnetic levitation inductively without external contact by inductive means.
In order to exploit this containerless environment for thermophysical property measurements of liquid metals, electromagnetic levitation must be combined with non-contact diagnostic tools [1]. Generally, these tools are based on optical techniques like pyrometry, which applies Planck's law of radiation for temperature measurement, and videometry, which uses high-speed cameras for an analysis of the static and dynamic shape of the levitated drop.
However, in electromagnetic levitation under earthbound conditions, the sample droplets are not force free. The gravity deforms the droplet to a non-spherical shape and distorts the measurement of certain properties, like surface tension. Furthermore, the magnetic fields used to heat and levitate the sample will also generate turbulent fluid flows inside the melt, which strongly disturb measurements of e.g. growth velocities, or melt viscosities [2].
These problems are almost completely removed when electromagnetic levitation is performed in the essentially forceless microgravity environment. Here, the used positioning fields are strongly reduced and, consequently, also the side effects. This has led to the development of the

microgravity electromagnetic levitation facility "EML". It is currently under construction for the use onboard the "International Space Station (ISS)", and will provide an ideal processing environment for undisturbed measurements of thermophysical properties of electrically conductive melts.

In this paper, we report on two proposed extensions of the EML: One is the "Sample Coupling Electronics (SCE)" and the other is the "Oxygen Sensing and Control Unit (OSC)". Both measurement devices have been proposed for integration into the EML facility.

The SCE measures by a contactless, inductive method the electrical resistivity and the diameter of a spherical levitated metallic droplet by evaluating the voltage and electrical current applied to the levitation coil. Any change in the electrical or volumetric properties of the sample can be measured this way. The SCE is therefore a comparatively simple but highly effective diagnostic tool which complements the existing video diagnostics and elegantly expands the spectrum of properties that can be measured.

The necessity of the OSC comes from the insight that properties like surface tension or, eventually viscosity cannot seriously be determined without knowing the conditions of the surrounding atmosphere. Oxygen is one of the most important surface active elements for liquid metals. Only a few ppm can decrease the surface tension by more than 10%. Such a dramatic effect can also lead to a sign reversal of its temperature coefficient and, hence, to a reverse Marangoni flow. In order to study and control these effects, not only the measurement, but also the control of the oxygen partial pressure plays an important role. Both can be achieved by the OSC.

Electromagnetic Levitation under Microgravity

For the stable electromagnetic positioning of the sample, the EML facility uses a magnetic quadrupole field, generated by two parallel and coaxial "positioning coils" carrying alternating currents of the same strength but opposite directions. Since the alternating electromagnetic levitation fields repel electrical conducting samples from areas of high field strengths, the weightless metallic sphere is fixed in the center of the two coils, where the magnetic field strength is weakest, see Fig. 1.

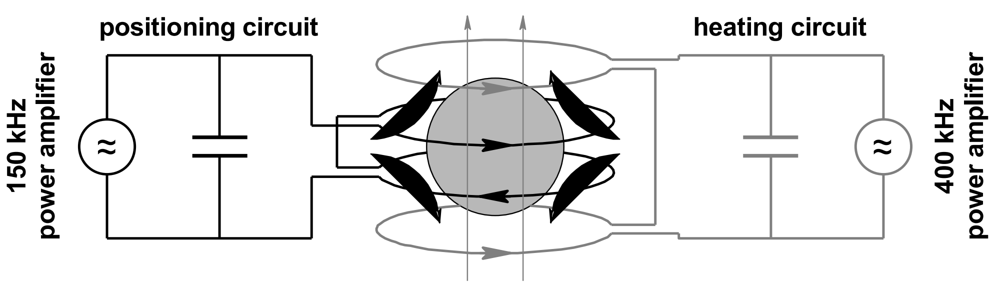

Fig. 1: Principal sketch of the electrical oscillating circuits of a microgravity levitation facility including the positioning coil (black, near the equator of the sample) generating an alternating (~150 kHz) magnetic quadrupole field (curved arrows), and the heating coil (gray, above and below the sample) generating an alternating (~375 kHz), homogeneous magnetic dipole field (straight arrows). Each of the circuits is powered by its own current supply. The actual EML circuits, basing on the superposition principle, differ in details from those shown above.

Since, moreover, the residual accelerations under microgravity, which have to be compensated by the positioning field, are relatively small, the remaining magnetic field strength around a droplet can be decreased under microgravity to values that are considerably weaker than those

necessary to position the same sample against earth gravity.
On the other hand, the positioning of the sample in a region, where the magnetic field strength is weakest, prevents an efficient heating and melting by the quadrupole field. Therefore, an additional, independent, highly efficient "heating coil", connected with its own power generator for the alternating current supply, has been provided in the EML facility. This coil arrangement has several advantages:

- The very poor heating efficiency of the positioning (quadrupole) field (see Fig. 1 left) and the very low center of gravity forces applied on the sample by the nearly homogeneous heating (dipole) field (see Fig. 1 right), enables an almost independent positioning and heating of the sample under microgravity.
- The high efficiency and the homogeneity of the heating field allows also its use as a detection field for a contactless, inductive determination of electrical and volumetric sample properties

Sample Coupling Electronics (SCE)

The "Sample Coupling Electronics (SCE)" uses simultaneously the high frequency magnetic heating field of the EML also for the inductive, contactless determination of the electrical resistivity of the levitated metallic droplet and its thermal expansion [3].

Inductive Measurement Principle

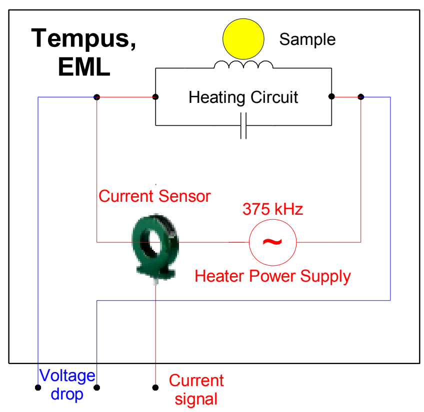

Fig. 2: Schematic sketch of the EML heating circuit with the electrical signal outputs. A power supply feeds a resonant current (~375 kHz) in the parallel oscillating circuit, the inductivity of which consists just of the heating coil and the inductively coupled metallic sample. The signal of the alternating current I through the circuit as well as the alternating voltage drop U across the circuit is conveyed to the outside.

As already indicated in Fig. 1 and shown in Fig. 2, the relation between the measurable quantities, i.e., U_0: amplitude of the alternating voltage drop across the levitation circuit, I_0: amplitude of the alternating current through the levitation circuit, φ: phase difference between voltage drop and current, as well as ω: angular frequency of voltage and current, and the sample properties, i.e. ρ: sample resistivity and a: sample radius, is given by the simple complex impedance relation

$$\frac{I_0}{U_0}e^{-i\varphi} = \frac{1}{Z_{cap}(\omega)} + \frac{1}{Z_{coil}(\omega) + Z_{sample}(\omega, \rho, a)},$$

where $Z_{cap}(\omega) = (i\omega C)^{-1}$ is the capacitor impedance, $Z_{coil}(\omega) = R + i\omega L$ is the impedance of the empty coil and $Z_{sample}(\omega, \rho, a)$ is that part of the coil impedance resulting from the inductively coupled sample. By a measurement of I_0, U_0, φ, and ω, real and imaginary part of the complex sample impedance $Z_{sample}(\omega, \rho, a)$, depending on the sample properties ρ and a, can be determined, after a preceding calibration measurement without sample provided the circuit parameters C, L and R.
For a spherical sample shape and a homogeneous magnetic induction field, two conditions which are largely satisfied in the EML facility under microgravity, $Z_{sample}(\omega, \rho, a)$ assumes a relatively simple mathematical form [4] allowing its inversion for a calculation of ρ and a from the "measured" values of $\mathrm{Re}\{Z_{sample}\}$ and $\mathrm{Im}\{Z_{sample}\}$. Both quantities are, however, relatively small compared to the real and imaginary part of Z_{coil} and Z_{cap}, respectively. Therefore, to obtain the temperature dependent electrical resistivity $\rho(T)$ of liquid samples with reasonable accuracy, the necessary resolution of the measurement quantities has to be correspondingly high:

$$\Delta U_0/U_0 < 8 \cdot 10^{-4}, \qquad \Delta I_0/I_0 < 8 \cdot 10^{-4}, \qquad \Delta\varphi < 0.15°, \qquad \Delta\omega/\omega < 2 \cdot 10^{-5}.$$

Test Results

A development model of the so called "Sample Coupling Electronics (SCE)" has been designed and constructed by DLR for the EML facility onboard the International Space Station (ISS). The SCE supplies dc voltages proportional to the measurement quantities: U_0, I_0, and φ with the above mentioned resolution from the alternating voltage and current signals of the levitation facility, see Fig. 2. These signals are then sent to the EML "Data Acquisition (DAQ)" unit, which converts the analogue dc voltages with a rate of 10 Hz into 16bit digital values. Finally, all digitized SCE data are stored synchronously with the sample temperature data, provided by the pyrometer of the levitation facility, to enable the calculation of the temperature dependent resistivity ρ and radius a of the sample with the help of the theoretical model of $Z_{sample}(\omega, \rho, a)$ given in Ref. [4].
To visualize the resolution of the SCE, Fig. 4 shows results of the electrical resistivity ρ and the radius a of a solid, spherical tungsten test sample for different sample temperatures.

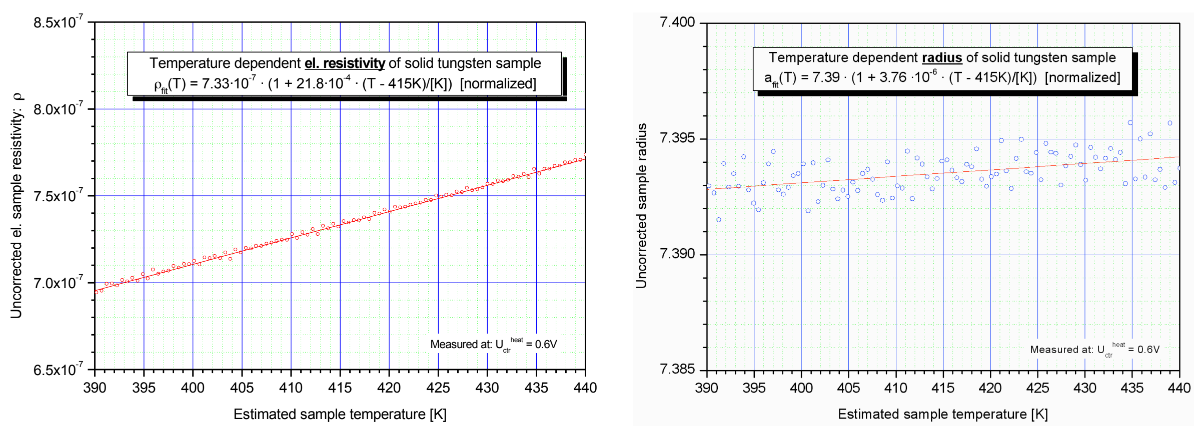

Fig. 4: Plot of the uncorrected electrical resistivity (left) and the radius (right) of the solid tungsten test sample against the estimated sample temperature. The open circles show the values evaluated from the measured SCE data. The straight lines present a linear fit of these data points.

The scatter of the resistivity data (Fig. 4 left) is extremely low. This is also due to the fact, that the sample itself is solid and fixed within the coil during the test. The fitted absolute values of the resistivity are arbitrary, because there was no previous calibration with a sample of known properties providing a correct "coupling constant".
Due to the very low increase of the sample radius with the temperature: $\approx 3.76 \cdot 10^{-6}[K^{-1}]$ (see Fig. 4 right) and the necessarily much higher resolution of this diagram compared to that of Fig. 4 left, the data scatter of the radius values is higher. Nevertheless, the radius increase of the test sample with increasing sample temperature is clearly visible, proving that the above listed data resolution of the SCE is sufficient.

Oxygen Sensing and Control Unit (OSC)

Using the OSC, the oxygen partial pressure in the atmosphere of the EML experiment chamber can be measured and controlled. This enables a measurement of critical properties, such as surface tension and viscosity in dependence of an adjusted oxygen partial pressure.

Technical Realization

The OSC consists of an oxygen loading system (OLS), a solid state potentiometric sensor (SS1) and a gas circulation pump. The SS1 is located at the outlet of the EML chamber and the OLS at the inlet. Due to the design constrains in the EML facility, the OLS and SS1 are mounted outside the chamber and thus require gas circulation.
Both, the oxygen loading system (OLS) and the potentiometric solid state sensor (SS1) are based on an ionic conductor, yttrium-stabilized zirconium (YSZ), operated at the temperature sufficiently high to enable the transport of O^{2-} ions throughout the electrolyte, but low enough to suppress electronic conduction. The oxygen partial pressure adjusted by the pump depends on the electric current I, total pressure p_{tot}, total gas flow J_{tot} and the initial oxygen partial pressure in the carrier gas p^0_{O2} as follows:

$$p_{O2} = p^0_{O2} + \frac{p_{tot}}{J_{tot}} \frac{I}{4F},$$

whereas F is the Faraday constant. As shown in Fig. 5, the tube of the oxygen ion pump is covered with platinum paste at three regions i.e. the large pumping area, the reference electrode and the counter electrode. The reference electrode is used to monitor the electromotive force, and thus p_{O2}, which is given by the Nernst equation. Due to the large distance between the pumping and reference electrode, no impact of the pumping current on the Nernst potential is observed.
The oxygen partial pressure is also measured by an additional potentiometric solid state sensor (SS1) located at the outlet of the chamber.

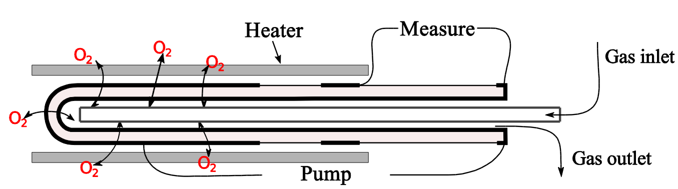

Fig. 5: The schematic view of oxygen ion pump. The carrier gas is delivered through a tube into the active area, where electric current I is applied and, therefore, oxygen ions are transferred throughout the electrolyte. An additional electrode is provided where the Nernst potential and, therefore oxygen partial pressure is measured.

Both, the oxygen ion pump and the sensor are operated at 870 K. This relatively low temperature ensures sufficiently high oxygen ion mobility and long-term stability of the system as required for the electromagnetic levitation experiments.

Since the system is operated in an environment, where strong electromagnetic noise occurs, commercial temperature controllers do not fulfill the stability requirements under such conditions. Therefore, a robust custom device is built. In order to reduce the cross-feed between the power supply and monitored temperature, commonly used thermocouples are replaced with resistive temperature sensors. Moreover, shielding for control electronics and for entire OLS is provided. The pumping current I of at most 40 mA is adjusted by a pulse width modulation control based on a PID algorithm. Thereby the polarity of the current can be changed. The controller achieves a resolution of about 1 μA. At maximal current about 8 cm^3 of O_2 can be transferred throughout the electrolyte within an hour. In order to adjust the oxygen partial pressure at two different potentiometric sensors, the system features a cascade PID controller.

Test Results

The OLS system is tested in two different environments. Laboratory conditions, free of strong electromagnetic fields and dust particles in carrier gas due to evaporation of liquid samples, enable precise determination of oxygen pump's performance, response time and signal stability. In case of the experiments, where the oxygen partial pressure is adjusted during levitation, strong electromagnetic fields impact potentially the stability of the control system.

The result of oxygen ion pump controlling p_{O2} at the carrier gas (Ar 99.999 %, p_{O2}=1.6×10^{-4} bar) is shown in Fig. 6. Here, the oxygen partial pressure is varied stepwise between 10^{-7} and 10^{-3} bar. Remarkable is the very short response time of less than 90 s and signal stability of $\Delta\log(p_{O2}/\text{bar}) < 0.02$. Since the oxygen control system features switching of the pumping current polarity, it is possible to control p_{O2} below and above oxygen's partial pressure in the carrier gas.

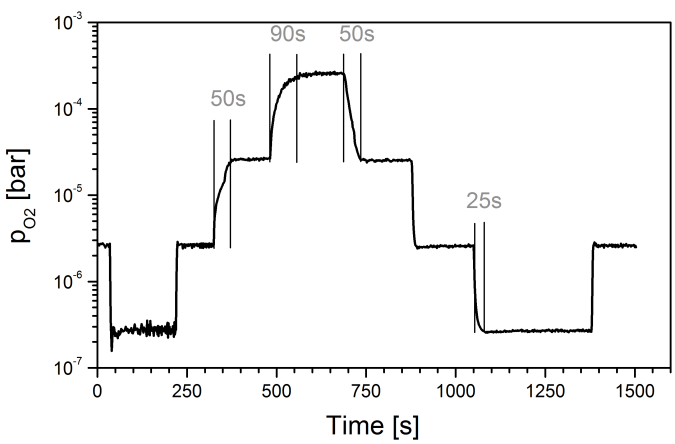

Fig. 6: The oxygen partial pressure adjusted by the OLS.

The results of OSC operated in parallel with a ground based electromagnetic levitator are shown in Fig. 6. The system proves to operate stable under these conditions, even if the levitator is operated at full power required to levitate and heat the sample in 1g conditions. Thanks to the use of resistive Pt100 sensors, the fluctuation of the temperature is negligible. The electromagnetic interference the OSC was exposed to in this test is much stronger than expected in EML (under μg conditions) since the ground levitator uses fields that are approximately three orders of magnitude larger than in the EML under µg. Therefore, this was a very harsh test providing a large confidence level that the OSC will work well in an µg-EML environment

The response time of OSC varies between several seconds and an hour. It depends strongly on the experimental conditions like e.g. the gas flow rate, kind and purify of levitated material as well as presence of unintended buffer mixtures like H_2/H_2O, CO/CO_2 or C_xH_y/CO_2. In particular, the liquid sample acts an oxygen buffer and its influence on the measurement and control of p_{O2} cannot be ignored.

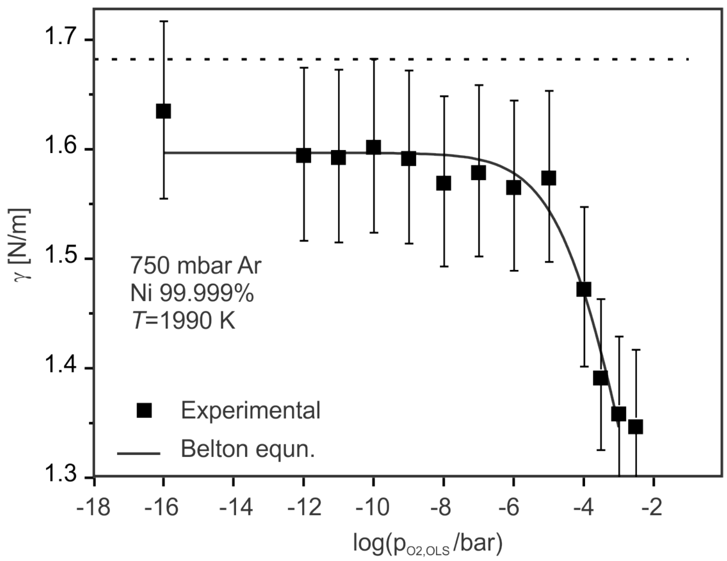

Fig. 7: Surface tension of liquid Ni at 1990 K versus $p_{O2,OLS}$ together with data from Ref. [8] (dotted line).

During levitation, the liquid sample performs spontaneously excited surface oscillations. The sample is observed by a fast digital C-MOS camera (400 frames per second) and the frequency spectra of the surface oscillations are obtained from image analysis software. Using the sum formula of Cummings and Blackburn [6] the surface tension γ can be calculated from a spectrum. This is shown in Fig. 7 for a liquid Ni sample of 99.999 % purity at 1990 K where γ is plotted versus $p_{O2,OLS}$.

For $p_{O2} < 10^{-6}$ bar, γ remains constant at a value of 1.6 N/m. It decreases with increasing p_{O2} when the oxygen partial pressure becomes larger than 10^{-6} bar. The results can be described by the Belton-equation [7] and the agreement is very good, as shown in Fig. 7b.

At the corresponding temperature of 1990 K, the surface tension of pure Ni is 1.68 N/m, Ref [8], which is slightly larger than the value of 1.6 N/m that was found in this experiment. However, this discrepancy is still within the error bar of ±5 %, so that it can be stated that a good agreement with the reference data is obtained.

Summary

Two advanced measurement devices for the microgravity "electromagnetic levitation facility (EML)", which is currently under construction for the use onboard the "International Space Station (ISS)", have been presented. One is the "Sample Coupling Electronics (SCE)" and the other is the "Oxygen Sensing and Control Unit (OSC)".

The SCE measures by a contactless, inductive method the electrical resistivity and the diameter of a spherical metallic droplet, levitated in the EML under microgravity conditions, by evaluating the voltage and electrical current applied to the levitation coil. A development model of the SCE has been designed, constructed and tested under laboratory conditions by DLR. These tests show a sufficiently well resolution of the electronics for a temperature dependent determination of those measurement quantities.

The OSC measures the oxygen partial pressure of the atmosphere in the EML experiment chamber. The necessity of the OSC comes from the insight that properties like surface tension or, eventually viscosity by the oscillating drop method in the EML facility cannot seriously be determined without knowing the conditions of the surrounding atmosphere. A technology demonstrator of an OSC system for the use at the ISS-EML has been developed and successfully tested. The tests were carried out under ideal laboratory conditions as well as in real levitation environment under gravity conditions. In both test it was shown that the device works reliably. An example experiment, the measurement of the surface tension of liquid Ni as function of the oxygen partial pressure, succeeded convincingly. The obtained data could be described by the Belton equation.

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