MAGNETOHYDRODYNAMICS Vol. 61 (2025), No. 1–2, pp. 157–164
DOI: 10.22364/mhd.61.1–2.16

EXPERIMENTAL STUDY OF THE HEAT TRANSFER IN AN ELECTROMAGNETICALLY LEVITATED LIQUID METAL DROPLET UNDER A SUPERPOSED HORIZONTAL MAGNETIC DC FIELD

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An effect of the DC magnetic field directed horizontally and imposed over an electromagnetically levitating droplet of liquid metal is studied via temperature measurements at the equatorial and polar parts of the droplets of Ni and Cu. It is demonstrated that while the application of the DC magnetic field lower than 3.5 T destabilizes the droplet, a DC magnetic field of 4.5 T stabilizes the position of the droplet that provides less noisy temperature measurements. However, there is no clear evidence of the damping of the convective heat transport inside the droplet.

Introduction.

Coupling electromagnetic levitation and application of a DC magnetic field could be an attractive solution that provides a possibility of non-contact manipulations with an electrically conducting sample while damping of the convective flow inside that sample should be expected. Yet, to our knowledge, this kind of the AC/DC coupling is employed only in a PROSPECTUS setup which uses a DC magnetic field directed vertically, i.e. aligned with the gravity vector [1, 2]. As shown elsewhere [3], in an axially symmetric configuration, the vertically directed magnetic field interacts with the radial component of the fluid flow in a levitating sample that creates an eddy current circulating in the polar direction and that finally results in a radially directed force opposite to the one generating the fluid motion. Consequently, the intensity of the fluid flow decreases, as it was demonstrated numerically [3, 4].

In the present work a setup, where AC electromagnetic levitation is coupled with a DC magnetic field directed horizontally, i.e. perpendicular to gravity, is explored. The horizontally directed magnetic field $B_{\mathrm{DC,h}}$ tends to align the axis of the vortices occurring in the liquid along the lines of $B_{\mathrm{DC,h}}$, while the damping is expected at the less extent compared to the effect of the vertical DC magnetic field of the same intensity [3]. On the other hand, it is necessary to keep in mind that the geometry of the levitation coil is not really axially symmetric, hence, the liquid flow inside the droplet is three-dimensional, therefore, the damping effect of the horizontal magnetic field can be more pronounced compared to the one observed in numerical modeling. In particular, we expected that the convective heat transport from the equatorial volume of the droplet toward its pole would decrease and that this effect could be detected by the temperature measurement. Moreover, in case of diffusive heat transfer, the procedure of modulated calorimetry [5] could be employed to define the thermal conductivity of the liquid metal.

1. Experimental setup.

In the experiment, the magnetic field is generated by a helium cooled superconducting split-coil magnet, whose enclosure has a vertical and a horizontal bore (Fig. ure 1). The vertical bore allows us to place the AC chamber which contains the electromagnetic

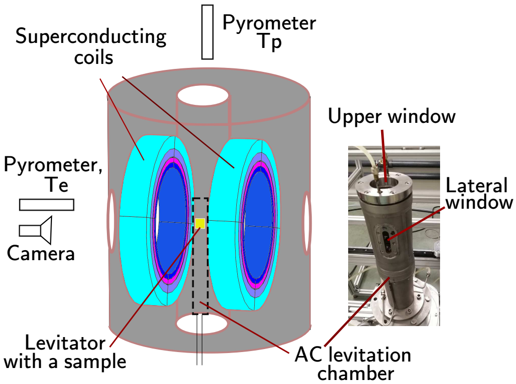

Fig. 1. Sketch of the DC magnet indicating the super-conducting coils placed in a helium-cooled case (gray color) which produce the horizontal magnetic field. A position of the AC levitation chamber with the levitation coil is shown. A photo of the AC chamber demonstrates two windows allowing observations and measurements.

coil used for levitation at the magnet's centerline and to measure the temperature at the sample's pole via a quartz window at the top lid of the AC chamber. A second horizontal bore throughout the DC magnet allows visual observation of the sample in levitation and temperature measurement at the equatorial area of the sample through the lateral window. The levitation coil used in the experiments has the same geometry a s in our previous works and operates with the AC current of nearly the same 140 kHz [6, 7].

With the aim of measuring the thermal conductivity of liquid metal, we conducted experiments using samples of the largest possible size that could be introduced into the levitation coil. It should be noted that the larger size of the droplet means also a higher Hartmann number (Ha) generally employed to characterize the effect of the magnetic field on the flow [8]. In the experiments with $B = 4.5\,\mathrm{T}$, $\mathrm{Ha} \approx 270$ for Ni and $\mathrm{Ha} \approx 711$ for Cu if the radius of the droplet is taken as a characteristic size.

2. Experimental results.

Several experiments with copper and nickel samples were performed with the sample temperature measurements throughout the experiments. In all experiments, a sample was put in levitation and melted first and only after that the DC magnet was switched on. Then, the intensity of the DC magnetic field was gradually increased to 4.5 T with some time intervals during which the intensity of the magnetic field was kept constant while the intensity of the AC electric current circulating in the levitator could be modulated. The Ni sample was levitated in the argon atmosphere as the emissivity of Ni, $\varepsilon_{\mathrm{Ni}} \approx 0.33$, was high enough to produce radiative cooling of the sample and compensate Joule heating. Yet, the emissivity of the liquid copper is lower $\varepsilon_{\mathrm{Cu}} < 0.2$, therefore, to avoid overheating and evaporation of the copper droplet, helium gas was supplied to the AC chamber to increase the conductive-convective cooling of the droplet.

2.1. Levitation of a nickel sample. The variation of the intensity of the effective AC current circulating in the levitator, the intensity of the DC magnetic field, and the equatorial and polar temperatures measurement for the Ni droplet with the mass $m_{\mathrm{Ni}} = 1.775 \cdot 10^{-3}\,\mathrm{kg}$ are shown in Fig. 2. The temperature outburst when the intensity of the DC magnetic field grows from 0 T to nearly 3 T is caused by a large amplitude oscillation of the droplet during which its surface approaches too close to the coils of the levitator, consequently getting more inductive heating. These oscillations even lead to

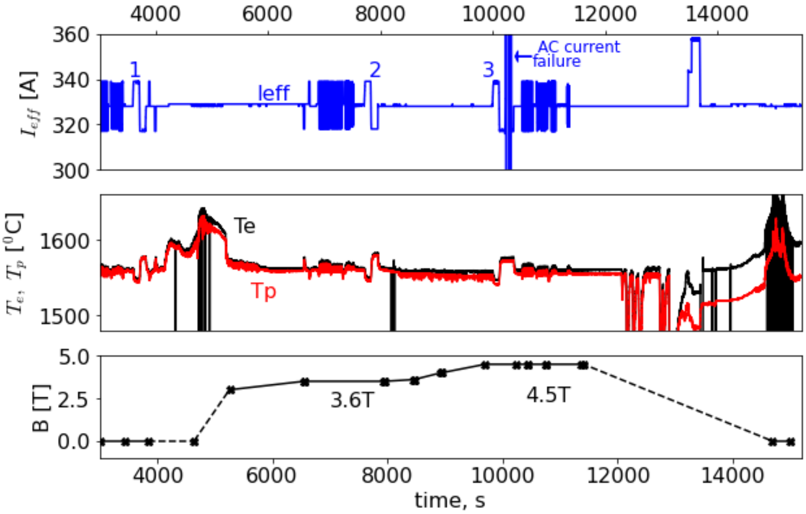

Fig. 2. Levitation of the nickel sample: variation of the effective intensity of the electric current in the levitator I_{eff} (top), temperature responses registered at the equatorial T_{e} and polar T_{p} parts of the droplet (middle) for different intensity of the DC magnetic field $B_{\mathrm{DC,h}}$ whose variation is shown in the bottom graph.

the instantaneous lost of the signal from the pyrometers when B_{DC} increases, as seen in the temperature graph in Fig. 2. A similar signal loss due to the oscillation of the droplet occurred also when the intensity of the DC magnetic field decreased, yet, the temperature did not increase because He gas was added at this stage. Nevertheless, the average temperature of the droplet remained nearly constant throughout the main part of the experiment, i.e. between 5000 s and 12000 s f or the time indicated in Fig. 2.

Different types of modulation of the AC electric current intensity were tested, among which a rectangular modulation (RM) that is marked as events 1, 2 and 3 in the top graph of Fig. 2, while the intensity of the DC magnetic field was different. A detailed view of the measured temperature responses for RM modulations of the AC electric current is shown in Fig. 3. The variation of I_{eff} was identically imposed, yet the AC generator followed the protocol in slightly different ways. An instantaneous failure of the AC electric current happened at the end of the imposed modulation (Fig. 3, green line), but it did not affect the thermal responses of the droplet. It is counter-intuitive that the increase of the value of I_{eff} makes the temperature of the Ni droplet decrease despite more power submitted to the system. This already was observed in [7] and has been confirmed by the present experiment and happens because with the increase of I_{eff} the magnetic pressure acting on the droplet increases and the droplet goes upwards, the distance between the droplet's surface and the coil increases, decreasing so the intensity of Joule heating. It should be noted that, as shown in the next section, the situation is different for the Cu sample.

The effect of the DC magnetic field appears in a less noisy signal and in a more pronounced exponential form of the signal. Fitting the curves of T_{e} and T_{p} with a function $C - A \cdot \mathrm{e}^{-B \cdot t}$ that corresponds to the transition between two stationary thermal states of the sample due to its heating gives $B = 6.36 \cdot 10^{-2}\,\mathrm{s}^{-1}$ for the equatorial temperature and $B = 6.87 \cdot 10^{-2}\,\mathrm{s}^{-1}$ for the polar temperature. The coefficient B presents the ratio given by Eq. (1), where S is the area of the droplet, $\sigma_B = 5.67 \cdot 10^{-8}\,\mathrm{W/(m^2{\cdot}K^4)}$ is the Stefan–

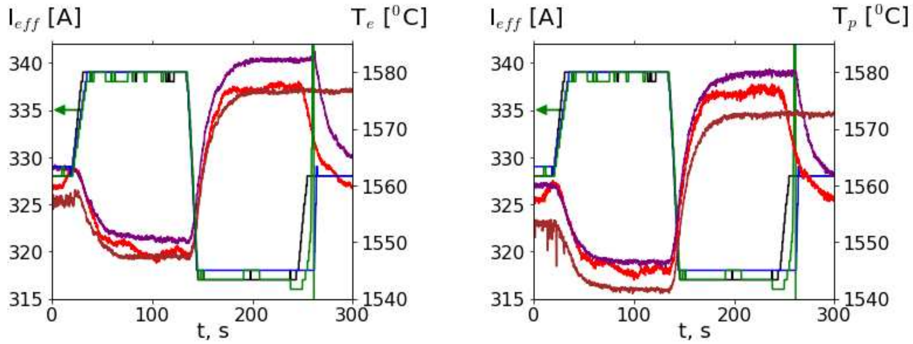

Fig. 3. Variation of the effective intensity of the AC electric current $I_{\rm eff}$ (black, blue, green) and the response of the equatorial temperature $T_{\rm e}$ (left) and polar temperature $T_{\rm p}$ registered with the DC magnetic field intensity $B_{\rm DC,h} = 0\,{\rm T}$ (red curve), $B_{\rm DC,h} = 3.5\,{\rm T}$ (purple curve) and $B_{\rm DC,h} = 4.5\,{\rm T}$ (brown curve) for the Ni sample sample.

Boltzmann constant, $\overline{T}$ is the average temperature (in Kelvin) at which measurements are made, h is a convective heat transfer coefficient, m is the sample's mass, and C_p is the specific heat [5]:

$$B = S \cdot \left[4\varepsilon_{\rm Ni}\sigma_B \bar{T}^3 t + h\right] / (m \cdot C_p). \qquad (1)$$

The convective heat exchange with the environment remains at the order of 12% of the radiative heat flux and can be neglected. Then, if the value of emissivity is known, the value of the coefficient B can be used to find the specific heat. In particular, for $\varepsilon = 0.33$, $C_p = 692\,{\rm J/(kg{\cdot}K)}$ was obtained that corresponds rather well to the value known for Ni at this temperature.

As it is mentioned above, the intensity of the AC current was modulated in different ways, however, the highest available modulation frequency was determined by the electrical circuit of the generator, and in our experiments it was $f^{\rm mod}_{\rm max} = 0.25\,{\rm Hz}$. According to [5], a phase shift of the thermal responses for the inductively and conductively heated parts of the droplet with respect to the imposed heating can be expected at this frequency, and the value of the phase shift would depend on the Biot number Bi and on the volume fraction heated inductively. The Biot number presents a ratio of the external and internal heat transfer coefficients, the latter is be detrmined both by thermal conductivity and convective heat transport. Consequently, if the application of the DC magnetic field damps the fluid flow inside the droplet, a different phase shift of thermal responses might be detectable in the measurements. The variations of the temperatures $T_{\rm e}$ and $T_{\rm p}$ registered during the sinusoidal modulation of the current with $f^{\rm mod}_{\rm max} = 0.25\,{\rm Hz}$ without application of the DC magnetic field and with $B_{\rm DC} = 4.5\,{\rm T}$ look nearly identical (Fig. 4). However, the calculation of the cross-correlation functions indeed shows that the phase shift between the signals of $I_{\rm eff}$ and $T_{\rm e}$ increased by 6^o when the DC magnetic, field was applied while, the phase shift between the $I_{\rm eff}$ and $T_{\rm p}$ decreased by 13^o. It should be taken into account that the overall the thermal behavior similar to the one reported for a rectangular-type modulation of the AC current can be observed: both temperatures decrease when the intensity of the electric current increases, and vice versa, that is related to the position of the sample with respect to the levitator coil.

It should be noted, however, that the character of the variation of $T_{\rm e}$ is clearly different compared to that of $T_{\rm p}$, yet, to understand the origin of the difference, three-

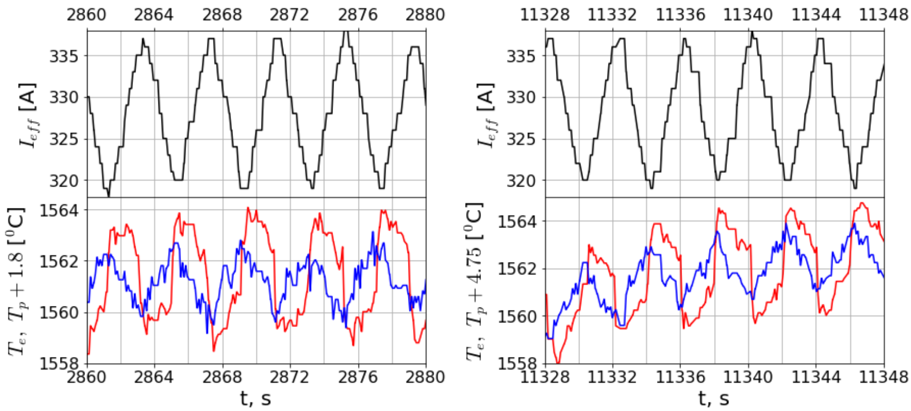

Fig. 4. Variation of the effective intensity of the AC electric current I_{eff} (upper graph, black) and response of the equatorial temperature T_{e} (red) and polar temperature T_{p} (blue) registered at the intensity of the DC magnetic field $B_{\mathrm{DC,h}} = 0\,\mathrm{T}$ (left), and $B_{\mathrm{DC,h}} = 4.5\,\mathrm{T}$ (right). Note that the measured values of T_{p} are shifted up at 1.8^0C and 4.5^0C (left and right graphs, respectively) to have better visualization.

dimensional modeling is needed accounting for the motion of the droplet under the electric current oscillation. Such numerical study is foreseen by the authors. The absence of a clear effect of the DC magnetic field on the thermal responses can be explained using a different assumption. In particular, the size of the inductively heated volume of the droplet might be too large that makes the two-zone heat transfer description questionable. It should be reminded that the electromagnetic skin depth in case of Ni is about of 1.3 mm, that means that the zone of Joule heating actually extends up to a thickness of 1.7 mm. Also, the variation of the droplet's position during the modulation of the AC current intensity and, consequently, the displacement of the inductively heating zone can alter the expected results.

2.2. Levitation of a copper sample. In the experiment with the copper sample with the mass $m_{\mathrm{Cu}} = 1.7180^{-3}\,\mathrm{kg}$, both temperatures, T_{p} and T_{e}, gradually decreased during the experiment (Fig. 5). This is related to the gradual replacement of the Ar gas by He gas inside the chamber that intensifies the heat exchange between the droplet and the surrounding atmosphere. The difference between the temperatures T_{e} and T_{p} increases with time and does not disappear when the intensity of the DC field becomes zero again, that also is an argument in favor of the variation of the heat exchange conditions. Similar to the experiment with Ni, RMs of the AC current intensity were made under the different intensity of the DC magnetic field. For the sake of clarity, in Fig. 6 the variations of the temperatures T_{e} and T_{p} registered during these modulations are presented only for $B_{\mathrm{DC}} = 0\,\mathrm{T}$ and $B_{\mathrm{DC}} = 4.5\,\mathrm{T}$ that corresponds to the events marked as 4 and 3 in the upper graph of Fig. 5.

In contrast to the case of Ni, the temperature of the Cu sample follows the variation of the intensity of the AC current I_{eff} although the sample also changes its position in the coil. However, it should be taken into account that the electric conductivity of copper is significantly higher then that of nickel [9, 10]. Therefore, at the nearly similar intensity of I_{eff} used in the experiments with Ni and Cu, the position of the copper sample inside the levitator is significantly higher compared to that of Ni. Consequently, it can be assumed that with the further increase of the intensity of the AC current, the copper

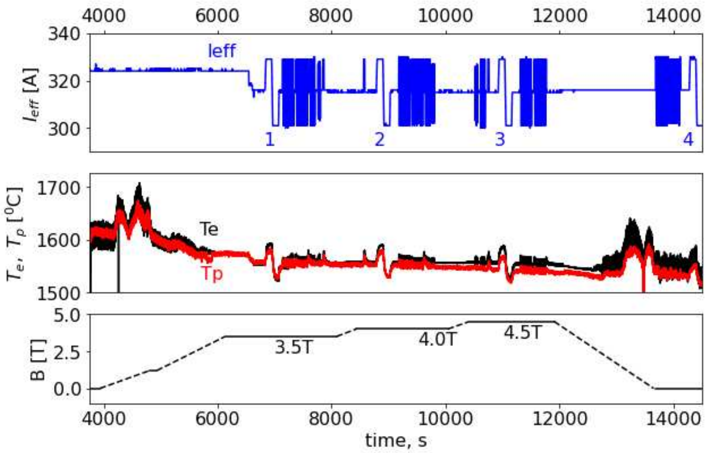

Fig. 5. Levitation of the copper sample: variation of the effective intensity of the electric current in the levitator I_{eff} (top), temperature responses registered at the equatorial T_{e} and polar T_{p} parts of the droplet (middle) for different intensity of the DC magnetic field $B_{\text{DC,h}}$ whose variation is shown in the bottom graph.

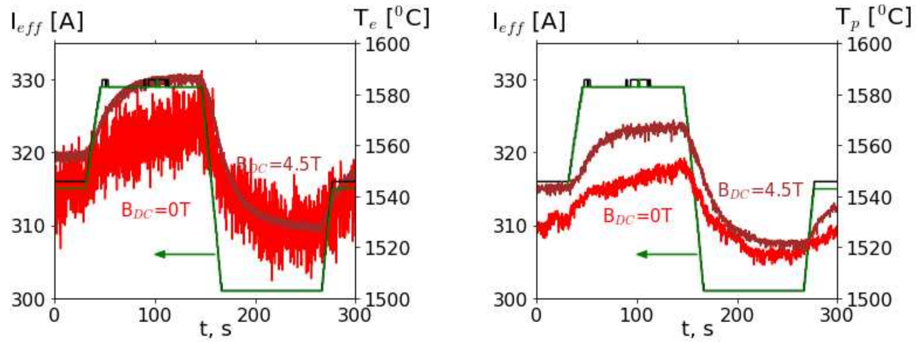

Fig. 6. Variation of the effective intensity of the AC electric current I_{eff} (black, green) and response of the equatorial temperature T_{e} (left) and polar temperature T_{p} registered at the intensity of DC magnetic field $B_{\text{DC,h}} = 0\,\text{T}$ (red curve) and $B_{\text{DC,h}} = 4.5\,\text{T}$ (brown curve) for the Cu sample.

sample becomes even closer to the upper coils and gets Joule heating at the upper part, while for the nickel droplet the distance from the bottom coils increases, yet the distance to the upper coil is still too large.

The measurement of the equatorial temperature of the Cu sample at $B_{\text{DC}} = 0\,\text{T}$ displays a very high level of noise making the estimation of the temperature variation hardly feasible. Yet, it is easily seen that with $B_{\text{DC}} = 4.5\,\text{T}$ the temperature variation during the heating and cooling stages changes from nearly linear to exponential for both T_{e} and T_{p}, whereas with the stationary intensity of the AC current both temperatures indeed approach stationary values. This indicates the stabilization of the droplet under the DC magnetic field of 4.5 T, similar to the Ni sample. For the case of Cu, it is common to fit the cooling curves as the stationary state becomes more stable, i.e. the fitting is made in the form $C + A \cdot e^{-B \cdot t}$, and Eq. (1) for the B coefficient is valid. This gives the values $B = 3.62 \cdot 10^{-2}\,\text{s}^{-1}$ calculated for the equatorial temperature and $B = 3.38 \cdot$

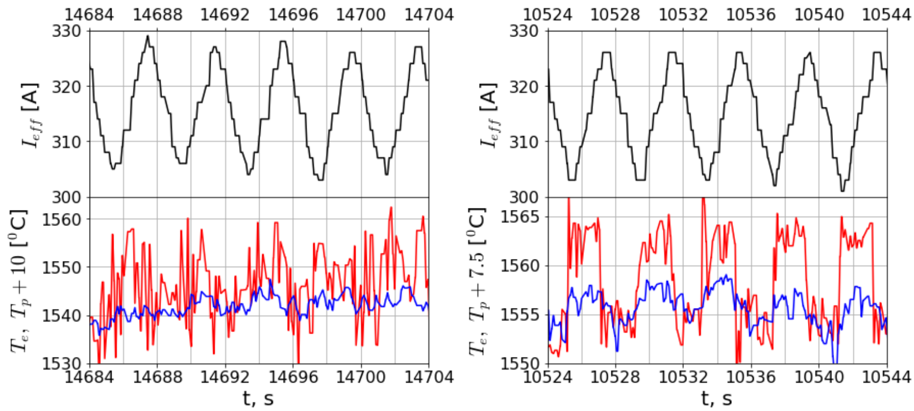

Fig. 7. Variation of the effective intensity of the AC electric current $I_{\rm eff}$ (upper graph, black) and response of the equatorial temperature $T_{\rm e}$ (red) and polar temperature $T_{\rm p}$ (blue) registered at the intensity of the DC magnetic field $B_{\rm DC,h} = 0\,{\rm T}$ (left) and $B_{\rm DC,h} = 4.5\,{\rm T}$ (right). Note that the measured values of $T_{\rm p}$ are shifted up at 10°C and 7.5°C (left and right plots, respectively) for better visualization.

$10^{-2}\,{\rm s}^{-1}$ when calculated for the polar temperature. Yet, the knowledge of the convective heat transfer coefficient is crucial for the copper sample as the experiment clearly showed that the convective heat exchange of the levitating droplet with the atmosphere inside the chamber was comparable with the radiative heat losses of the sample. Consequently, further analysis is required for feasible estimating of C_p for the copper sample.

The experimental results obtained with the modulation of the intensity of the AC current performed at $f^{\rm mod}_{\rm max} = 0.25\,{\rm Hz}$ are illustrated in Fig. 7. The measurements made in the absence of the DC magnetic field cannot be used directly and require pre-processing. Again, the effect of the DC magnetic field as a low-pass filter is well presented on the right graph of Fig. 7, which represents the measurement made at $B_{\rm DC,h} = 4.5\,{\rm T}$. Interestingly, the thermal responses to the sinusoidal AC current modulation for the Cu droplet looks rather similar to the case of the Ni droplet: the equatorial temperature is maximum when the AC current is minimum, and it drops almost vertically once the AC current takes the highest level. The variation of the polar temperature has a smoother character, yet, based on these data, it is not possible to state whether the convective heat transfer is still present in the droplet.

3. Conclusions.

Application of the DC magnetic field directed horizontally to the electromagnetically levitating liquid metal droplet stabilizes the latter. This makes the analysis of the thermal data obtained during the experiment feasible. In particular, the thermal response of the droplet registered during the low-frequency modulation of the AC electric current intensity allows one to define a characteristic time for the external heat exchange between the droplet and the atmosphere. This characteristic time can be used for the estimation of specific heat of the material provided the emissivity of the latter is known, or vice versa. However, convective heat transfer to the environment should be taken into account for materials with low emissivity. Application of modulated calorimetry can be feasible, yet, require knowledge on the relationship between the intensity of the electric current, sample position and Joule heating of the sample. That can be achieved with three-dimensional modeling considering the actual geometry of the levitator. Finally, it is demonstrated that the thermal reaction of the Ni sample to the variation of the intensity of the AC electric current circulating in the levitator is opposite to that of the Cu sample, that gives an interesting example for numerical modeling.

Acknowledgments.
The authors acknowledge the CNES support via the Material Science program. The laboratory SIMaP is part of the LabEx Tec 21 (Investissements d'avenir – 638 Grant Agreement No. ANR-11-LABX- 0030).

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Received 24.11.2024