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Simultaneous Induction Heating and Electromagnetic Stirring of a Molten Glass Bath

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Abstract

This paper studies solutions for an efficient induction heating and a strong electromagnetic stirring of the molten glass bath through the action of Lorentz forces in a direct induction furnace. Different spatial configurations of AC magnetic fields - travelling, rotating or helicoidal, and the generated molten glass electromagnetic stirring are studied with one-way coupled electromagnetic and hydrodynamic models. For imposed value of the active power induced in the molten glass, the numerical experiments offers the values of the total inductor current and of the supply frequency for which an efficient electromagnetic stirring of molten glass is achieved.

Key words: molten glass, induction heating, electromagnetic stirring, finite element models, travelling magnetic field, rotating field, helicoidal field, fluid dynamics computation

Introduction

The electromagnetic stirring generated by Lorentz forces in electro-conductive bodies like molten glasses in the presence of AC magnetic fields is not independent on the heat generation by the Joule effect of induced currents [1], [2]. All solutions studied in this paper, able to ensure first of all an intense electromagnetic stirring in cold crucible induction furnaces, are characterized by the same value of the power induced in the molten glass bath. Results issued from three-dimension (3D) models for electromagnetic field and for molten glass flow concern for the same geometry and physical properties of the molten glass bath in Table 1, and:

Table 1: Molten glass bath properties

Volume [m ³]	0.14
Electric conductivity [S/m]	15
Viscosity [Pa·s]	1.0
Density [kg/m ³]	2700

- (a) a one-phase inductor of a reference furnace for molten glass induction heating;
- (b) an eight-phase inductor of travelling magnetic field type for induction heating and electromagnetic stirring;
- (c) a thirty-two-phase inductor of rotating magnetic field type;
- (d) a thirty-two-phase inductor of helicoidal magnetic field type.

Electromagnetic and fluid dynamic models applied to the reference one-phase induction cold crucible furnace.

The reference furnace is an induction cold crucible furnace for nuclear waste immobilization in glass [3], [4]. The conversion of the electric energy into heat in this device is the result of the Joule effect of the induced currents in the molten glass placed in the AC magnetic field generated by the inductor. The FLUX3D-EM model of the reference furnace takes into account the active components - the one-phase *reference inductor* and the molten glass charge, Fig. 1, solid conductor regions, which are surrounded by an infinitely extended non-conductive and non-magnetic region. The surface impedance model of the inductor is considered in the computation of the electromagnetic field. The steady state AC magnetic problem for the frequency 285 kHz considers the intensity of the inductor current for which the power in the molten glass has the *reference value 150 kW*. The current density in the inductor turns and in the molten glass region and the arrows representation of Lorentz forces are presented in Fig. 2 and 3.

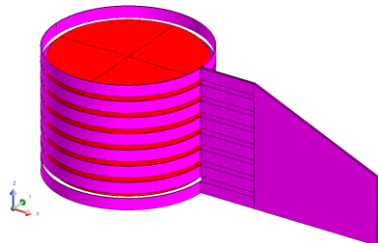


Fig. 1. The EM computation domain

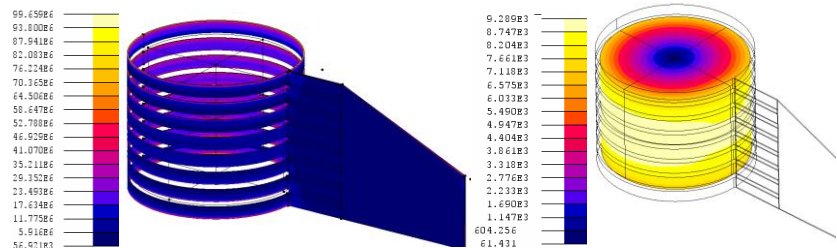


Fig. 2. Current density [A/m²] in the inductor and molten glass regions

The FLUENT-CFD model of the viscous molten glass flow considers the Lorentz force volume density imported from the EM model/problem. The calculation is made upon the following assumptions: the flow is laminar, the molten glass is incompressible and the flow is isothermal. Main results feature the arrows of the velocity in the vertical xOz plane, Fig. 4, and the flow streamlines in Fig. 5. The molten glass flow, Fig. 4 and 5, is the result of the radial bath compression, which is maximal in the middle. In connection with the molten glass stirring effect of the electromagnetic field, the values of the maximum Lorentz force volume density in the molten glass is only 3.354 N/m^3 , Fig. 3, and the maximum of the velocity is only 0.54 mm/s , Fig. 5. With such a small value of the velocity, the electromagnetic stirring of the molten glass bath in the *reference furnace* is completely negligible.

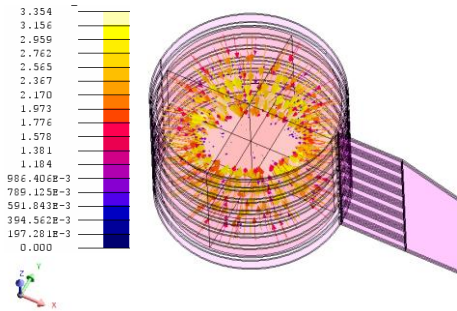


Fig. 3. Arrows of Lorentz force volume density [N/m^3]

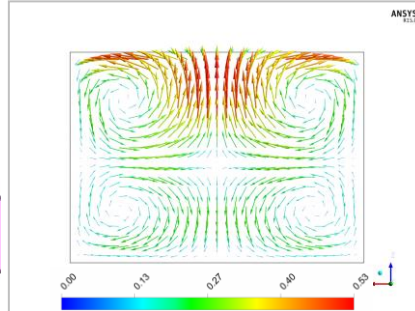


Fig. 4. Velocity vectors of the molten glass [mm/s]

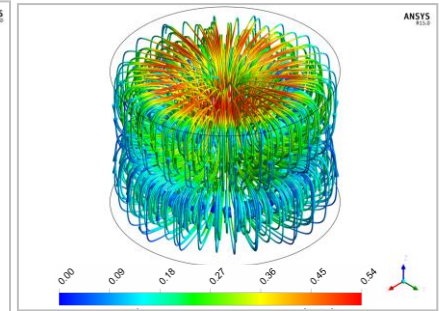


Fig. 5. Volume streamlines coloured by local velocity [mm/s]

Induction heating and electromagnetic stirring with an inductor of travelling field type.

The studied *travelling field inductor* consists in eight co-axial circular turns, Litz type/filiform conductor made, around the molten glass bath, Fig. 6. The eight currents of frequency 2 kHz are evaluated so that the power induced in the molten glass has roughly the value 150 kW in order to have the same heating as in the reference furnace. To generate an one-pole travelling field, the phase-shift between two successive currents of the inductor is $180/8 = 22.5$ degrees.

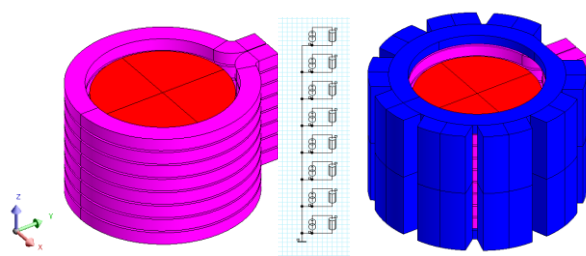


Fig. 6. Inductor of traveling field type without and with magnetic core

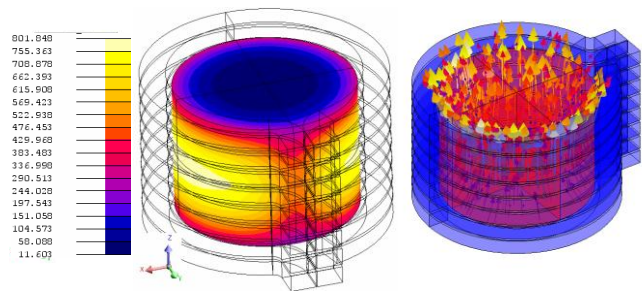


Fig. 7. Color map and arrows of Lorentz force volume density [N/m^3] in traveling field

The lines of induced currents in travelling field are circles in horizontal planes. Their intensity decreases in radial direction, from the lateral wall of the molten glass bath to the value zero on the vertical axis. Consequently, the molten glass induction heating effect decreases from the lateral wall to the bath axis, where becomes zero. The maximum of this effect characterizes a circle in the middle of the cylindrical wall of the bath.

The vectors of Lorentz force density, Fig. 7-right, are vertical upward orientated. Their magnitude decreases from the lateral surface of the bath to the vertical axis, where becomes zero. The electromagnetic stirring will be the result of the upward electromagnetic driving in the neighboring of the lateral wall of the bath and the downward flow in a volume around the axis. The power 152.5 kW in the molten glass corresponds to the current 19.53 kA in the phases of an inductor with magnetic core. The maximum of the Lorentz force density, 847.4 N/m^3 , is incomparable higher than in the *reference inductor*.

The results of the FLUENT model of the molten glass flow in traveling magnetic field, Fig. 8 and 9, reflect the good efficiency of the electromagnetic stirring. Values of the velocity not much lower than the maximum value 259.7 mm/s , characterize a consistent volume of the lower half of the bath.

The existence of the terminals of the inductor turns in the neighboring of the yOz symmetry plane, Fig. 6, explains the difference between the two arrow representations in Fig. 8 of the velocity in the vertical planes xOz and yOz.

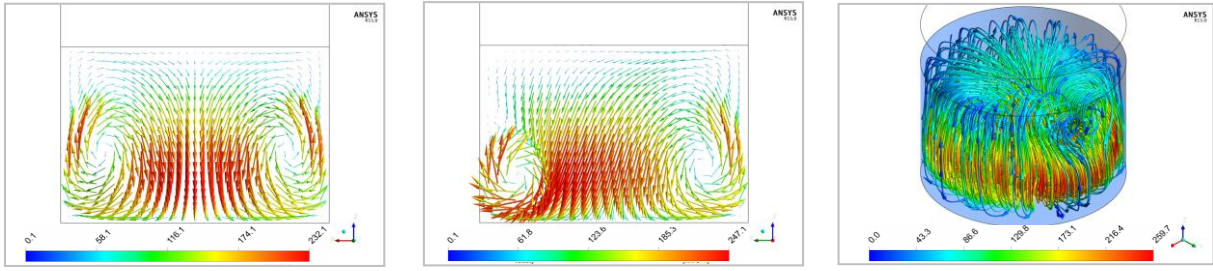
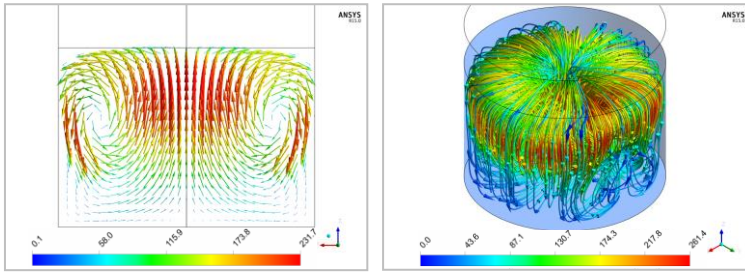


Fig. 8. Arrows and streamlines of the velocity field [mm/s] for upward orientation of the traveling field



An important change of electromagnetic stirring in a one-pole travelling field it results when reverses the field direction of propagation. As shown in Fig. 9, the effect consists in the displacement of the main stirred part of the molten glass volume from the lower to upper half of the bath.

Fig. 9. Velocity field [mm/s] for downward orientation of the traveling field

Induction heating and electromagnetic stirring in rotating magnetic field type.

The *rotating field inductor*, able to generate a two-poles rotating magnetic field, consists in thirty-two identical Litz type conductor regions with axial orientation, Fig. 10, uniformly distributed around the molten glass region. These thirty-two conductors, representing from physical point of view the thirty-two phases of the inductor, are supplied with currents having the same rms value. To obtain a two-poles rotating magnetic field, the currents in two successive phases are characterized by the phase shift $360/32 = 11.25$ degrees. Same supply frequency 2 kHz as previously is considered.

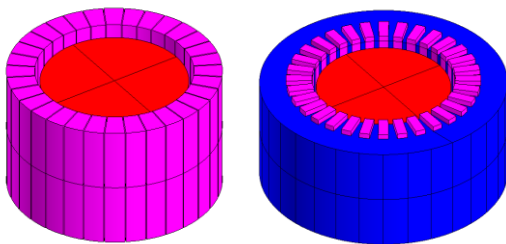


Fig. 10. Rotating field type inductor, 32 phases, without and with magnetic core

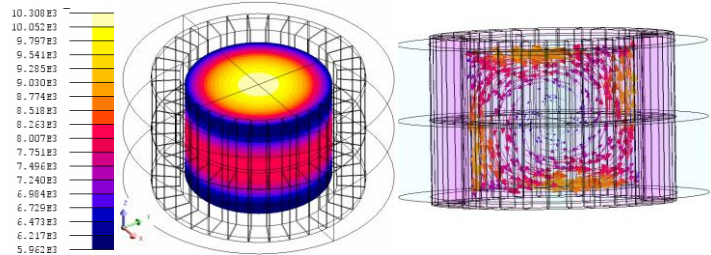


Fig. 11. Color map and arrows of the current density [A/m²] induced in the molten glass bath

Compared to the travelling magnetic field previously studied, a completely different spatial configuration of induced currents, respectively of molten glass induction heating, characterizes the rotating magnetic field. In rotating field the induced currents closes in vertical planes, Fig. 11-right, and the maximum of the power volume density is located in the centre of the upper free surface, Fig. 11-left, and the centre of bath bottom.

In *rotating magnetic field* the vectors of the Lorentz force density, Fig. 12, are tangent to circles in horizontal planes. The driving effect of the rotating field decreases in radial direction, from the maximum value on the lateral wall to zero on the bath axis. Consequently, the electromagnetic stirring in rotating field consists in the horizontal glass rotation.

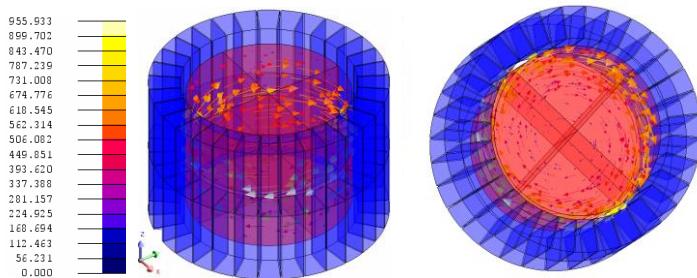


Fig. 12. Lorentz force density [N/m³] in rotating field

In case of the rotating field inductor without magnetic core, Fig. 10-left, the power 153.5 kW is induced in the molten glass for the current 33.8 kA in the inductor phases. The correspondent maximum value of the Lorentz force density, 955.9 N/m³, is incomparable higher than in case of the *reference inductor*. An inductor including a

magnetic core with slots, Fig. 10-right, is much more efficient. The power 157.5 kW is obtained for only 13.9 kA that insures an important decrease of the Joule losses in the inductor. The maximum of the Lorentz force density increases at 1100.6 N/m^3 . The molten glass flow, Figs. 13 – 15, is characterized by high values of the velocity. In a consistent annular volume of the bath the Lorentz force density is not much lower than the maximum value 842.2 mm/s .

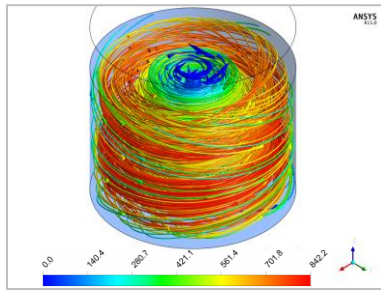


Fig. 13. Streamlines coloured by local velocity [mm/s]

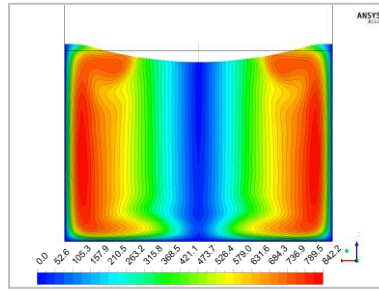


Fig.14. Map of glass velocity [mm/s] in the xOz axial plane

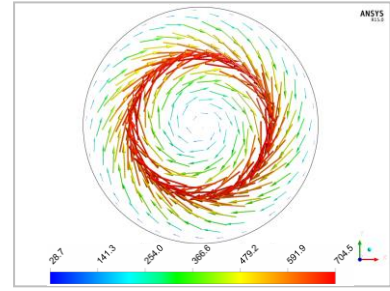


Fig. 15. Vectors of velocity [mm/s] on the free molten glass bath surface

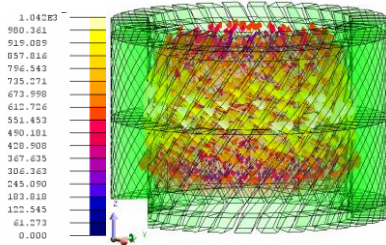


Fig. 16. Lorentz force density [N/m³] in helical magnetic field

Induction heating and electromagnetic stirring in helicoidal magnetic field. If the thirty-two phases of the inductor in Fig. 10 are twisted, Fig. 16, the rotating magnetic field becomes a *helicoidal magnetic field*. The vectors of Lorentz force density have a component in horizontal plane that generates a rotation motion and a vertical component with similar action as in travelling magnetic field. The maximum Lorentz force density in an inductor with magnetic core and helix angle 30 degrees is 1146.3 N/m^3 . The CFD results in Fig. 17 emphasize the maximum values 740 mm/s of the horizontal component of the velocity that characterize the molten glass rotation motion and 130 mm/s of the vertical component. In order to intensify the vertical motion of the molten glass, the helix angle of inductor turns must be increased.

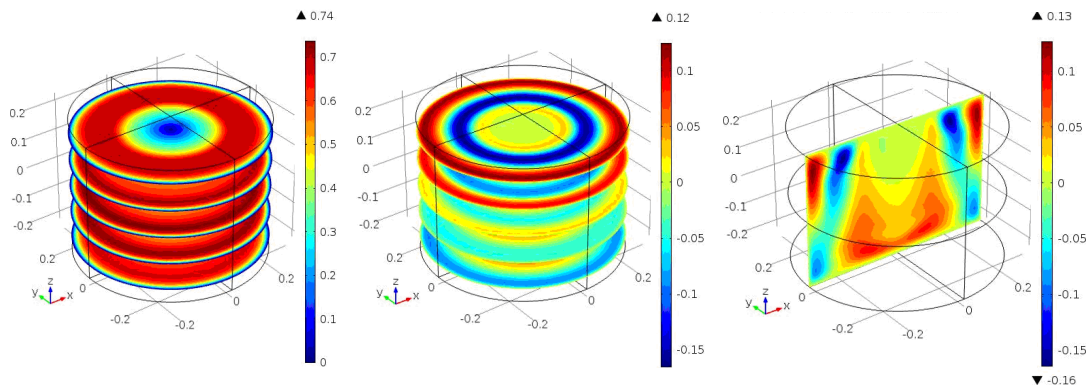


Fig. 17. Molten glass motion in helicoidal field - horizontal and vertical components of glass velocity in [m/s] in different horizontal planes and the vertical component of the velocity in a vertical symmetry plane

Conclusions

The calculations establish that the simultaneous direct induction heating a strong electromagnetic stirring of a viscous molten glass bath is workable by using inductors that generate high magnitude Lorentz forces with multi-phase AC magnetic field. The inductors, intended for travelling, rotating or helical field, operate at relatively low frequency and have important pole pitches. Thus an efficient stirring featuring a velocity above 200 mm/s in a significant volume of the molten glass associated with a reasonable heating of the bath is achieved. Such significant electromagnetic stirring able to generate important and well oriented driving effects in the molten glass may be promising for the nuclear waste vitrification technology, which require important mass and heat transfer in order to incorporate and melt solid particles.

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