

Materials Science at University of Miskolc



Edited by
A. Roósz and K. Tomolya

TTP TRANS TECH PUBLICATIONS

Modelling of Crown on Cold Rolled Aluminium Sheet S. Pálincás, G. Krállics and Z. Bézi.....	115
Development of a Complex Optimizing Model of Wire Drawing Technology S. Kovács and V. Mertinger.....	125
Design Curves for High-Cycle Fatigue Loaded Structural Elements Z. Koncsik and J. Lukács.....	135

Chapter 3: Solidification

A New Method to Examine the Annealing of Two Alloying Elements of 3004-Grade Cast Aluminum by Resistivity and Thermoelectric Power F. Tranta.....	147
Comparison of Measured and Numerically Simulated Angular Velocity of Magnetically Stirred Liquid Ga-In Alloy C. Nagy, A. Rónaföldi and A. Roósz.....	157
Investigation of Microstructure of Cast Iron by Color Etching I. Kardos and Z. Gácsi.....	167
Development of Amorphous and Microstructured Surface Layer by Laser Surface Treatment M. Svéda and A. Roósz.....	175
Effect of the Technological Parameters on the Thermal Conditions of Die-Casting Tool J. Dül, Z. Leskó and B. Juhász.....	183
The Effect of Homogenization on the Annealing of Al-1,5%Mn Aluminium Alloy T. Hegyes and P. Barkóczy.....	193

Chapter 4: Simulation

Simulation of Isothermal Nucleation of Austenite in Spheroidite Plain Carbon Steels G. Karacs and A. Roósz.....	201
Modelling of Flow Properties of Asphalt Mastics R. Géber and L.A. Gömze.....	209
Simulation of Grain Coarsening Using One-Dimensional Cellular Automaton S. Gyöngyösi and P. Barkóczy.....	217

Chapter 5: Polymers

Preparation and Evaluation of Novell Wood-PVC Systems T. Kuknyó and T. Szabó.....	221
The Effect of Technological Parameters on the Quality of UHMWPE Products I. Kállai.....	227

Effect of Crystallinity on P E. Kun and K. Marossy....	
Tribological Testing Result T. Szívós and G. Zsoldos..	

Chapter 6: Miscellanies

The Effect of Aluminium on Metals in the Course of ICF O. Bánhidi.....	
Modelling of Ion Distribution Used for Biomedical Application P. Kaali and G. Czél.....	
Optimally Balanced Active-Coatings Featuring Proper Carbon Nanotubes A. Gergely and T.I. Török..	
Laboratory Preparation and of Industrially Produced Al T.I. Török, J. Pázmán, M. S....	
The Effect of Micro-Impulse from Chloride Solutions T. Kulcsár, Z. Dobó and T....	
Scanning Transmission Electron Microscopy G. Zsoldos.....	

Keyword Index.....

Author Index.....

Comparison of measured and numerically simulated angular velocity of magnetically stirred liquid Ga-In alloy

Cs. Nagy^{1, a}, A. Rónaföldi^{1, b}, A. Roósz^{1, c}

¹MTA-ME Materials Science Research Group, Miskolc-Egyetemváros, Hungary

^antsart@gmail.com, ^belkronar@uni-miskolc.hu, ^cfemroosz@uni-miskolc.hu

Keywords: gallium, indium, magnetic, MHD, stirring, simulation, angular velocity, revolution number, melt flow

Abstract. A measurement of the angular velocity/revolution number of magnetically stirred liquid gallium-indium alloy was realized with newly developed angular velocity measuring equipment. To get additional information about the flow of the melt, a numerical simulation model was performed with ANSYS FLUENT 13.0 with a single phase 2D k- ϵ turbulence solver. The aim was to reproduce the flow as accurate as possible, so the measured and computed angular velocity data was compared, to see if the system can be modeled fairly well.

Introduction

During the solidification of metals and alloys – under Earth circumstances – flows emerge inside [1-3]. The trait and intensity of these flows are strongly affecting the structure of the solidified metals and alloys and by this, the properties too. This affect can be quite significant; because of this the investigation of the phenomena is really important.

The inspection is a process in which externally induced flows – with different intensity and direction – arise in the metal- or alloy-melt (collectively designated as molten metal) for solidification. These streams induced from outside, have to be more intense than those inside, namely the effect of the outer stimulation should be dominant. We can draw conclusions on the flows without outer stimulation as well according to examinations achieved this way.

This paper runs on flows induced by MHD rotating magnetic field (RMF). The used experimental MHD stirrer can produce significantly higher inductions (~90 mT) than other equipment in the literature.

To get a clear view of the properties of the flow, the revolution number/angular velocity of 75,5%Ga-24,5%In alloy-melt was measured with newly developed “pressure compensating” equipment [4]. The data is useful, but additional flow parameters are necessary, so a numerical model was prepared with ANSYS FLUENT 13.0. Simulations of magnetically stirred melts were also developed by Budenkova et al. [5,6]. Our model was created to be as simple as possible – two dimensional axis symmetrical k- ϵ turbulent model with the inducing force filed. The measured and computed angular velocity data was compared to see the accuracy and possibilities of the model.

The MHD system

The operation of the facility is based on the Maxwell equations. If the conducting fluid is put into the rotating magnetic field, an eddy current is induced in it. By the law of Lenz, the melt is trying to obstruct the inducing field, so it starts rotating. The force – which makes the stirring – is the Lorenz force – see Fig 1. and Eq. 1.

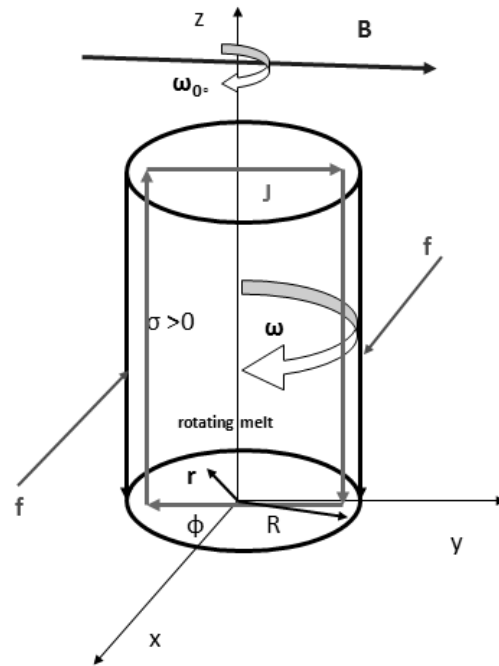


Figure 1. The MHD system

$$F_{\text{Lorenz}} = 0,5 \sigma B_0^2 r [\omega_0 - \omega] \quad (1)$$

Where:

- σ is the electrical conductivity of the melt – $3,58 \cdot 10^6$ S/m
- B_0 is the magnetic induction – strength of the magnetic field,
- r is the distance from the axis,
- ω_0 is the synchronous angular velocity of the MHD stirrer,
- ω is the angular velocity of the fluid (molten metal/alloy).

The measuring method [4]

The metallostatic pressure belonging to the "h" height is in equilibrium with the " Δp " pressure difference developing between the pressure along the "R" radius and the pressure being on the axis. The pressure difference depends on the height of liquid column (h), the density of melt (ρ_{melt}) as well as on the gravitation constant (g):

$$\Delta p = h \rho_{\text{melt}} g \quad (2)$$

The height of the magnetically stirred liquid alloy, with stable, non-conducting tank:

$$h = \omega^2 R^2 / 2g \quad (3)$$

From Eq. 2 and Eq. 3:

$$\Delta p = \rho_{\text{melt}} g [\omega^2 R^2 / 2g] \quad (4)$$

The angular velocity can be determined on the basis of Eq. 4:

$$\omega = [1/R] [2 \Delta p / \rho_{\text{melt}}]^{0.5} \quad (5)$$

The average revolution number is:

$$n = [60/2\pi] \omega \quad (6)$$

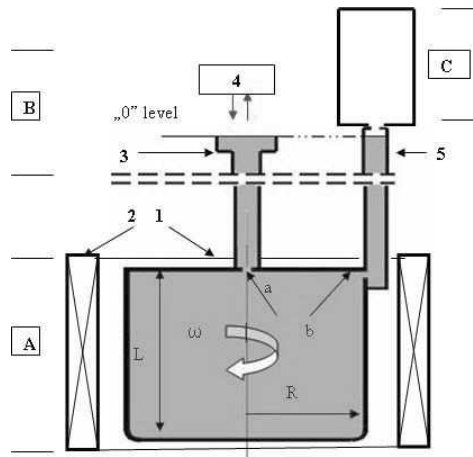


Figure 2. The measuring equipment

It is difficult to measure the pressure developing in the melt without disturbing the melt flow; therefore instead of measuring directly the developed metallostatic pressure, by which it could be compensated, was measured. The sketch of equipment - using a pressure compensation method for the average revolution number measurement - assembled with the MHD stirrer is shown in Fig. 2. The equipment consists of the following three main units:

- A. MHD unit, where the (non-conducting, stable) measuring cell /1/ is placed in the MHD inductor /2/
- B. Measuring unit, where the measuring tank /3/, the distance meter /4/ and the compensation chamber /5/ can be found
- C. "Overpressure" unit, where the compensation pressure develops and it is measured

The measuring cell is a closed tank that is connected to the distance meter and to the compensation chamber through a small hole indicated by "a" and "b" in Fig. 2. The result of the measurement is a volume average of the revolution number/angular velocity. The measured data can be seen in Table 2. and Table 3.

The setup of the numerical model

The aim of the work was to build a model as simple as possible and reproduce the main flow of the melt. By this, a two dimensional axis symmetrical single phase model was created. This choice makes the work faster and lowers the computational requirements. The geometry is a simple 60 mm high and 5 mm wide rectangle. This produces the 10mm inner diameter and 60mm high crucible from the measurements [4]. This crucible was filled fully with the molten alloy. The mesh was a simple hexa mesh with – size = 0,1 mm. The turbulence solver was Realizable k-ε model with Enhanced Wall Treatment.

The Lorenz force field had to be modeled via a User Defined Function (UDF). The coordinate and velocity dependent force was programmed with a C source code. Every cell had a different amount of tangential momentum source at every time step – like it happens in reality.

Two different model series were set to have clear view of the possibilities of simulating the flow with FLUENT. The first was with 50 Hz of inductor frequency; the second was with 150 Hz. The higher frequency makes stronger force, and by this, faster flows. 5 – 5 different inductions were used in each simulation series – see Table 1.

Table 1. The used inductions in the two simulation series – 50 Hz and 150 Hz inductor frequency

50 Hz	150 Hz
Induction [mT]	
22,6	16,8
37,4	26,2
51,5	37,2
68,5	48,2
89,1	65,0

The simulated flow field

It is good to see the properties of the flow pattern first. Fig. 3a-d show the contours of tangential velocity, Fig. 4a-d show the contours of axial velocity and Fig. 5a-d show the contours of radial velocity of models with two inductions with two frequencies.

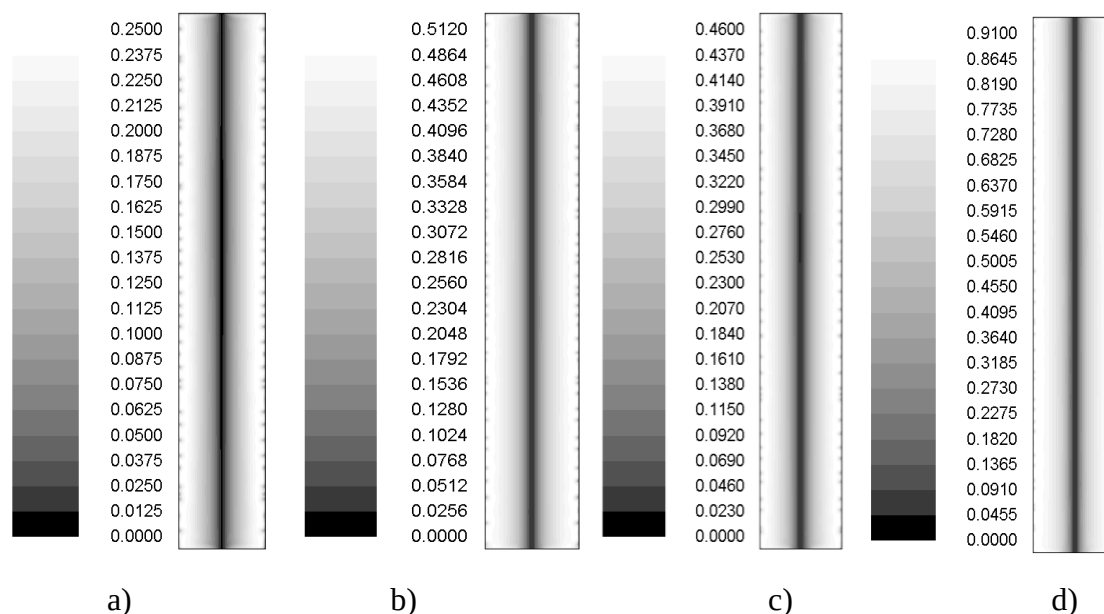


Figure 3. Contours of the tangential velocity [m/s] inside the melt with a) 37 mT induction and 50 Hz inductor frequency, b) 37 mT induction and 150 Hz inductor frequency, c) 69 mT induction and 50 Hz inductor frequency and d) 65 mT induction and 150 Hz inductor frequency

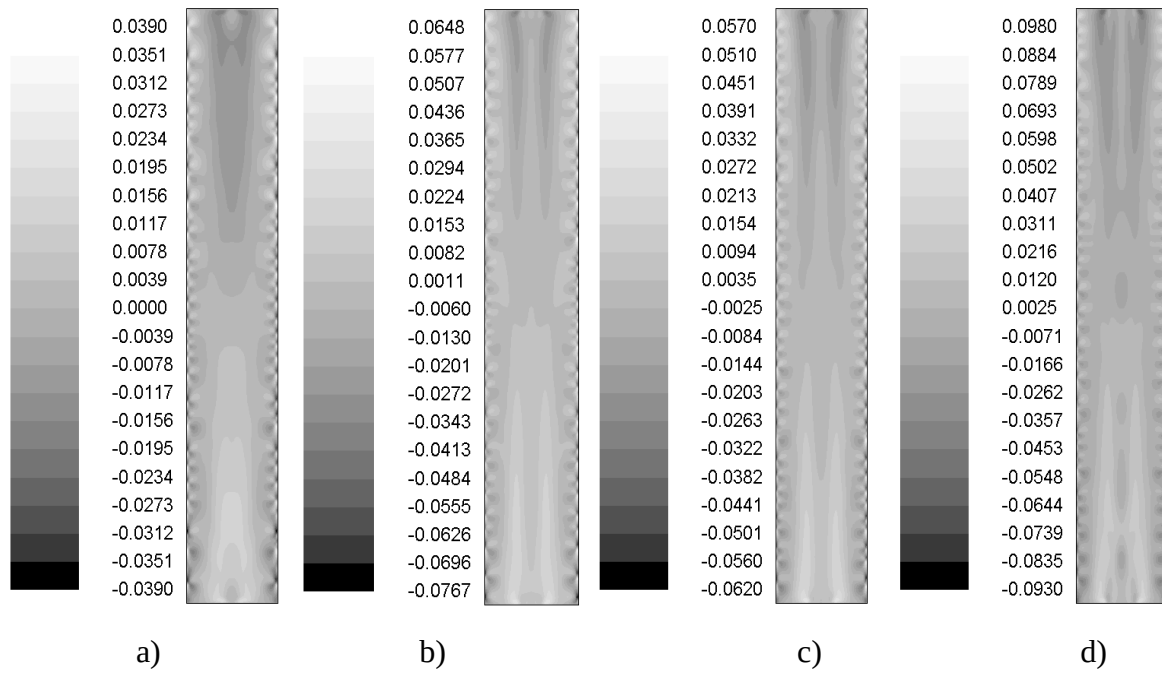


Figure 4. Contours of the axial velocity [m/s] inside the melt with a) 37 mT induction and 50 Hz inductor frequency, b) 37 mT induction and 150 Hz inductor frequency, c) 69 mT induction and 50 Hz inductor frequency and d) 65 mT induction and 150 Hz inductor frequency

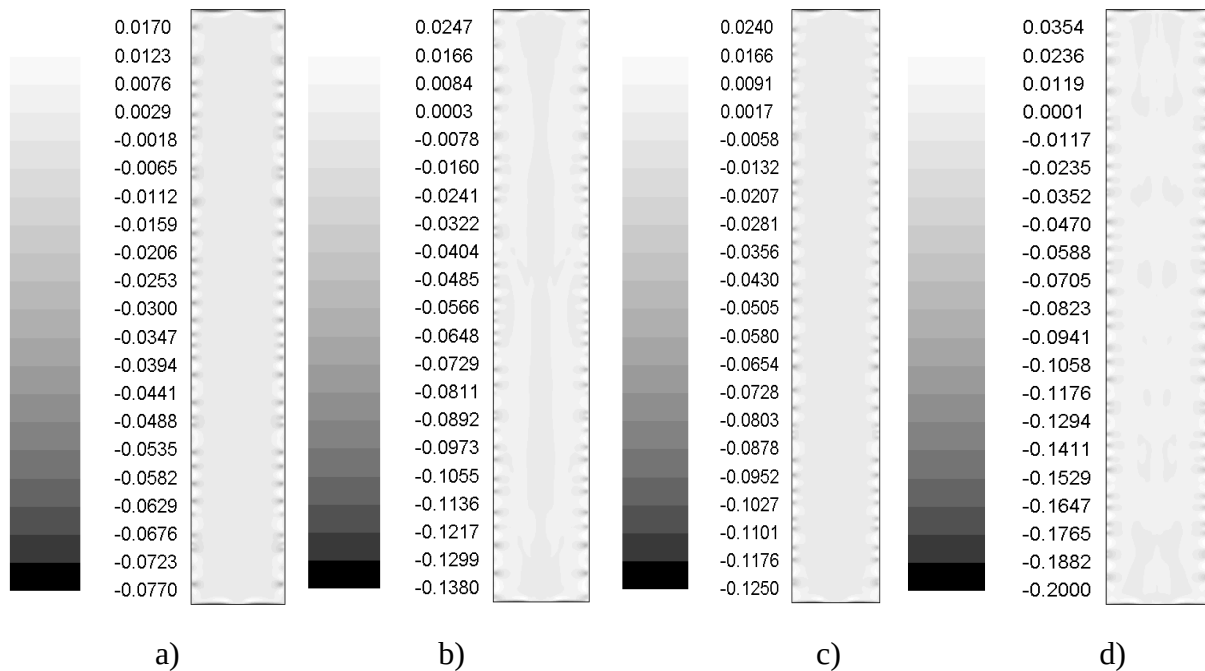


Figure 5. Contours of the radial velocity [m/s] inside the melt with a) 37 mT induction and 50 Hz inductor frequency, b) 37 mT induction and 150 Hz inductor frequency, c) 69 mT induction and 50 Hz inductor frequency and d) 65 mT induction and 150 Hz inductor frequency

As visible, there is no major difference with different setups; just the velocity values are different. With same induction, but higher frequency, the velocities are also higher. It comes from the stronger magnetic field – see Eq. 1. The higher frequency provides higher ω_0 , and stronger Lorenz force. To prove the similarity better see Fig. 5a-d. The path lines run identical.

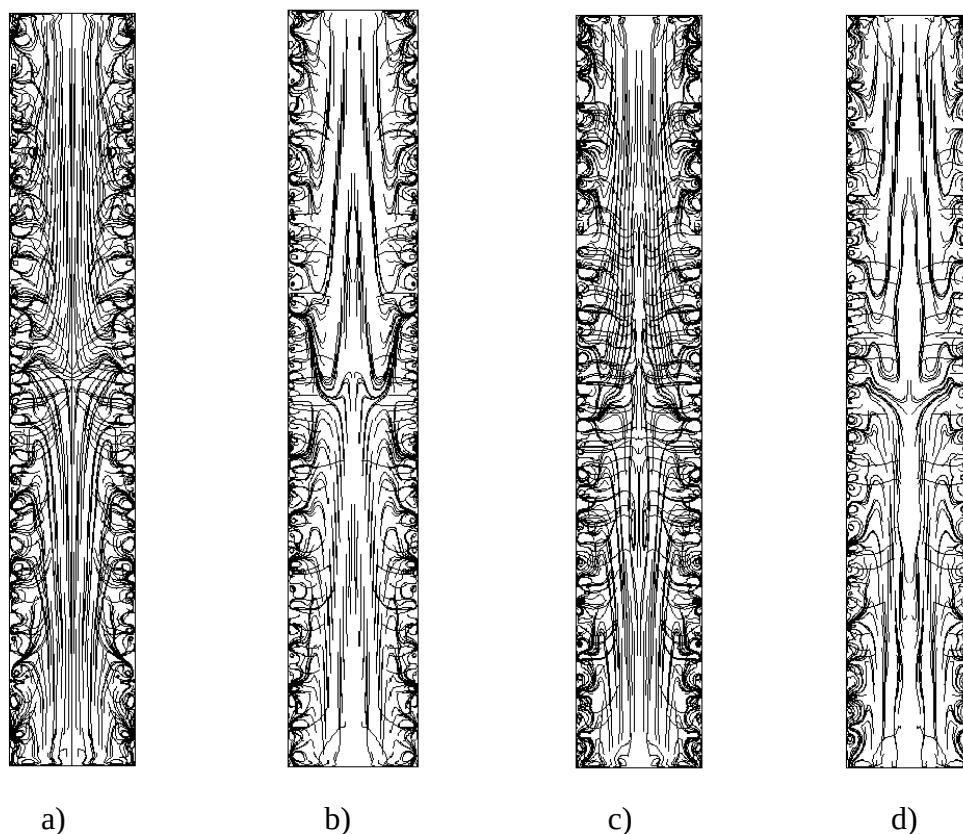


Figure 6. Path lines of the flow inside the melt with a) 37 mT induction and 50 Hz inductor frequency, b) 37 mT induction and 150 Hz inductor frequency, c) 69 mT induction and 50 Hz inductor frequency and d) 65 mT induction and 150 Hz inductor frequency

The angular velocities – time dependence and radial distribution

Theoretically the melt can't reach the synchronous angular velocity of the inductor. It is because of the wall friction, the viscosity and the breaking effect of the melt – see $(\omega_0 - \omega)$ part of Eq. 1. First the melt accelerates constantly and then it starts to reach the possibly maximum with the current conditions – synchronous angular velocity of the inductor, melt material properties, magnetic induction, crucible radius, etc.

The curves of the simulated models can be seen in Fig. 7a for 50 Hz and in Fig. 7b for 150 Hz. The shapes of the curves are similar to the theoretical. The settle of the flow is slower with lower induction and lower frequencies, because of the weaker Lorentz force fields.

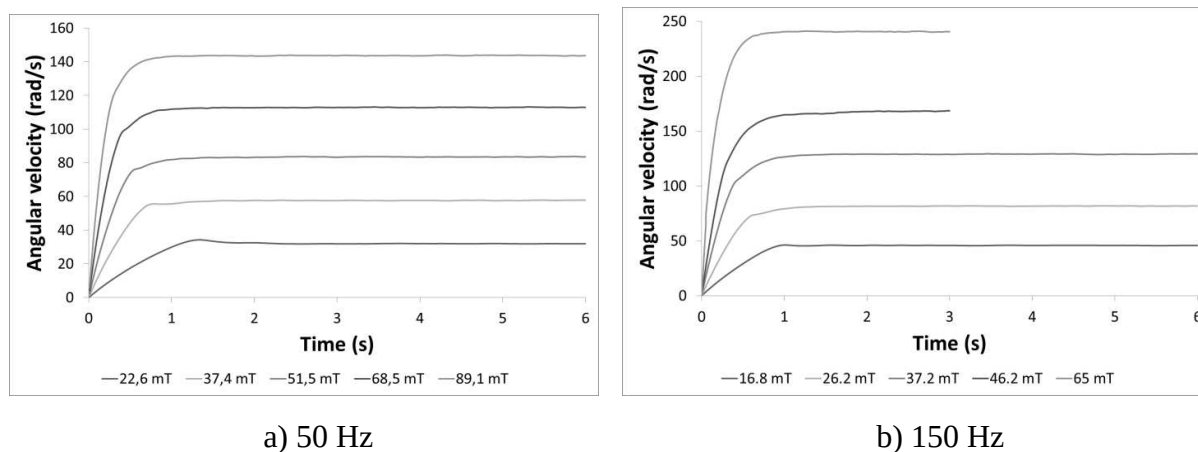


Figure 7. Angular velocity as a function of time

These curves were used to check the model during the iterations. The data was gathered from the velocity field as in Eq. 7:

$$\omega_{\text{vel.method}} = v_t / r \quad (7)$$

The distribution of the angular velocity (computed from tangential velocity – Eq. 7) can be seen in Fig. 8. As the flow is getting faster, the distribution of the angular velocity is getting more anisotropic – the middle of the melt is getting faster. Nearby the axis, the flow is less disturbed with turbulence. In this region there is a pump effect, a laminar uplift or downdraft depending on the vertical coordinate – see Fig. 4 and 6. The wall friction is making small eddies, which slow down the primary flow.

The diagrams in Fig. 8. also can be used to see how the distribution is changing with time, because the flow is faster with bigger induction and slower with lower induction. The flow pattern is changing constantly – or morphing into each other. If we would ‘stop’ the flow at a time, it would be the same as a settled flow induced by a lower induction.

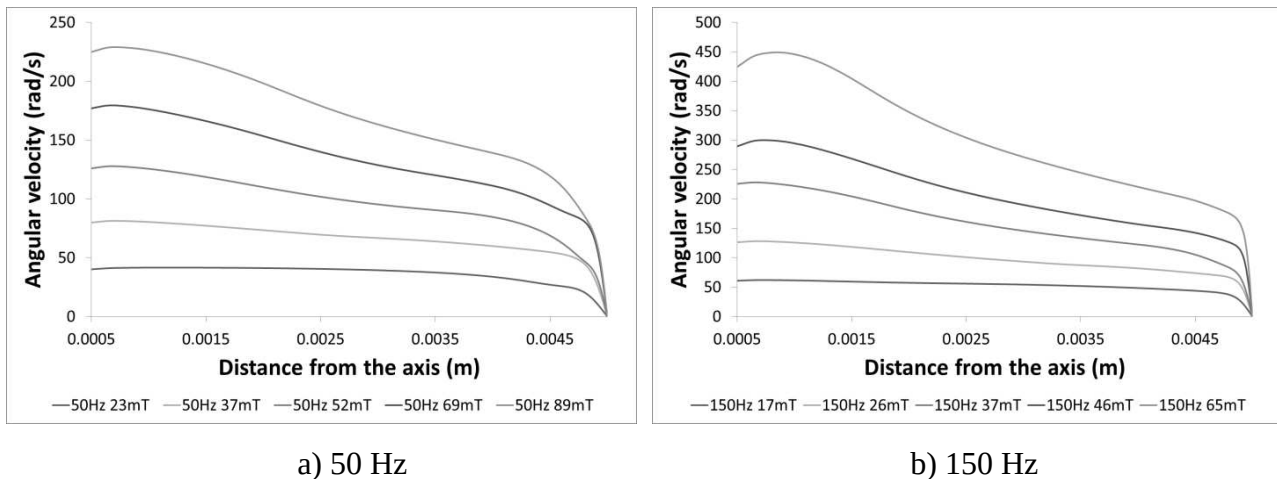


Figure 8. Distribution of the angular velocity along the radius

Comparison with the measured data and error analysis.

The angular velocity was computed from the measured pressure difference, so we did the same in the case of the calculations. The pressure pattern inside the melt for two inductions with two frequencies can be seen in Fig. 9a-d.

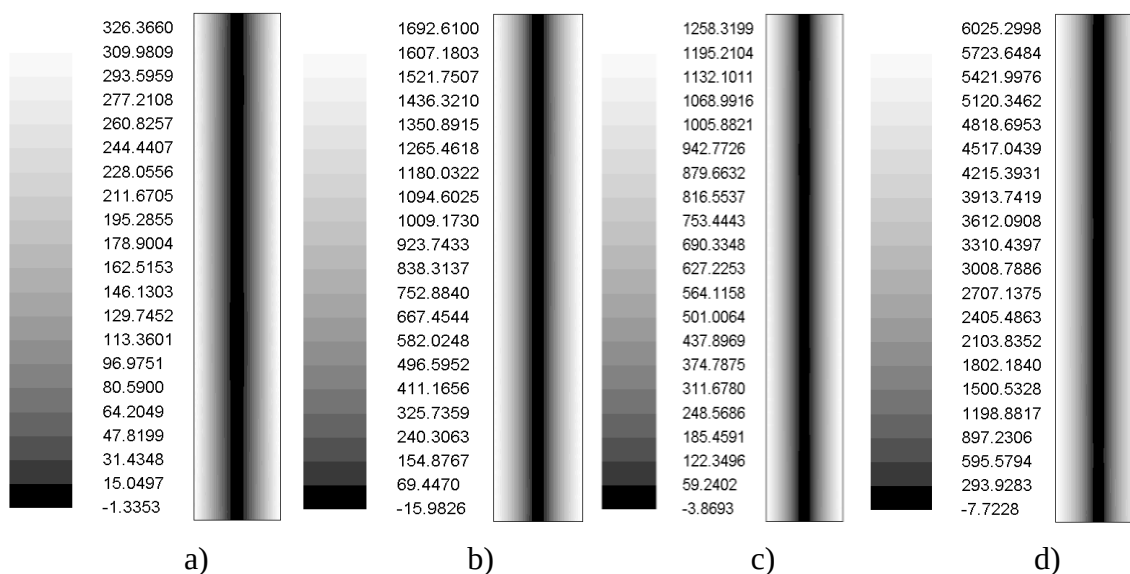


Figure 9. Contours of the static pressure [Pa] inside the melt with a) 37 mT induction and 50 Hz inductor frequency, b) 37 mT induction and 150 Hz inductor frequency, c) 69 mT induction and 50 Hz inductor frequency and d) 65 mT induction and 150 Hz inductor frequency

Using the metallostatic pressure difference, the angular velocity of the melt can be computed with the following equation:

$$\omega_{\text{press. method}} = \sqrt{\frac{2\Delta p}{\rho r^2}} \quad (8)$$

Where

- Δp is the metallostatic pressure difference
- ρ is the density of the melt – 6350 kg/m³
- r is the radius of the crucible.

The computed and measured pressure differences and the compared angular velocities can be seen in Table 2. for 50 Hz and on Table 3. for 150 Hz.

Table 2. The measured and computed pressure differences, the calculated angular velocities from the data and the relative error of the simulated angular velocities – 50 Hz

50 Hz					
B_0 (mT)	Δp_{sim} (mbar)	Δp_{meas} (mbar)	ω_{sim} (rad/s)	ω_{meas} (rad/s)	Relative Error of ω_{sim} (%)
22.60	1.03	1.20	35.98	38.83	7.34
37.40	3.28	3.60	64.25	67.30	4.53
51.50	6.87	7.30	93.06	95.98	3.04
68.50	12.62	11.50	126.10	120.37	-4.76
89.10	20.37	19.80	160.19	156.69	-2.23
Absolute average					4.38

Table 3. The measured and computed pressure differences, the calculated angular velocities from the data and the relative error of the simulated angular velocities – 150 Hz

150 Hz					
B_0 (mT)	Δp_{sim} (mbar)	Δp_{meas} (mbar)	ω_{sim} (rad/s)	ω_{meas} (rad/s)	Relative Error of ω_{sim} (%)
16.80	2.07	2.80	51.08	59.24	13.77
26.20	6.66	8.80	91.59	104.98	12.75
37.20	17.09	17.20	146.72	146.96	0.17
46.20	29.46	31.80	192.65	199.82	3.59
65.00	60.36	56.00	275.76	266.80	-3.36
Absolute average					6.73

Fig. 10. shows the relative error of the models graphically.

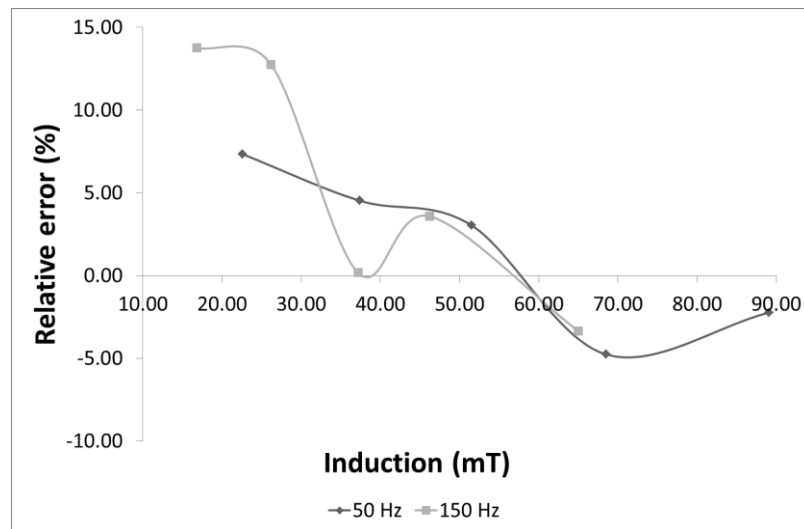


Figure 10. Relative error of the simulated angular velocities compared to the measured data

The error is visibly higher with lower inductions. It can be from the measuring difficulties of the lower pressures. There are other causes of the deviance between the measured and simulated data. The alloy – which was used for the measurements – was mixed by the research group. If the composition of the alloy is not exactly 75,5%Ga-24,5%In, the material properties are different. The

digression of the electrical conductivity can make serious differences in the Lorenz force and by this, the angular velocity. There is another point with σ . The data was gathered from literature. We can't be sure if the data is 100% correct. On the other hand, the produced model is as simple as possible. The flow is simplified into an axis symmetrical system; however the flow is not completely axis symmetrical.

Conclusions

The properties of the flow of magnetically stirred liquid Ga-In alloy have been investigated via measurements and numerical simulations. It is clear, that the flow can be modeled with ANSYS FLUENT on a fairly accurate level. However a three dimensional model should be made to have a complete view of the flow pattern.

Acknowledgement

This work has been carried out as part of the TÁMOP-4.2.1.B-10/2/KONV-2010-0001 project within the framework of the New Hungarian Development Plan. The realization of this project is supported by the European Union, co-financed by the European Social Fund.

References

- [1] K. Stransky, F. Kavicka, B. Sekanina, J. Stetina, V. Gontarev, J. Dobrovska: The effect of electromagnetic stirring on the crystallization of concast billets. *Materials and technology* 45, pp. 163–166. (2011)
- [2] B. Yue-long, X. Jun, Z. Zhi-feng, S. Li-kai: Annulus electromagnetic stirring for preparing semisolid A357 aluminum alloy slurry. *Trans. Nonferrous Met. Soc. China* 19, pp. 1104–1109. (2009)
- [3] S. Steinbach, L. Ratke: The effect of rotating magnetic fields on the microstructure of directionally solidified Al–Si–Mg alloys, *Materials Science and Engineering A* 413–414 pp. 200–204. (2005)
- [4] A. Rónaföldi, J. Kovács, A. Roósz: Revolution number (RPM) measurement of molten alloy by pressure compensation method. *Materials Science Forum* 649 pp 275-280. (2010)
- [5] O. Budenkova, A. Noppel, J. Kovács, A. Rónaföldi, A. Roósz, A-M. Bianchi, F. Baltaretu, M. Medina, Y. Fautrelle: Comparison between simulation and experimental results of the effect of RMF on directional solidification of Al-7wt.%Si alloy. *Materials Science Forum* 649, pp 269-274. (2010)
- [6] O. Budenkova, F. Baltaretu, J. Kovács, A. Roósz, A. Rónaföldi, A-M. Bianchi and Y. Fautrelle: Simulation of a directional solidification of a binary Al-7wt%Si and a ternary alloy Al-7wt%Si-1wt%Fe under the action of a rotating magnetic field. *Modeling of Casting, Welding and Advanced Solidification Processes*, Rolduc, Netherlands (2012)