# FLOAT-ZONE CRYSTAL GROWTH WITH A NOVEL MELT FLOW CONTROL

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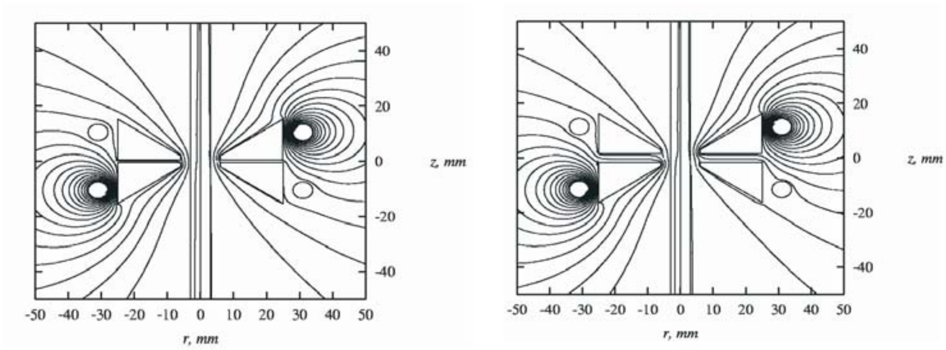
**Introduction.** Quality of the materials solidified by the floating zone method strongly depends on the growth conditions, particularly, on the shape of the solidification front. To obtain single crystals of high physical and chemical quality, a convex to the melt growth interface is often desirable. The shape of the solid-liquid interface can strongly be influenced by the convective heat transport in the melt. One of the major mechanisms driving the melt flow in the floating zone method with radio frequency (RF) heating is the electromagnetic force. This force is directed against the phase gradient of the magnetic field. In case of a usual single-phase heating, there is a natural phase gradient arising due to the diffusion of the magnetic field into the conducting medium. In this case the electromagnetic field is directed almost normally to the free surface of the melt with the maximum of the force at about mid-height of the floating zone. Hence, the electromagnetic field drives a melt flow directed radially inwards at mid-height of the floating zone. At the axis of symmetry the radially converging flow splits into two jets directed against the solid-liquid interfaces. The heat advected by the axial jets melts the central parts of the solid-liquid interfaces so rendering them concave towards the solid phase, resulting in an unfavourable condition for single crystal growth. Favourable growth conditions require the flow to be directed away from the solidification front at the axis of symmetry and, respectively, to be directed against it at the free surface of the floating zone. This flow can be generated by an electromagnetic force directed along the free surface towards the solidification front. In order to obtain such an electromagnetic force along the free surface, the phase gradient of the AC magnetic field has to be created in the corresponding direction. It can be done by using a two-phase magnetic field instead of the usual single-phase one. A two-phase magnetic field requires a composite inductor with a separate part for the second phase.

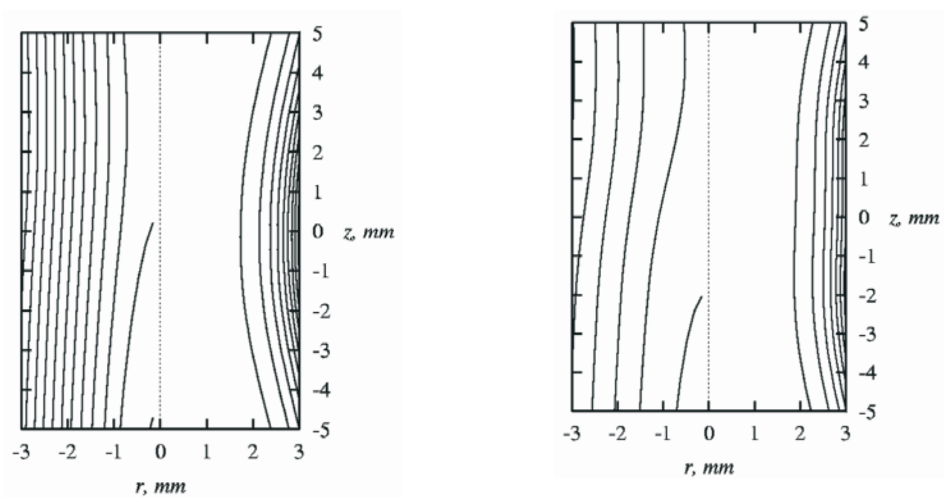
**1. Numerical results.** Here we present the numerical results pertaining to the control of phase interface shape of 6 mm diameter Ni rod by means of a two-phase inductor composed of two identical coils. Magnetic flux lines for the inductors with various vertical spacing between the primary and secondary coils are shown in Fig. 1. Calculated temperature distributions together with the streamlines and vector fields of the meridional flow in the floating zone are shown in Fig. 2. Numerical results evidence that increase of the vertical spacing between the coils increases the minimal current necessary for melting of the rod. For 250 kHz AC frequency the minimal current is about 305 A and 313 A for 1 mm and 5 mm vertical gaps, respectively. Increase of the vertical spacing between the coils correspondingly increases the vertical extension of the heated region that, in turn, is accompanied by the vertical extention of the molten zone. The minimal length of the floating zone close to the radius of the rod is obtained with vertical spacing of 1 mm between the coils. At a larger vertical spacing the minimal zone length is at least as large as the vertical gap between the coils. Current rise




(a) (b)

*Fig. 1.* Magnetic flux lines for two-phase inductors with 1 mm (*a*) and 3 mm (*b*) gap between the primary (upper) and secondary (lower) parts of the inductor. Magnetic flux lines in phase with the current in the primary coil and delayed in phase by 90 degrees are show on the left and right from the symmetry axis.

results in a relatively quick elongation of the zone. Thus the current increment by about 4 A that is about 1–1.5% of the current amplitude results in the zone length comparable to the diameter of the rod. Distributions of the heating power and the phase of magnetic field in the rod about the center of the inductor are shown in Fig. 2. Note that the heating power is proportional to the magnitude of the electromagnetic force at the given position, whereas the phase distribution defines the direction of the force, namely, the latter is directed against the phase gradient. The heating power density is the highest in the middle between the coils when the vertical gap is small (1 mm) but there appears a minimum in the middle when the coils are moved further apart. For larger vertical gaps there are two maxima of the heating power located directly against the coils. Phase distribution is characterised by two components of the gradient. First, the phase is decreasing radially inwards from the free surface because of the skin effect. In this case the skin layer defines the characteristic distance of the phase variation. The thinner




(a) (b)

*Fig. 2.* Patterns of Ohmic heating density and phase distributions shown on the left and right hand sides from the symmetry axis in the crystal rod about the mid-plane of mirror-symmetric inductors with 1 mm (*a*) and 3 mm (*b*) gaps between the primary and secondary coils at 250 kHz AC frequency

the skin layer, the stronger the corresponding phase gradient. Second, there is an externally imposed axial phase gradient due to the phase lag of 90 degrees in the secondary coil. Note that in the present calculations the primary coil is located at the top but the secondary one at the bottom that, however, may be not the optimal configuration from the experimental point of view.

The imposed phase variation takes place over the vertical gap between the coils. Numerical results show that the largest vertical phase variation over the molten zone is achieved when the vertical gap is comparable to the radial one between the inductor and the rod. This effect is reflected in the increased vertical inclination of the phase isolines with the increase of the vertical distance between the coils. As already noted above, the main factor affecting the vertical inclination of phase isolines and so the relative magnitude of the axial force is the skin layer which depends on the AC frequency. Thus inclination of phase isolines is noticeably more pronounced at 100 kHz, where the skin layer is thicker than at 250 kHz.

The pattern of melt flow driven by the electromagnetic force depends on both the amplitude and the phase distributions of the magnetic field. In the case of single phase AC field, when the only cause of the phase shift is the skin effect, the phase gradient is almost radial and the electromagnetic force is directed radially inwards with maximum about the middle of the molten zone. In this case the electromagnetic force drives a radially-inward melt flow in the middle of the floating zone that results in a flow pattern consisting of two toroidal vortices. The two-phase field considered here gives rise to the axial phase gradient that causes a corresponding axial inclination of the electromagnetic force which is expected to drive the melt consisting of a single toroidal vortex provided that the inclination is strong enough to overcome the aforementioned effect related to the axial variation of the amplitude of the magnetic field. Numerical results evidence that the axial force is strong enough at 100 kHz as well as at 250 kHz AC frequency to drive a single toroidal vortex. Because of the skin effect the electromagnetic force is concentrated in the outer part of the floating zone at the free surface, in this region the melt is flowing in the direction of the axial force, directed from the secondary coil to the primary one, whereas a return flow in the opposite direction takes place in the inner part about the axis of symmetry. Thus the hot melt is convected along the surface towards the outer part of the interface at the primary coil, where the melt cools down by releasing a part of the heat to the interface. As the result, the outer part of this interface is molten down that renders this interface more convex. Remaining part of the heat is convected back by the return flow along the symmetry axis to the interface at the secondary coil, where it streams to the interface in its central part so rendering it more flat or even concave when the flow is strong enough.

The calculated interface shapes are plotted in Figs. 3. In order to assess the effect of the electromagnetically driven convection, interface shapes are plotted together with the ones resulting from pure heat diffusion. As seen for the shortest zone length, the interface shapes with electromagnetic convection are very close to the ones due to the pure heat diffusion implying that the effect of electromagnetic convection is weak in this case. The effect of electromagnetic convection increases with the length of the floating zone, which is caused, first, by increase of the driving force as the current is raised and, second, by the reduced hydrodynamic resistance at increased zone length. Thus current increase causes descent of the outer part of the bottom interface, while the inner part first slightly rises and then goes slightly downwards at higher currents that renders this interface more convex. The upper interface at the primary coil, which is originally convex-like to the lower one, is flattened with the current increase and eventually may become

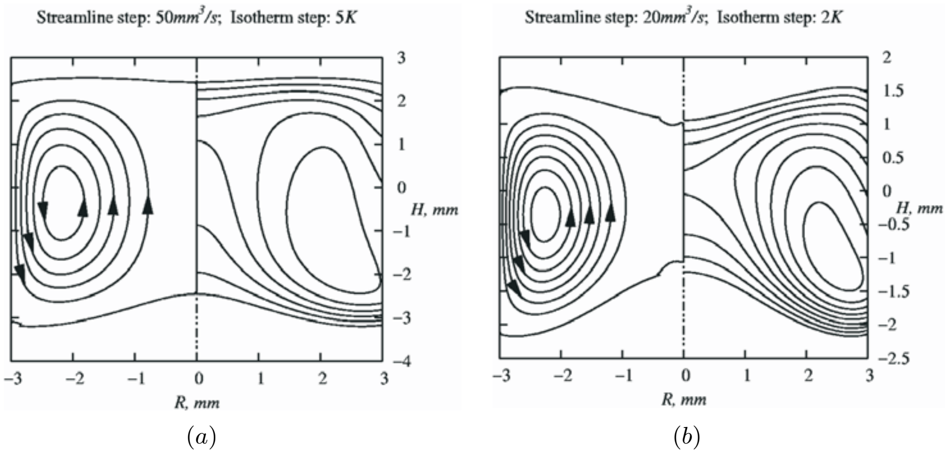



*Fig. 3.* Streamlines and isotherms on the left and right hand sides from the symmetry axis in the floating zone of 6 mm Ni rod at 250 kHz AC frequency for various currents and vertical gaps between the inductors: 310 A and 1 mm gap (*a*) and 308 A and 3 mm gap (*b*).

concave at a strong enough current. The effect of electromagnetic convection on the interface shape is stronger at larger vertical gaps between the coils because of the lager current necessary for throughout melting of the rod and the larger zone length resulting from a stronger current and the increased length of the heated region. With respect to the frequency, the effect of electromagnetic convection on the interface is slightly more pronounced at 100 kHz than at 250 kHz AC frequency which may be because the first frequency according to the previous report is close to the optimal one yielding maximum of the axial thrust on the Ni rod of 6 mm diameter.

**2. Conclusions.** We have considered a composite inductor containing a secondary coil, where the electric current is induced by the primary coil. The necessary 90 degrees phase shift is obtained by short-circuiting the secondary coil through a capacitor chosen to ensure the resonance in the secondary circuit. Besides the capacitor, the secondary circuit contains also an additional active load to adjust the amplitude of the resonance current to be approximately the same as in the primary coil. We have developed a numerical method to calculate the parameters of such a composite two-phase inductor and the generated magnetic field that is used further for the numerical simulation of the associated heat transfer and flow field in the RF float-zone problem. The coupled thermal and hydrodynamic problem was solved by a control volume method on a triangular grid adapted to the shape of solid-liquid interfaces varying in the course of the solution. The equations were integrated in time by an implicit scheme using conjugate-gradient-type iterative solvers accelerated by incomplete $LU$ factorization.

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