Note

New Method and Devices for Electromagnetic Drip- and Leakage-Free Levitation Melting

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In conventional melting devices with electromagnetic levitation (EML) axisymmetric magnetic fields are used that generate force distributions at which the Lorentz force vanishes on the vertical z -symmetry axis.¹⁾ Therefore, at the bottom of a levitated load a singular point P appears for the Lorentz force, in which the melt outflow and leakage can be hindered only by its surface tension, hence the charge weight is limited. The application for larger loads of several coils fed with different frequencies and displaced relatively to each other so that the singular point of one coil is covered by the other is disadvantageous because of the coils magnetic coupling, causing the dissipation of significant amounts of power in the copper tube coils.¹⁾ In the particular case of a three-frequency levitator composed of three orthogonally arranged coils with complicated geometries required to ensure a stable EML,²⁾ the magnetic fields of the two outer coils are damped by the eddy currents induced in the coils located at their interior and the melt handling and casting is restricted by the coil parts situated under the charge. Even by a two-frequency supply of the inductor winding divided into a heating and a levitation coil, an EML force cannot be produced on the axis of a melting furnace without a crucible³⁾ or with a cold crucible (CC),^{4,5)} respectively. The EML force density vanishes also on the axes of conventional electromagnetic valves and consequently, valves with inner cores supported by complicated holding arms have to be used.^{6–8)}

In this paper, a new method to exert EML forces along the z -axis is presented, consisting in the utilization of two homogeneous sinusoidal magnetic fields of different frequencies, whose field lines in absence of a charge are horizontal and reciprocally normal.^{9,10)} In the two fields, a lift force density is exerted on the melt axis also in the lowest point P and therefore the weight of the levitated charge can be increased. The levitated sample position is axisymmetrically stabilized in the two fields by their reciprocally normally exerted Lorentz forces. The frequencies of the two magnetic fields must be different, in order not to produce a rotational field. The applicability of the method was experimentally examined and proved by tests performed in two laboratory setups, as well as by simulation of the electromagnetic field and the free surface using the Finite Differ-

ence Method (FDM) in cylindrical coordinates (r, φ, z) , yielding results in good agreement with the measurements.

The two magnetic fields can be generated by two single-phase windings embedded in the axial slots of the magnetic cores M (Fig. 1). The new levitation method can be used for the melting furnace without a crucible (Fig. 1(a)) or with a cylindrical Cold Protective Wall (CPW) instead of a CC, composed of several annular segments or of a single, helically wound copper tube C (Fig. 1(b)), as well as for the coreless induction valve.^{9,10)}

The two-frequency device shown in Fig. 2(a), comprises a magnetic core composed of a yoke Y and four teeth T (Fig. 3), onto which four copper tube coils are wound. In a vertical quartz tube, Al-alloy samples of 30 mm diameter and

Fig. 1. Two-frequency EML melting furnaces without crucibles (schematic): (a) without and (b) with a cold protective wall composed of a copper tube C . M , magnetic core; F , fluid metal.

Fig. 2. Laboratory EML melting device: (a) with a levitated 28.6 g solid Al-alloy cylinder, immediately after the two-frequency feeding of the inductor; (b) view from above of the melted Al-sample.

Fig. 3. Two-frequency laboratory setup for EML melting (schematic): T and Y , tooth and yoke of ferrite magnetic core; $C1$, $C2$, $C3$, $C4$, copper tube coils.

15 mm height, were drip- and leakage-free melted. The teeth are indirectly water cooled by eight lateral copper plates with brazed-on cooling copper tubes. The first magnetic field of frequency 28.6 kHz is generated by the coils *C1* and *C2* and the second field of 22.7 kHz, by the coils *C3* and *C4*, respectively. The two coil pairs being by 90° one in relation to the other, they are not coupled magnetically.

The two electromagnetic fields produced by the two coil pairs were computed by the calculation method detailed presented in Refs. 10) and 11), respectively. Because the magnetic induction component B_ϕ decrease opposite to the teeth, e.g. $B_\phi = 0$ at point *P* on the tooth surface with a distance of 28 mm from the *z*-axis (Fig. 3), the Lorentz forces also decrease and as a result, the outer form of the melted sample is not circular, having larger radii opposite to the teeth (Fig. 2(b)), i.e. a larger outer radius in the vertical *C-C* plane than in the *D-D* plane.

For the free surface determination, the simplified method developed in Ref. 12) for the two-dimensional calculation of steady free surfaces was applied. Within each step of this iterative algorithm, a Poisson equation is solved for the pressure in all inner completely filled and all partially filled surface cells by using only the resulting force density field and Neumann's homogeneous boundary condition. Subsequently, the free surface is determined by a linear pressure-dependant approximation for the melt volume contained in the surface cells.¹²⁾ The applicability and generality of this model were tested both for a large frequency range, between 50 Hz and 30 kHz, and for the different free surface profiles of various recirculated, rotational semi- or entirely-levitated flows, driven in mono- or rotational three-phase magnetic fields.^{13,14)}

In this paper, in order to compute the non-circular free surface form (Fig. 2(b)) by the method established in Ref. 12), the pressure is three-dimensionally determined by applying FDM for a grid with an angular spacing in ϕ -direction of $\pi/4$. Because of the periodicity with a period of $\pi/2$, the pressure and the free surface profiles could be simplified determined only in the two vertical planes *C-C* and *D-D* (Fig. 3).

A validation of the new levitation concept was obtained by the following experimental and simulation results (Fig. 4): 1) the sample was axisymmetrically levitated and drip- and leakage-free melted; 2) like the experiment (Fig. 4(a)), also the calculations yield a practical horizontal lower free surface (Fig. 4(b)); 3) for the measured as well as for the calculated distance in vertical direction, *d*, between the upper surface of the ferrite tooth and the lower free surface (Fig. 3) the same value $d = 0$ mm was obtained (Fig. 4); 4) the outer radius of 19.5 mm of curve *1* determined in the *C-C* plane is likewise close to the visually measured radius of 19.2 mm (Fig. 4(a)).

A CPW composed of a water cooled copper tube coil *C* (Fig. 1(b)) was employed for protecting the magnetic core against heating caused by the melted charge. The transmission of the outer magnetic fields into the inner of the CPW is performed inductively like in the case of mould stirring by means of an outer inductor¹⁵⁾ the electric currents induced in the exterior walls of the copper tube by the outer two-frequency magnetic field of the four coils, are passed through the interior tube walls and produce a second two-frequency magnetic field inside the CPW. The utilization of

Fig. 4. Laboratory EML melting device: (a) view from *E* (Fig. 3) of the setup with a 28.6 g melted Al-alloy sample; (b) calculated free surface shapes in the planes (Fig. 3): 1, *C-C*, 2, *D-D*.

Fig. 5. Laboratory two-frequency EML device comprising a CPW between the inductor and the quartz tube: (a) with an axisymmetrically levitated solid Al-alloy cylinder, immediately after the 29.2 kHz/16.7 kHz feeding of the four inductor coils; (b) the CPW composed of a copper tube coil with 6 insulated turns.

the bottomless CPW has, compared to the CC, the following advantages: 1) the castable melt mass is not diminished anymore and the melted alloy composition is not influenced anymore by a solidified scull on the charge bottom;¹⁶⁾ 2) heat losses fail to appear through a bottom scull; 3) the melt can be cast through the CPW, i.e. without disadvantageously tilting the melting device. An experimental verification of the CPW utilization was carried out by the levitation of a solid 39 g Al-alloy sample in the EML device shown in Fig. 5.

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