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The Maximum Volume of a Rare-Earth Metal Molten Droplet During Levitation Melting in an Axisymmetric Inductor

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The maximum volumes of molten droplets stably levitated by an electromagnetic field in an axisymmetric inductor were determined for a number of rare-earth metals of the yttrium group (Y, Tb, Dy, Ho, Er, Yb). The experimental values of the maximum volumes are compared with values calculated using the surface tension, specific electrical resistance, and density of the rare-earth metals in the molten state.

Keywords: rare-earth metals, levitation melting, high temperatures, pure metals.

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Rare-earth metals (REMs) are highly chemically active and require special conditions for melting. Crucibleless levitation melting with electromagnetic suspension of a molten droplet is well suited for REM remelting and producing alloys based on such metals [1]. This method allows for the production of a well-mixed high-temperature molten droplet without contact with a container. It is used to obtain alloys based on REMs, remove gaseous impurities from them, and determine the surface tension of the melt. The application of levitation melting is limited to obtaining small quantities of alloys for further physical and chemical studies.

Inductors used for levitation melting of metals always have regions of a weaker field through which liquid metal does not escape only due to the pressure produced by the forces of surface tension on a curved surface (Laplace pressure). An estimate of the equilibrium conditions for a levitating droplet was proposed in [2] and is considered below. A pressure equilibrium is established at any point on the surface of a droplet:

$$\sigma_t = \sigma_e + \sigma_g + C,$$

where σ_t is the pressure due to surface tension, σ_e is the pressure of the electromagnetic field on metal, σ_g is the hydrostatic head, and C is the pressure due to surface tension at the top of a droplet, which may be neglected if the top surface is flat. $\sigma_t = 2\alpha/r$, where α is the surface tension and r is the surface curvature radius at a given point.

The pressure of the electromagnetic field on metal with surface penetration of the field into it is written as $\sigma_e = \mu H^2/4$, where H is the amplitude of the magnetic field strength on the metal surface.

Hydrostatic pressure $\sigma_g = hdg$, where h is the droplet height (vertical droplet size), d is the liquid metal density, and g is the gravitational acceleration. The following holds true for the lower part of a droplet:

$$2\alpha/r + \mu H^2/4 = h_{\max} dg,$$

where $h_{\max}$ is the maximum droplet height. The minimum radius of the lower surface of a droplet cannot be smaller than depth Δ of penetration of the electromagnetic field into metal, since a droplet smaller in size is transparent to the field of a given frequency.

This implies that the maximum height of a liquid metal column depends on the capillary constant. The following expression for the maximum volume of metal in stable levitation may be obtained:

$$V_{\max} = (1/6)\pi(a^2/\Delta)^3, \quad (1)$$

where a is the capillary constant of the metal [cm],

$$a = \sqrt{2\alpha/dg}, \quad (2)$$

Here, α is the surface tension [N/m], d is the density of molten metal [kg/m^3], and g is the gravitational acceleration. Δ — depth of penetration of the electromagnetic field into metal [m],

$$\Delta = \sqrt{\rho/\mu\pi f}, \quad (3)$$

where ρ is the specific resistance [$\Omega \cdot$ m], f is the field frequency [Hz], and μ is the permeability [H/m].

Volume $V_{\max}$ in formula (1) is the volume of a sphere with a diameter equal to the maximum droplet height. Since the actual droplet shape is not spherical, this formula overestimates slightly the maximum volume of a stably levitating molten droplet.

It should be noted that the maximum achievable volume of a molten metal droplet may be limited by the experimental setup parameters (namely, the generator power and the permissible inductor voltage) needed to reduce the likelihood of electrical discharge. In the present study, REM droplets were levitated with a generator power of

Comparison of calculated and experimental parameters of levitating droplets of rare-earth metals

Metal	Surface Tension α, N/m (at $T_m + 250\,^\circ$C)	Density d, g/cm^3 (at $T_m + 250\,^\circ$C)	Capillary constant a, cm	Specific resistance ρ, $\mu\Omega \cdot$ cm	Penetration depth Δ, cm	Estimated maximum mass m_o, g	m_{exp}, g	$V_{\max}$, cm^3
Y	0.792, 0.851	4.09, 4.18	0.628, 0.65	80	0.0960	150.1, 183	30	7.32
Tb	0.799, 0.648	7.72, 7.7	0.459, 0.414	130	0.122345	21, 11.1	15	1.94
Dy	0.891, 0.623	7.72, 8.01	0.485, 0.399	110	0.112541	37, 11.9	20	2.59
Ho	0.619	8.21, 8.19	0.392, 0.393	90	0.101797	15.5, 14.9	30	3.65
Er	0.607	8.47, 7.98	0.382, 0.394	90	0.101797	13.7, 14.8	15	1.77
Yb	0.294	5.91, 6.07	0.319, 0.314	110	0.05033	2.58, 2.15	12	2.03

approximately 15 kW (and a maximum power of 30 kW), and the used frequency of 220 kHz was significantly lower than the frequency of 400 kHz that is recommended as the limit not to be exceeded so as to avoid electrical discharges [1,2]. In addition, the same inductor was used for all metals, and levitating droplets of similar sizes were located in a region with approximately the same magnetic field gradient. Thus, the experimental setup parameters do not impose any constraints on the maximum REM droplet volume; the primary influence is exerted by the capillary constant of the metal.

In the present study, a number of pure REMs were melted, and the maximum volumes of a stably levitated liquid droplet were compared with the values calculated using literature data on the density, specific resistance, and surface tension of REM melts. It should be noted that the literature values of these parameters for REM melts have a significant spread, which may be attributed both to the use of different methods for their determination and to the difference in concentrations of gaseous and metallic impurities in the studied metals.

All REMs except scandium and yttrium have low capillary constant values ($a \sim 0.5$ cm) and are levitated in smaller droplets than other metals. The surface tension of molten metals depends strongly on the concentration of impurities (primarily gaseous ones). For example, the approximate surface tension for pure aluminum at the melting point (933 K) is 1.05 N/m, but decreases to 0.85 N/m when aluminum is saturated with oxygen [3]. Even oxygen concentrations as low as 0.0005 % may lead to surface saturation, which has a significant influence on surface tension. The mechanism of influence of dissolved gases at the surface of molten metal was discussed in detail in [4]. Published data on the surface tension of molten rare-earth metals do not specify the content of gas impurities. It is fair to assume that the results of our experiments correspond to samples of sufficient purity, since gaseous impurities are removed when the material is subjected to levitation melting. Literature data on the capillary constant and density [5–7] and the electrical resistance [8,9] of molten REMs were used to calculate the maximum droplet volumes. Since the coefficients of surface tension and density of molten REMs depend on temperature, the values corresponding to a temperature 250 °C higher than the melting point (with the data from [5,6] taken into account) were used in calculations.

REMs were melted in an inductor with a parallel counter turn at a field frequency of 220 kHz. All the studied REMs were levitated stably in the form of molten droplets with a diameter of 1.5–2 cm with steady-state temperatures 200–300 °C above the melting point. The maximum supported droplet weight was determined by increasing successively the weight of a levitating molten REM droplet with a manipulator (controlled from outside the vacuum chamber) to the level at which the droplet could no longer be suspended electromagnetically. This method provides an opportunity to determine the maximum droplet weight with an accuracy better than 0.5 g. To prevent intense droplet evaporation, the melting chamber was filled with purified helium.

The table presents literature data on surface tension α and density d at a temperature 250 °C above the melting point and specific resistance ρ at T_m, which were taken primarily from reviews [5,6]. Two values may be indicated for each parameter if they differ significantly in different literary sources. The values of capillary constant a and penetration depth Δ calculated using formulae (2) and (3), respectively, are also listed. The values of maximum weight m_o of a levitating droplet of the studied REMs calculated using formula (1) (with account for scatter of literature data) and the experimentally obtained values of maximum weight m_{exp} and the corresponding maximum volume of a levitating droplet $V_{\max}$ are presented in the last columns.

The maximum weight of all the studied metal droplets falls within the range of 10–30 g, although the values of surface tension, density, and resistivity of specific metals may vary greatly, leading to large differences in calculated maximum masses.

Let us examine the results for different metals.

(1) Yttrium has the highest surface tension among the metals considered, and the calculated maximum droplet weight is within the range of 150–183 g, while the experimental result is 30 g. This discrepancy is attributable to the presence of a large amount of gas impurities

(primarily oxygen), which may reduce the surface tension of molten metal both as a dissolved impurity and by forming Y_2O_3 oxide particles. Since the density of Y_2O_3 ($5\,g/cm^3$) is significantly higher than that of molten yttrium ($\sim 4.1\,g/cm^3$), particles move toward the lower part of a droplet, affecting the melt properties at the bottom point.

(2) Terbium, dysprosium, and erbium. The measured maximum weights of terbium (15 g; the corresponding calculated value is 11.1–21 g), dysprosium (20 g; 11.9–37 g), and erbium (15 g; 13.7–14.8 g) droplets agree closely with calculated data. Note that the maximum weight of a droplet of molten dysprosium was sufficient to obtain castings in the form of flat washers, which were used to enhance the magnetic field in a superconducting solenoid by 3 T in a gap of 2 mm.

(3) Holmium and ytterbium. The values of surface tension of these metals are given in literature with no indication of their purity. The maximum weight of these metals calculated in accordance with Eq. (1) turned out to be lower than the one obtained experimentally. The calculated and experimental weight values are 14.9–15.5 and 30 g for holmium and 2.15–2.58 and 12 g for ytterbium, respectively. This difference indicates that the actual surface tension values of these metals are higher than those provided in literature.

In general, the experimental results demonstrate that axisymmetric inductors are suitable for melting only small amounts of rare-earth metals. A number of modifications to the inductor system aimed at increasing the weight of levitated molten metal have already been proposed. The first proposal was to use inductors extended in one direction in the horizontal plane [10], where molten metal assumes the form of a cylinder. This has a significant positive effect on the mass of levitated melt. Note that the maximum amount of metal suspended electromagnetically in this manner is again determined primarily by the surface tension in the lower melt zone. Another system of inductors producing horizontal fields of complex configuration and different frequencies (with several weaker field regions) instead of a vertically oriented field has been proposed recently in [11]. This complex system provides an opportunity to increase significantly the volume of suspended molten metal (up to 0.5 kg for aluminum).

Thus, both calculations of the maximum weight of molten REM droplets and the experimental values obtained for a number of REMs of the yttrium group demonstrate that the simplest axisymmetric inductors allow one to obtain stably levitating droplets 10–30 g in size, which is sufficient for production of REM alloys for further physical and chemical studies.

Conflict of interest

The authors declare that they have no conflict of interest.

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