Two cylinder permanent magnet stirrer for liquid metals

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Abstract. To achieve a uniform liquid metal composition and temperature distribution, stirring is often necessary for industrial processes. Here, a novel permanent magnet system for liquid melt stirring is proposed. It promises very low energy consumption and options for multiple different flow types compared to traditional travelling magnetic field inductors or mechanical stirrers. The proposed system has a simple design: it consists of two rotating permanent magnet cylinders, which are magnetized transversely to the axis of the cylinders. The experimental device was developed and tested under various regimes using GaInSn alloy in a cylindrical crucible. Aluminum stirring by permanent magnets in laboratory scale is tested, and stirring impact on directional solidification of metallic alloys is experimentally investigated.

1. Introduction

In metallurgy, liquid metal flow control - transport and stirring – is an especially challenging task due to the high temperatures and aggressive environments. Molten metal stirring is necessary to achieve uniformity of composition and temperature throughout the volume of liquid [1]. For these tasks, mechanical stirring is limited due to high temperatures and erosion of the walls, leading to melt contamination and short service life. For contactless flow control, traveling or rotating magnetic field AC inductors are commonly used. Due to high power losses in windings caused by the resistance and resulting in useless Joule heating, the efficiency of these systems is low [2]. Permanent magnet systems contrarily do not consume any energy to create a magnetic field. Driving motors only need to overcome forces related to induced secondary magnetic fields in conducting media (both liquid metal and conducting construction elements). Nowadays increased availability of NdFeB permanent magnets allows creating affordable large permanent magnet systems, which can be successfully used to create motion in liquid metals [3-5]. Since magnetic flux decreases rapidly with the distance from the permanent magnet, the size of magnets should be comparable to the distance from the magnets to the liquid metal.

We propose a novel rotating permanent magnet system that provides easy transition between various types of the flow patterns, even switching between mixing in of the particles and stirring, and pumping, dependent what would be required at the production stage. Compared to traditional traveling field AC inductors, the proposed system consumes less energy and, more importantly, provides many options for various configurations. As a substitute for liquid aluminum for some experiments in a laboratory environment, GaInSn eutectic alloy is used. It has similar properties to liquid aluminum and it is convenient to use since it is in a liquid state at room temperature. Ultrasonic velocimetry has been successfully used to measure GaInSn alloy flow velocity.

During solidification of liquid metals, the actual problem is segregation and temperature anisotropy at the solidification interface. Thus, forced convection in the melt can be the beneficiary and help to improve the solidified alloy microstructure [6]. Solidification experiments have been done, and motion influence on the structure has been investigated, demonstrating that flow control is an
instrument to modify the solidification process [7,8]. In solidification experiments Al-5%wt.Cu and Sn-10%wt.Pb were used.

2. Experimental setup

The experimental setup was built taking account physical and geometrical similitude so the model results would help to determine potential industrial applications of such system. Principal scheme and picture of the experimental setup are shown in figure 1. The experimental system consists of electric motor, two cylindrical magnets (D=40 mm, H=80 mm or D=50 mm, H=100 mm) type N50 with a remanent flux density of 1.4 T, that are connected by a system of timing pulleys and belt, allowing synchronous rotation either in one direction or opposite directions. Two permanent magnet cylinders, which are magnetized transversely to the axis of the cylinder, are placed on opposite sides of the liquid metal container. A relatively large distance between the magnets ensures minimal magnetic interaction between themselves, therefore providing a smooth and energy efficient system of operation. By changing the magnet’s position relative to the container it is possible to create numerous types of flows even with no axial symmetry, which can be very beneficial in certain types of situations. Such versatility and simplicity of the system enables it for a wide range of different applications.

![Figure 1. Experimental setup. A) schematic illustration; B) Experimental device.](image)

The system is designed in such way that it is possible to vary magnet positions along all three axes and tilt ($\theta$) relative to the container, thus enabling us to create numerous types of flows. Tilt angle $\theta$ is defined as the angle between the main axis of cylinder and z-axis. The magnetic flux density distribution is calculated by Comsol 5.0 software. Numerical results of the magnetic field at a distance between aligned magnet cylinders of 20 cm is given in figure 2. These numerical results were compared to Gaussmeter measurements and agreement is good. The strength of the magnetic field in liquid metal volume ranges from 20 mT at the center and 60 mT near the edge of the container in case of 40 mm magnets which were used in GaInSn stirring experiments.
3. Order of magnitude estimates of flow velocity

In this study, we develop an estimation to scale experimental results to different geometries and material properties. Ultrasound velocity measurements were done at the GaInSn alloy experiment at room temperature, and results were used for scaling to different materials and crucible sizes. In this work, we performed several experiments to demonstrate electromagnetic stirring and stirring influence on directional solidification of a metallic alloy. Experimental parameters are summarized in table 1.

Table 1. Summary of experimental conditions

|                | $\rho$, kg/m$^3$ | $\sigma$, S/m | $R$, mm | $H$, mm | $B$, mT | $f$, Hz ($\omega_r$, rad s$^{-1}$) | $N$     | $\Omega_d$ |
|----------------|------------------|----------------|---------|---------|--------|----------------------------------|---------|-----------|
| GaInSn         | 6360             | $3.3 \cdot 10^6$ | 70      | 130     | 20     | 2.9 (18.2)                      | 0.0014  | 0.370     |
| Sn-10%wt.Pb    | 7000             | $2 \cdot 10^6$  | 30      | 100     | 50     | 10 (62.8)                       | 0.0014  | 0.014     |
| Aluminum       | 2400             | $4 \cdot 10^6$  | 30      | 100     | 50     | 5 (31.4)                        | 0.0211  | 0.177     |

Following dimensionless criteria must be met for physical similitude between two cases. Physical similitude requires full similarity of the geometry of the two setups and identity of a set of dimensionless criteria. Order of magnitude estimates of the flow velocity is done neglecting viscosity and assuming that the induced magnetic field is much smaller than the field produced by the magnets.
Firstly, the magnetic interaction parameter (Stuart number) $N$ is the ratio between electromagnetic and inertial forces, secondly, and $\Omega_d$ is the dimensionless frequency characterizing the skin effect of an alternating magnetic field. Since there is no given flow velocity scale electromagnetic interaction parameter is defined by applying velocity scale of travelling magnetic field speed $\omega \cdot R$. If these parameters are similar, then similar force distributions and flow regimes can be expected.

$$N = \frac{k \cdot \sigma \cdot B^2}{\rho \cdot \omega} \quad \text{and} \quad \Omega_d = \sigma \cdot \omega \cdot \mu_0 \cdot R^2$$  \hspace{1cm} (1)

where $\rho$ is the density of the melt, $\sigma$ is conductivity, $\omega$ is magnet angular speed, $\mu_0$ – magnetic permeability, $R$ - characteristic length, in this case radius of metal pool and $B$ is the magnitude of the magnetic field induction in the liquid metal region. Dimensionless coefficient $k$ is introduced to account for geometry of induced current loop’s. In following estimate, it is set to 0.5.

$$k = \frac{1}{1 + \left(\frac{\tau}{H}\right)^2}$$  \hspace{1cm} (2)

$\tau$ is the azimuthal distance over which the phase of the magnetic field changes by 180 degrees. $H$ is the height of the magnet or the melt region (whichever is the smallest). In case similitude criteria are met, the velocity of the liquid metal can be expressed by balancing electromagnetic and inertial forces, which yields (3). This estimate is valid when $\Omega_d \ll 1$ and it does not include viscosity and turbulence.

$$\frac{1}{2} \cdot k \cdot \sigma \cdot \left(\omega - \frac{u}{R}\right) \cdot R \cdot B^2 = \frac{\rho \cdot u^2}{R}$$  \hspace{1cm} (3)

Solving equation respect to $u$ and substituting $\frac{k \cdot \sigma \cdot B^2}{\rho \cdot \omega}$ with $N$ yields equation for velocity (4)

$$u = \omega \cdot L \cdot \left(\sqrt{N^2 + 2 \cdot N} - N\right)$$  \hspace{1cm} (4)

For $f$=10 Hz in liquid Sn-10%wt.Pb $\Omega$ is 0.014 which is a small value. Similar $N$ in GaInSn flow is achieved at $f$=2.9 Hz, which gives a maximum flow velocity of 7 cm/s.

At field rotation frequency of 10 Hz, we get a maximum velocity in Sn-10%wtPb alloy of 25 cm/s and 40 cm/s for Al-5%wt.Cu alloy. The calculated Peclet number is $4 \cdot 10^2$. Therefore, these velocities are sufficiently large and will have a significant effect on heat transfer in the liquid metal volume and its solidification.

For efficient stirring, not only flow velocity, but also the flow type is important. With proposed system, it is possible to create numerous different flow types even with no axial symmetry. Four characteristic flow types are shown in figure 3. In the case counter rotation (figure 3A), we observe complex flow with fluctuations in velocity and sometimes change in direction. The achieved velocities are comparatively low. The second configuration is co-rotating magnets (figure 3B,) created flow is one fast spinning eddy. This setup has highest tangential velocity, however, there is little $z$ component of flow and in center, velocity approaches 0. If the magnets are tilted horizontally (Figure 3C) same circular motion is obtained, but now the plane of circulation is vertical(xz). By setting magnets at tilted position figure 3D, a combination of above-mentioned flows is obtained. This setup is most versatile of all providing high flow velocity and movement of fluid in all three dimensions.
4. Results and discussion

The measured maximal velocity in GaInSn container with horizontal and vertical magnet alignment is shown in figure 4. To calculate velocities in Sn-10%wt.Pb and in aluminum, we use scaling parameters.

![Figure 4](image)

**Figure 4.** Velocity ultrasound measurements in GaInSn. Characteristic velocity versus magnet rotation frequency.

Velocity measurements in figure 4 are characteristic values of the flow in the most intense direction around 2 cm from crucible wall to avoid any boundary layers. Measurements showed that in all variations higher velocities are in case of co-rotation. Vertical magnet position gives the highest velocities but has the lowest turbulence – so, it can be used in metal continuous directional solidification to refine grain size, but not for temperature and structure homogenization.

Intense turbulence and heavy surface deformations in the case of tilted magnet variation can be perspective to mix in particles or scrap, which is a common problem in industrial manufacturing. Aluminum scrap (~0.1-1 mm in diameter) were added to overheated aluminum, see figure 5.
Figure 5. Time steps of mixing in of the aluminum scrap in overheated aluminum. Magnets are tilted in a 45-degree angle.

Metal flow pulls in the scrap in liquid metal even when a heavy oxide layer is on the metal surface. In steady metal particles and scrap tends to stay on the metal surface and slowly melts – takes around 1 minute.

Solidification experiments with Sn-10%wt.Pb are carried out to verify the stirring effect on the microstructure of the alloy. The bottom of the crucible was cooled by a copper heatsink which was maintained at a constant temperature with water flow as shown in figure 6. The sample is melted and then directionally solidified under electromagnetic stirring. The temperature gradient is 18 K/cm, growth velocity 0.4 mm/s in reference experiments. Measurements and samples were taken at h=30 mm from the bottom. Also, it was observed that both types of stirring – horizontal and vertical configuration - decreased total solidification time by a factor of 2 when compared to reference with no stirring. With the faster rotation of magnet cylinders severe surface deformation of the liquid aluminum alloy was observed. This confirms the calculated velocity order of magnitude of 40 cm/s.

Figure 6. Setup for directional solidification with horizontal magnet configuration: a) concept; b) experimental setup.
Solidification structure is shown in figure 7. Horizontal and vertical cross-sections of the reference sample and the sample solidified under electromagnetic stirring are shown. In figure 5 (b) and (d) oriented electromagnetic stirring is directed from the right to the left side. It can be seen, that due to the stirring, the structure at the same solidification conditions is more uniform. Inducing metal flow solves an actual problem in some metallurgy areas where solidification structure is mainly defined by heat flow direction. Here it is shown that this orientation can be avoided by induced electromagnetic stirring. Although the average grain size is not decreased, the anisotropy of the structure is decreased. Feasibility to stir liquid aluminum alloys by permanent magnet stirrer has also been verified. The microstructure of alloy which is solidified under electromagnetic stirring is compared with the microstructure without stirring. Stirring decreases solidification time significantly due to enhanced convective heat transport.

![Figure 7](image.png)

**Figure 7.** Polished cross-sections of directionally solidified Sn-10\% wt.Pb alloy under electromagnetic stirring. Left side: xy plane (a) and xz plane (c) of reference sample (v=0.4 mm/s, grad(T)=18 K/cm); right side: xy plane (b) and xz plane (d) for solidification under stirring.

### 5. Conclusions

In this work the performance and potential applications of two-cylinder permanent magnet stirrer is investigated. Dimensionless characteristic numbers were introduced allowing scaling GaInSn test model results to different materials and crucible sizes. Two cylinder system performed as expected – multiple types of flow with high intensity can be created and used efficiently by such stirrer on liquid aluminum. Two most prominent flow types were tested in mixing in of the scraps and solidification experiments of Sn-10\% wt.Pb to verify forced convection influence on solidification structure. The study showed that scrap mixing in might be a prospective application of such stirrer with the potential to integrate it in industrial processes. As demonstrated in this work this setup might be used for metal
homogenization or structure improvement during solidification of various metals and that the solidification rate can be significantly increased with stirring.

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