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INVESTIGATION OF THE HYDRODYNAMIC PROPERTIES OF MAGNETICALLY STIRRED MOLTEN GALLIUM-INDIUM ALLOY BY NUMERICAL SIMULATION

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An experimental crystallizer – equipped with magneto-hydrodynamic (MHD) stirrer – was built by the MTA-ME Materials Science Research Group, to investigate the factors influencing crystallization. Several quests were done to get information about the hydrodynamic behavior of the molten metal in the crystallizer during stirring. The experiments were done with Ga-In alloy, which is molten on room temperature. To get additional information, which is not possible to measure, a numerical model was made with ANSYS FLUENT numerical simulation program. The Lorentz-force field, which makes the Ga-In alloy rotate, was generated with a **U**ser **D**efined **F**unction (UDF) to completely reproduce the MHD stirrer's effects on the melt.

Keywords: numerical, simulation, gallium, indium, stirring, magnetic, magneto-hydrodynamic, MHD

Introduction

Understanding crystallization in the industry is a very difficult task. In the case of continuous casting the ingot is not completely solid after it rolled out from the crystallizer. There are several complex flows inside, which have a strong effect on the structure and by this, on the mechanical, thermal, electrical, etc. properties. An experimental crystallizer – equipped with **magneto**-hydrodynamic stirrer – was built at the MTA-ME Materials Science Research group to understand these effects with controlled crystallizing. The magnetically stirred molten metal is lowered into water to be solidified. Several new structures can be made by this method. Because of the structure of the crystallizer, the hydrodynamic properties can't be examined well with classical methods. There were measurements on the free surface's sedimentation and the average angular velocity of the melt. These experiments were done with 74.5% Ga–25.5% In by A. Rónaföldi [1]. To get more information about what is happening in the melt a numerical model was made with ANSYS FLUENT 13.0. The induced Lorenz-force field – what's making the molten metal rotate – was made with a **U**ser **D**efined **F**unction (UDF). The work is discussed in the paper in details.

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1. The MHD system

The mentioned crystallizer's stirrer works by the laws of Maxwell equations [1]. If the molten Ga-In alloy (**hereinafter** referred to as "gallium") is put into the rotating magnetic field, an eddy current will be induced in it. By the law of Lenz the melt will try to weaken the inducing effect, so it will start rotating (and making a potential vortex). Figure 1 shows a schematic setup of the system.

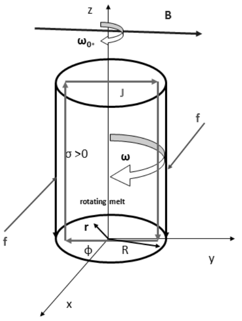

Figure 1. The force system in the inductor

The equation of the induced Lorenz force is:

$$f = \frac{1}{2}\sigma B^2 r(\omega_0 - \omega) \tag{1}$$

Where: σ is the electric conductivity of the melt (S/m), B is the magnetic induction (T), r is the actual **radius** (m), ω_0 is the synchronous angular velocity of the inductor (rad/sec), ω is the actual angular velocity of the melt (rad/sec).

By the effect of the force field the melt starts rotating and reaches a maximum angular velocity – an "equilibrium angular velocity". The melt can't reach the inductors synchronous angular velocity because of two main reasons. The first is visible in equation (1). As the melt accelerates, it stultifies the inducing force field. The second reason is the wall **friction**, which can extremely slow down the melts flow [2]. As can be seen on Figure 2, the melt's accelerating quickly first, but then reaches the maximum, which depends on the induction, the crucible's diameter etc.

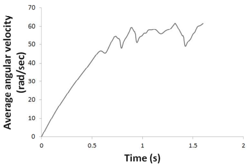

Figure 2. Radial average angular velocity as a function of time – the settling of the flow

2. Setup of the FLUENT model

The aim was to reproduce the gallium's flow with the measured parameters of A. Rónaföldi [1]. The data from the experiments with 10 mm, 25 mm and 35 mm diameter crucibles were chosen to be used in the FLUENT. The 10 mm is close to the crucible, which is used at the crystallization – with diameter of 8mm – the two other were used for checking the model's parameters.

Basically a 2D axisymmetric swirl solver was used with Volume of Fluid (VOF) multiphase model for 2 phases – the gallium and air. For the second, default material properties were used. The density of the melt was 6350 kg/m^3 and the viscosity was 0.00217 Pas. The turbulence was computed with a Realizable k-ε turbulence model (+ Enhanced Wall Treatment). Only the crucible was needed, so the simplified geometry was a simple rectangle – half cut of the cylindrical crucible's longitudinal slice – meshed with 45 000–75 000 hexa cells depending on the size of the crucible.

The Lorenz force field was programmed by a **U**ser **D**efined **F**unction (UDF). It's a C programming interface which contains eq. (1) with all of the time and coordinate dependent variables. These variables are the radius (***r***) and the gallium's current angular velocity (***ω***). The magnetic field has an effect, which cannot be neglected – it's the skin depth. The penetration depends on difference in the synchronous angular velocity of the inductor and the melt's angular velocity ($\omega_0 - \omega$), the magnetic permeability (***μ***) and the electrical conductivity of the metal (***σ***). The equation is:

$$\delta = \sqrt{\frac{2}{\mu\sigma(\omega_0 - \omega)}} \tag{2}$$

The inductivity of the magnetic field decreases exponentially by the skin depth:

$$B = B_0 * e^{-d/\delta} \tag{3}$$

Where B_0 is the maximal inductivity of the field and ***d*** is the distance from the wall of the crucible. This equation was also used in the UDF to determine the magnitude of ***B*** correctly in every cell. The force filed was set as a tangential momentum. An example for the stirred gallium is shown on Figure 3 [1].

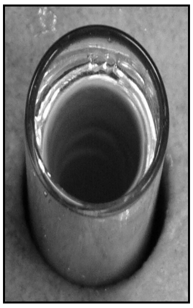

Figure 3. Magnetically stirred liquid Ga-In alloy in D = 14 mm crucible

3. Getting information from the model

The research group measured the average angular velocity of the melt. This data can be measured by two methods in the FLUENT.

First method is an average of the ratio of the tangential velocity (v_t) and the current radius (r) on a line (from the axle of the crucible to the wall) – equation (4).

$$\omega_{line} = \frac{v_t}{r} \tag{4}$$

Second is measured from the metallostatic pressure gradient. The gallium makes a potential vortex, and by this the pressure in the middle of the melt and at the wall is different. The liquid metal climbs up on the wall and the middle lowers. The average angular velocity can be computed from the distance of the lowest and the highest point of the melt according to equation (5) which has been derived from the general Bernoulli equation [1]. Figure 4 shows the empirical sketch for computing the angular velocity with eq. (5) from the distance between the high and low points (***2x***).

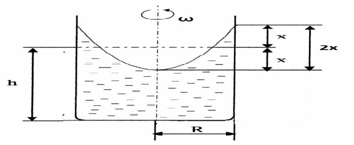

Figure 4. Sketch for computing the angular velocity

$$\omega_{press} = \sqrt{\frac{2 * 2x * g}{R^2}} \tag{5}$$

In Figure 4 the distance from the resting surface's height (***h***) is the same upwards and downwards. Proved experimentally [2] and with the numerical simulations that, by the effect of wall friction, surface tension, surface wetting and others, the upper distance will be smaller and there'll be a peak at the wall on the free surface, but the average angular velocity will also be smaller by this reason – also see Figure 3.

"2x" is easily accessible from coordinates of the interface between the gallium and the air. The anterior parameters were used to check the model's validity. The real measured data from [1] and the computed FLUENT data were compared. The exact errors will be discussed later.

4. Results

4.1. Angular velocity – line method

The model's running was checked by the plotting of the average angular velocity as a function of time on a line (from the axle of the system to the wall of the crucible). The plotted data is shown on Figure 5. "D10 B37" means 10 mm diameter crucible and 37 mT induction.

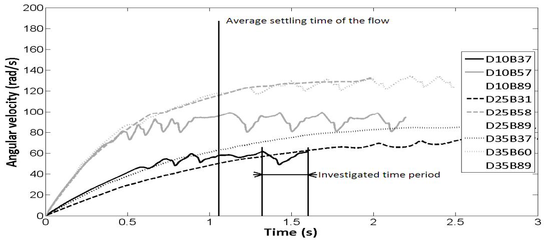

Figure 5. Angular velocities as a function of time from 0 seconds

The average settling times of the flows are at about 1.1 seconds. According to Figure 5, if the induction is the same, the values of the average angular velocity don't differ too much in higher diameters. An oscillating effect also can be seen on the curves. For the investigation of this effect see Figure 6, which shows the angular velocity measured from the axle to the wall of the crucible at 1.3, 1.4, 1.5 and 1.6 s of flow time. A difference can be found in the values nearby the wall, nevertheless the melt is faster near the axle.

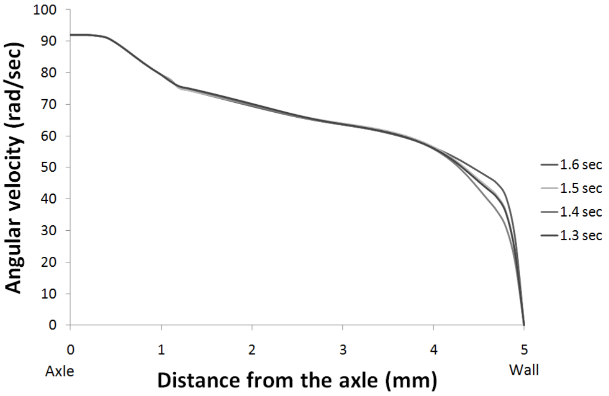

Figure 6. Angular velocity plotted from the axle to the wall, D = 10 mm, B = 37 mT

The form of the curve is similar in the 25 and 35 mm diameter, but the fastest point is at about the half of the radius – Figure 7. The reasons for the slowing effects and the peak on the higher diameters experiment's curve lie in the secondary flow of the melt. 10 mm and 35 mm diameters will be investigated. 25 and 35 mm cases show similar results.

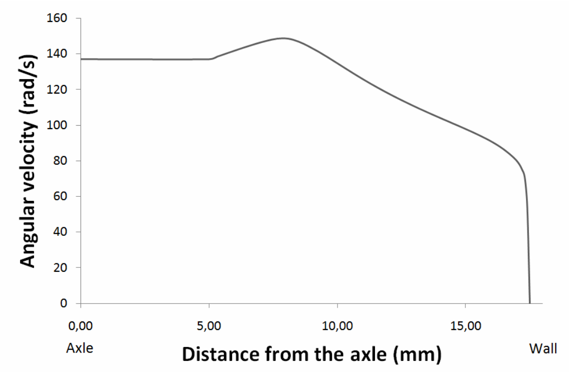

Figure 7. Angular velocity plotted from the axle to the wall, D = 35 mm, B = 37 mT

4.2. Free surface, angular velocity – pressure gradient method

The angular velocity data were also determined with equation (5). The lowest and the highest points of the free surface were measured for the calculations. Figure 8, shows the gallium's free surface at different inductions in 10 mm (a–c) and 35 mm (d–f) crucible.

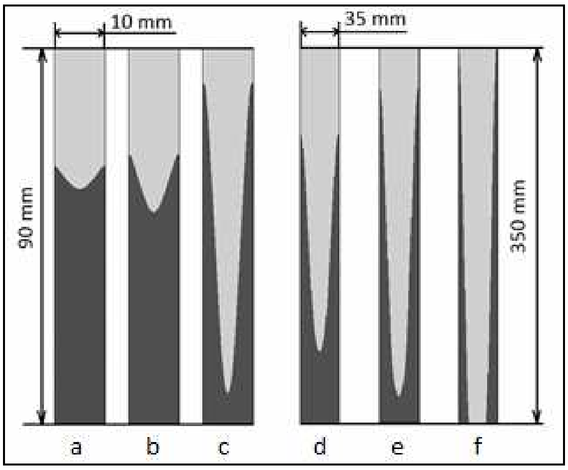

Figure 8. Contours of Ga (dark phase), (a–c) D = 10 mm, (d–f) D = 35 mm
(a, d) B = 37 mT, (b, e) B = 57 mT, (c, f) B = 89 mT

In the first approximation, the influence of the crucible's diameter is visible. As the diameter is getting higher, the depression on the free surface is getting stronger [1]. The case of figure 11f is not capable for pressure difference method, because the melt moved out to the wall and started rotating as a pipe.

4.3. Secondary flows

As mentioned before, the angular velocity's is not constant in the whole volume of the gallium. In an empirical forced vortex, the angular velocity is constant all over the flow. According to figure 6, the angular velocity significantly reduces near to the wall. The depression in the value is caused by "near-wall effects". Figure 9a shows the secondary flows in the volume of the melt in the 10 mm crucible. 92% of the volume is making turbulent secondary flows and slowing down the melt's rotation at the wall. The other 8 V/V% of the gallium makes an updraft [3, 4], which has a significant role in the crystallization of other alloys – like Al-Si-Mg ternary – transporting the alloying particles thru the melt. Without stirring the particles' distribution is uniform [5].

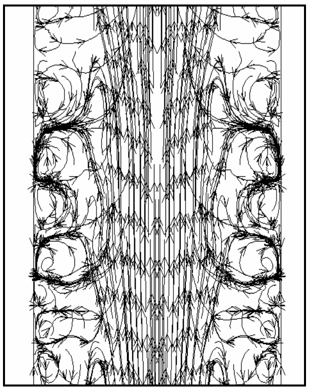

Figure 9. a)
Pathlines of the secondary flow
D = 10 mm

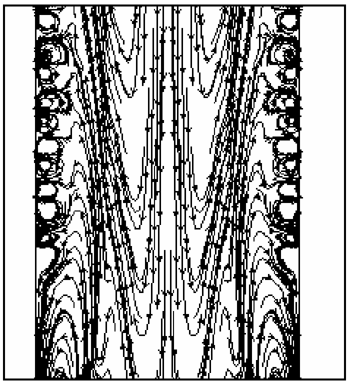

Figure 9. b)
Pathlines of the secondary flow
D = 35 mm

If the diameter of the crucible is bigger, the "near-wall effect" takes less action on the flow and less ratio – 46.5 V/V% – gets turbulent. The updraft is still visible, but in the middle of the "melt-cylinder" a downdraft appears. This movement feeds the updraft – see figure 9b. With 10 mm diameter there's not enough laminar zone to produce the downdraft. On account of the pressure difference between the middle and the edge of the melt, the updraft uses the whole laminar zone and the downdraft is forced out into the turbulent zone.

Figure 10. a)–10. d) show in order the gallium in the 10 mm crucible [scale bar shows the volume fraction of gallium, 10. a)], the contours of axial, radial and the tangential velocity [scale bar is in m/s, 10. b)–10.d)]. The turbulence is visible on all of the 3 velocity patterns and the contours of the tangential velocity [Figure 10. d)] proofs that the angular velocity decreases near the wall – see equation (4). Negligible amount of radial velocity's visible.

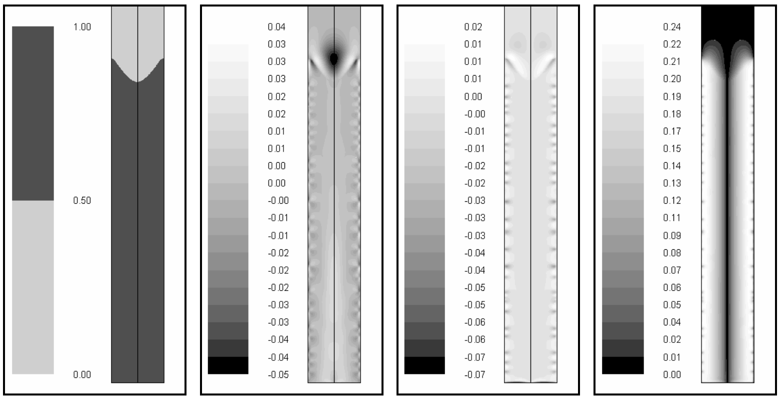

Figure 10. a) *Figure 10. b)* *Figure 10. c)* *Figure 10. d)*

*Contours of: **10.a**) volume fraction of gallium, **10. b**) axial velocity magnitude, **10. c**) radial velocity magnitude and **10. d**) tangential (swirl) velocity magnitude. Scale bar on **b) c)** and **d)** is in m/s; D = 10 mm, B = 37 mT*

The rate of the axial velocity in the updraft is 0.01–0.02 m/s. Compared to the tangential velocity – which's maximum is at about 0.22 m/s – the updraft is quite slow in the laminar zone, but can take enough action on the crystallization [4, 5].

Compared to the 35 mm diameter case [Figure 11. a)–11. d)], the axial velocity values change between 0.03–0.07 m/s. Negative value means downdraft and it seems to be double stronger than the updraft. The reason of the faster flow might be the smaller "flow cross-section" in the middle or that the turbulences don't affect the flow. The gravity can also cause difference. If the gravity is turned off in the model, the melt can "climb out" from the crucible. The velocity contours would be different too.

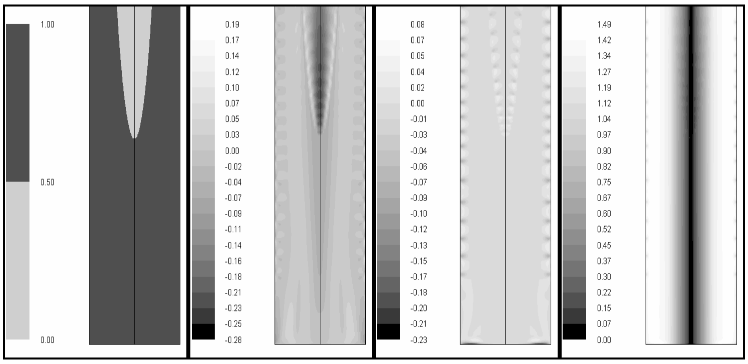

Figure 11. a) *Figure 11. b)* *Figure 11. c)* *Figure 11. d)*

*Contours of: **11. a**) volume fraction of gallium, **11. b**) axial velocity magnitude, **11. c**) radial velocity magnitude and **11. d**) tangential (swirl) velocity magnitude. Scale bar on **b) c)** and **d)** is in m/s; D = 35 mm, B = 37 mT*

Radial and tangential velocity distributions are similar to the 10 mm diameter one, but with different values and smaller area of turbulence. The tangential velocity's maximum is 1.5 m/s – see figure 10. b)–d) It's 625% of the tangential velocity maximum in the 10 mm crucible. The peak on the curve of figure 7 is caused by the effect of the axial velocity distribution. The fastest updraft and the peak appear at the half of the radius. The same peak appears in case of 10 mm, and also at the same place where the updraft is – in the middle of the melt. Less weakening is affected on the primary flow by these laminar zones and higher angular velocities can be reached.

Spiral flow lines can be found on the surface of the gallium on Figure 3 [1]. Those spirals are caused by the amount of the primary rotational flow and the (secondary) updraft (or any axial flow), which is occurred by the pressure difference in the melt.

5. Errors of the model

The measured data of Rónaföldi [1] for the angular velocity was used for validation of the model. The relative errors of the average angular velocity (from both line and pressure difference methods) are shown on Figure 13. a). The errors of the sedimentation are shown on figure 12. With line method, the angular velocity's error is average of 8% in 10 mm and 19.8% in 35 mm. With pressure method, this data is 14.1% in 10mm and 46.6% in 35 mm.

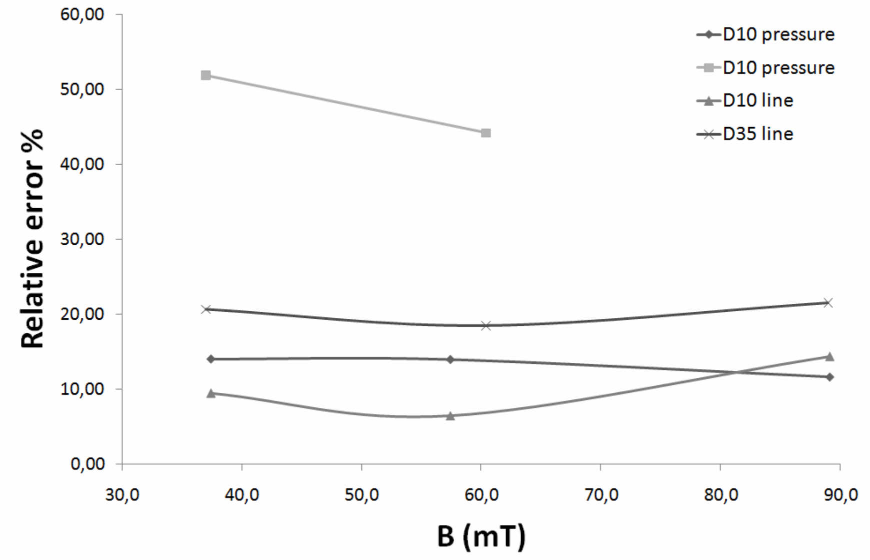

Figure 12. Relative error on the angular velocity measured with both methods as a function of the induction

Conclusions

A model for investigating the hydrodynamic properties of a Ga-In alloy during magnetic stirring was made. The Lorenz force field, which is rotating the melt, was programmed with User Defined Functions.

Two methods for measuring the angular velocity in the melt were used. The "line method" is appropriate to check the model during running and to measure the distribution of the angular velocity across the radius. The "pressure gradient method" is a faster technique for gathering averaged values and also handy to measure in any moment of the flow time – the oscillating effect in the "line method" (see Figure 5) can be eliminated. With line method, it's difficult to decide the time of measurement.

In the future a more detailed flow inspection could be useful and the turbulent model can be a good base for solidification modeling.

Acknowledgements

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