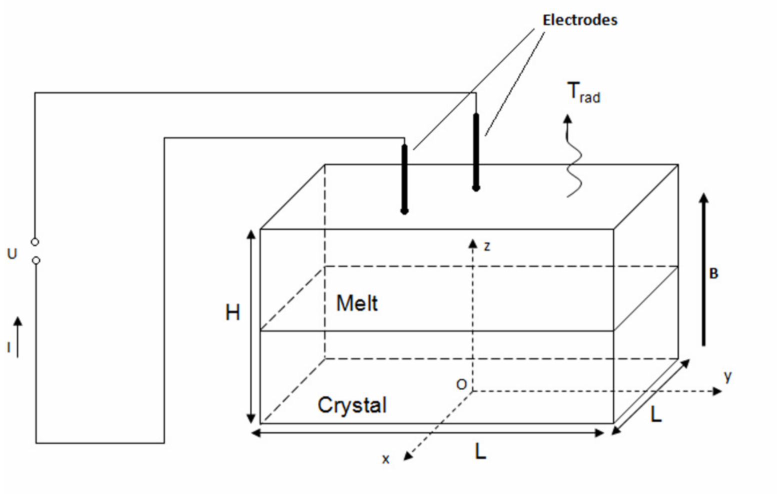
Scientific report

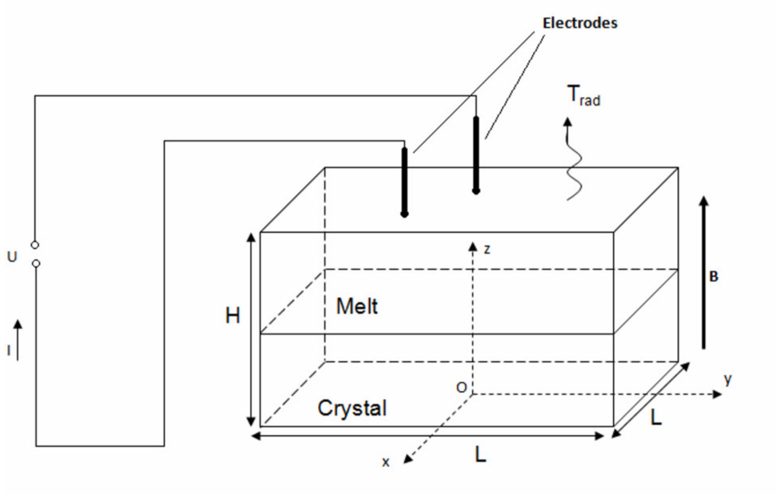
regarding the project implementation between October - December 2011

Activity 1.1. STHAMAS3D development for modeling an EMF configuration with 2 or more electrodes

The main idea of this project is to obtain a melt rotation in a rectangular crucible using a special configuration of electromagnetic field. The crucible with the silicon melt is placed in a vertical magnetic field and electrical current is injected into the melt through 2 or more electrodes. In Figure 1 two such configurations are presented (one with 2 electrodes and the other with 4 electrodes).



(a)



(b)

Figure 1. Electromagnetic field configurations that will be investigated

The melt flow is described by the three-dimensional time- dependent equations of mass, momentum, and heat conservation taking into account the Boussinesq approximation for an incompressible fluid $\left(\overrightarrow{f_g} = \rho\left(T_{ref}\right)\vec{g}\beta\left(T - T_{ref}\right)\right)$ and the Lorentz force density $\left(\overrightarrow{f_L} = \vec{j} \times \vec{B}\right)$. This gives the following set of equations:

$$\nabla\vec{u} = 0 \tag{1}$$

$$\rho\frac{\partial\vec{u}}{\partial t} + \rho(\vec{u}\cdot\nabla)\vec{u} - \mu\nabla^2\vec{\mathrm{u}} = -\nabla\mathrm{p} - \vec{\mathrm{f}}_\mathrm{g} + \vec{\mathrm{f}}_\mathrm{L} \tag{2}$$

$$\rho C_p\left[\frac{\partial T}{\partial t} + (\vec{u}\nabla)T\right] - k\nabla^2 T = 0 \tag{3}$$

ρ is the density, u is the melt velocity, p is the pressure, Cp is the heat capacity, k is the thermal conductivity, T_{ref} is a reference temperature, g is the gravitational acceleration, β is the thermal expansion coefficient, $\vec{j}$ is the electric current density, and $\vec{B}$ is the magnetic field induction.

The melt flow velocities along the boundaries at the crucible and at the crystal are set to $\vec{v}$=0 (no-slip). Along the surface of the melt "no shear stress" was considered. The temperatures along the lateral vertical side walls and at the bottom were considered to be fixed. At the free surface a radiative heat exchange to an ambient temperature of T_{rad} = 1713 K was applied.

The heat transfer in the solid is given by heat conduction. At the solid–liquid interface the latent heat generation is considered for the given crystallization velocity:

$$k_S\nabla T|_S - k_L\nabla T|_L = u_g\rho_g\Delta H \tag{4}$$

where k_S and k_L are the thermal conductivities in the solid and in the liquid, u_g is the growth velocity set at 10 mm/h in our simulations and ΔH is the latent heat.

For the calculation of the Lorentz force, the electric current density j, induced in the melt by the steady magnetic field is taken into account:

$$\vec{j} = \sigma\left(-\nabla\Phi + \vec{v}\times\vec{B}\right) \tag{5}$$

where σ is the electric conductivity and Φ the scalar electrical potential obtained by solving the equation:

$$\Delta\Phi = \nabla\left(\vec{v}\times\vec{B}\right) \tag{6}$$

with

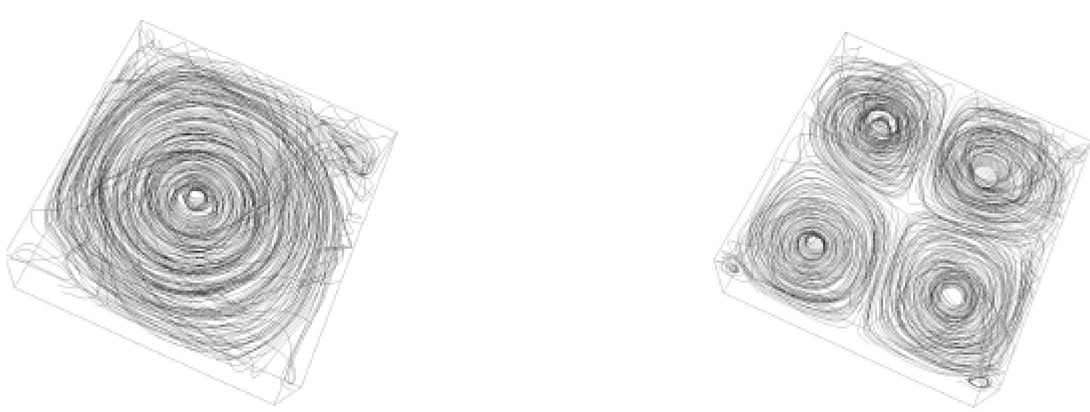
$$\nabla\vec{j} = 0 \tag{7}$$

In order to generate an electrical current in the melt two situations were considered: firstly, as can be seen from Figure 1a, the electrical current is injected in the melt through two electrodes placed at the melt surface and are connected to a DC power source. The second scenario, two pairs of electrodes are used as can be seen in Figure 1.b. The electrodes are considered to have a small diameter, therefore their effect on the field velocity and temperature can be neglected.

The STHAMAS3D software was developed in such a way that it will allow the numerical modeling of the mathematical model presented above. Mainly, a subroutine was developed to consider the boundary conditions given by the presence of the electrodes in the melt.

Two test runs were done:

- one for the configuration with two electrodes, Fig. 2.a, 10 mT magnetic field and 10 A electrical current
- one for the configuration with four electrodes, Fig. 2.b, 10 mT magnetic field and 2 A electrical current



(a) (b)

Figure 2. Particle tracking plots for different electrodes configurations

It can be seen that by applying an electromagnetic field, a melt flow is obtained. The melt rotation is characterized by a single convection cell in the case of 2 electrodes and four convection cells for the case with 4 electrodes. The next step is to study the influence of the magnetic field and electrical current on the melt convection.

Activity 2.1. Design and construction of the magnetic field generating coil

Technical requirement. Generating a unidirectional and uniform magnetic field inside the 70 × 70 × 70 mm^3 volume of an air gap. It is required that the magnetic field B to be adjustable by external means in the range of 0 ... 0.35 T.

General presentation of the solution. The proposed technical solution consists in the manufacturing of an countinous curent C-shaped electromagnet with a ferromagnetic core (Fig. 1). The air volume specified in the technical requirement is the electromagnet's gap. Since the requested magnetic field is not alternative or rotational, there will be no eddy current losses and therefore the ferromagnetic core can be made of solid steel. The created magnetic circuit (core + air gap) will be excited by an electrical winding passed by a continuous current, dimensioned so that in the reference volume the magnetic field can reach the value B = 0.35T.

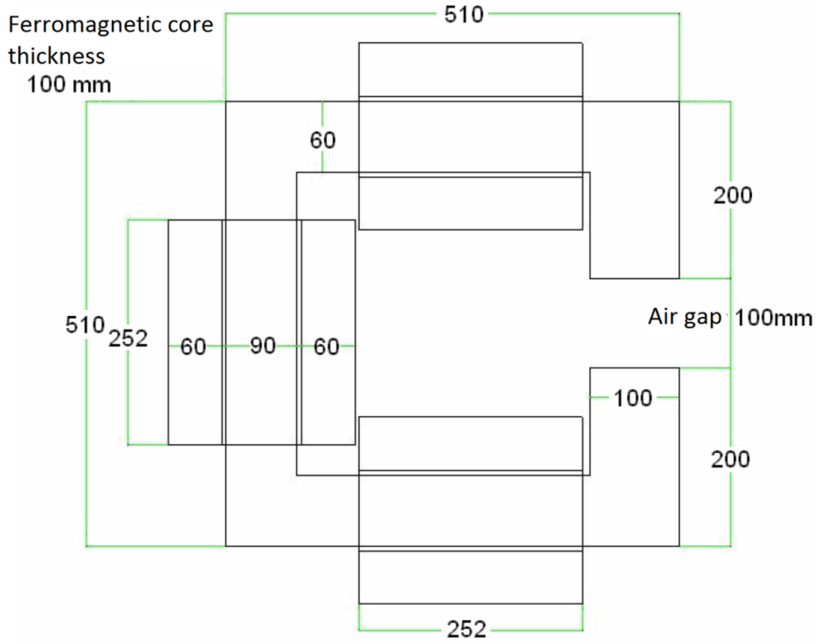


Figure 1. Schematic representation of a cross section of the electromagnet

Because of magnetic field lines bending at the margins of the air gap, its envisioned volume is greater - 100 × 100 × 100 mm3. To take advantage of the more uniform magnetic field in the middle of the air gap, experiments will be conducted within a volume of 70x70x70 mm3 in its center.

Simplified calculation of the electromagnet [1]. We are considering a series magnetic circuit consisting of a ferromagnetic core (Fe) and air gap (δ) and neglecting dispersion field lines. By applying the magnetic circuit law, we can calculate the magnetomotive force θ needed to achieve the magnetic filed B inside the air gap (I and N are the electrical current, respectively, the number of turns in the winding):

$$\theta = NI = H_{Fe} l_{Fe} + \frac{B}{\mu_0}\delta \qquad (1)$$

From the magnetization curve of steel H_{Fe}=200 A/m for B = 0.35 T. Also l_{Fe} is 1.58 m and δ is 0.1 m. Therefore it follows :

$$\theta = NI = 28168\ A\ x\ coil \qquad (2)$$

If you are considering a 10% dispersion of the field lines along the long linear portion of the ferromagnetic core and, equally, a deformation of the field lines in the air gap of 10%, it follows that the magnetomotive force needed to achieve the magnetic filed B = 0.35 T is:

$$\theta_{ex} = 34000\ A\ x\ coil \qquad (3)$$

Calculation of the winding. We use three identical separate coils, connected in series, each dimensioned considering the useful section of the core of dimensions 80 × 100. Therefore, the available section for winding is S_d=250·38=9500 mm^2 per coil. For a filling ratio of the winding of k_u=0.65 it follows that each coil can take a useful section of copper of S_u=k_uS_d=6175 mm^2. For a current density of j = 2 A/mm^2, the solenation which can be provided by the linkage in series of the 3 coils will be θ=3jS_u=37050A×spire. If we choose to use a conductor doubly enameled with a diameter of d=1.2 mm, S_c = 1.131 mm, specific electrical resistance R_s=15.36 Ω/km, then each coil will contain a number of coil turns N_{bob}=S_u/S_c=5460 turns/coil, and the total number of turns will be N = 16380 coil turns. The nominal current through the windings will be I = 2.26 A.

The average length of a turn will be l_{sp}=0.6m, hence the total length of the conductor necessary to make the 3 coils will be L = 9828 km. The winding will have a total electrical resistance of R = 151 ohm, which requires powering it from a DC source with a voltage of $U = RI$ = 341 V and minimum nominal power P = 771 W.

The two surfaces of the air gap will attract each other with force of $F = B^2 \frac{A\delta}{\mu_0} = 975N$.

Checking the air gap field design by simulation using finite element methods. For the simulation, the QuickField-Students [2] software package was used. The results confirm the achieving of the target value for the magnetic induction B in the air gap (Fig 2).

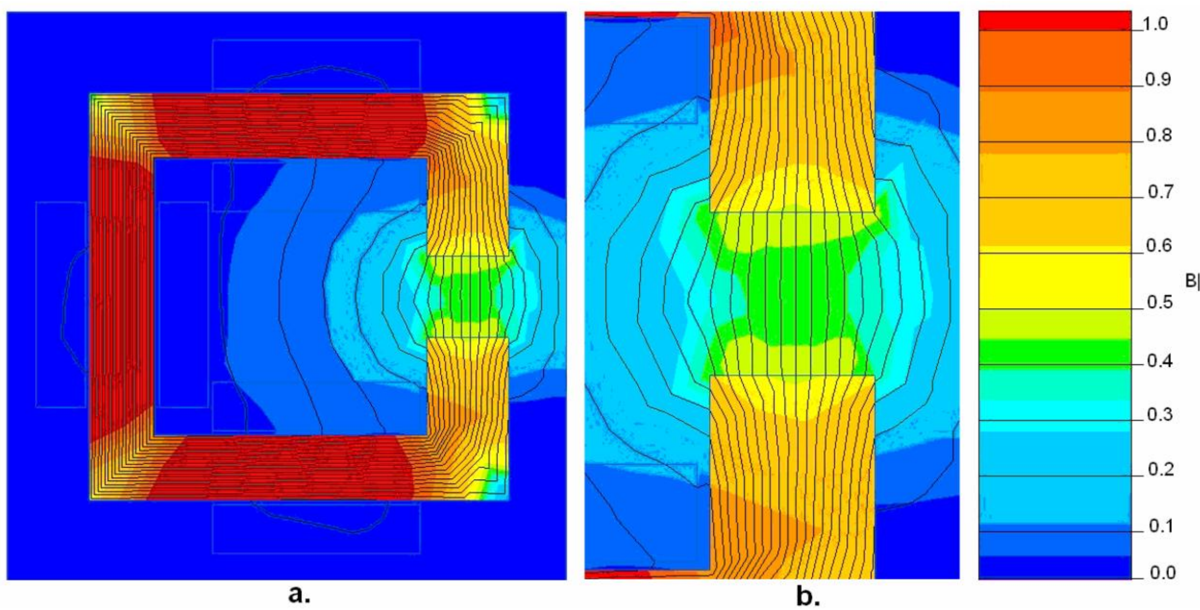


Figure 2. (a) Magnetic field configuration inside the electromagnet; (b) Detail of the air gap

References:

[1] Mocanu CI (1981) Teoria Campului electromagnetic, Ed. Didactica si pedagogica, Bucuresti.
[2] QuickField - Simulation Software for Electromagnetics, Heat Transfer and Stress Analysis. http://www.quickfield.com/

Project manager,

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