LIQUID METAL STIRRING BY ROTATING LOCALIZED MAGNETIC FIELD IN A CYLINDRICAL CONTAINER

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Abstract: Within the context of the Electromagnetic Processing of Materials, this paper addresses experimentally the electromagnetic stirring of a liquid metal. The analyzed problem consists in the flow of a shallow liquid metal layer (GaInSn) driven by an array of small rotating permanent magnets located at the bottom of a cylindrical Plexiglas container. The explored magnet arrays vary from one single magnet up to five magnets eccentrically located at a distance of 42.2 mm from the rotation axis. The radial velocity component was recorded using Ultrasound Doppler Velocimetry (UDV).

1. Introduction

The main idea behind electromagnetic stirring is to create a rotational Lorentz force in a conducting fluid by the interaction of electric currents with an external magnetic field [1, 2]. Electric currents can be produced by applying a potential difference between electrodes in contact with the fluid or can be induced in the fluid by time-varying magnetic fields. In metallurgical applications the use of AC magnetic fields at frequencies smaller than 60 Hz is more common. These fields can be produced by applying an AC current through specially located arrays of coils that result in different magnetic field distributions. Depending on the position in which coils are arranged and/or the way in which current is injected, we may obtain a Traveling Magnetic Field (TMF) [3], a Rotating Magnetic Field (RMF) [4] or a combination of both. The possibility of creating a Lorentz force that stirs the fluid in a nonintrusive way is very important for many technological applications. For instance, the quality of the ingots in the metallurgical industry greatly depends on the solidification process. The homogeneity in the distribution of elements in the melt plays an important role in the physical and chemical properties of the alloy. During solidification, segregation of elements occurs, that is, conglomeration of elements at the interfaces, namely, the free surfaces or the walls. Segregation can be avoided by using pulsed magnetic fields [5] where the understanding of spin-up flows is very important. We refer as spin-up flow to the transient flow produced by an increment in the velocity of a fluid initially at rest or in steady state. In this case, the increment in velocity is induced by an AC magnetic field. Experimental and numerical results [6, 7] show that these fields are able to generate vortices that avoid segregation at the boundary layers by throwing elements from the interfaces to the center of the container, enhancing the mixing process.

The principal disadvantage of magnetic fields produced through AC or DC current in coils is the high consumption of electric energy. An interesting alternative is the use of magnetic fields generated by compact and efficient magnet arrays requiring no continuous energy expenditure [8]. Permanent magnets can be fully competitive with electromagnets for applications in which magnetic fields are up to 2 T [9]. Although magnet arrays can give rise to static or variable, and uniform or non-uniform magnetic fields, fields with rapid spatial variation cannot be achieved using permanent magnets. Their limited operation temperature is also a drawback; however, advances in material science have produced magnets that can work up to 500 °C [10, 11] and cryogenic technology could be used to increase this operating temperature limit as well as the magnetic field within a cryogenic temperature range [12]. The use of magnet arrays for electromagnetic stirring applications has been barely investigated [13, 14] and, in part, this is one of the motivations of the present work. We experimentally analyze the stirring of a liquid metal (eutectic alloy GaInSn) in a cylindrical container, achieved through the rotation of permanent magnets that are small compared with radius of the container, and located close to its bottom.

2. Experimental setup

An experimental device, whose detailed description can be found in Ref. [15], was designed to investigate the influence of different magnet arrays on the electromagnetic stirring of a liquid metal in a cylindrical configuration. The setup consists in an acrylic cylindrical container with an inner diameter of 197.2 mm filled with the ternary alloy GaInSn up to a height 13 mm. At the bottom of the cylinder, different arrays that vary from one single magnet up to five Neodymium magnets (12.7 mm diameter) are placed in a rotating external acrylic disc driven by an electrical motor. The magnets are located equidistantly from each other on a circumference of a fixed radius (42.2 mm) centered on the rotation axis. The supporting base is attached to a synchronous pulley and mounted over a bearing. This subsystem is coupled by a timing belt to a smaller synchronous pulley mounted in a motor. Figure 1 shows a sketch of the electromagnetic stirrer. The rotation frequencies of the magnets vary from 0.4 to 7.3 Hz and in all cases presented here the rotation is in clockwise direction. The strength of the magnetic field at the bottom of the GaInSn layer is 0.065 T. In order to diminish the oxidation rate of the liquid metal, a 4 mm layer of hydrochloric acid solution was poured above it. The experiment consists in rotating a given array of small permanent magnets so that the time-varying magnetic field induces Lorentz forces that are able to stir the liquid metal. It is of particular interest to determine if small disturbances produced by the rotation of localized magnets originate a global stirring of the liquid metal. The flow was characterized using the UDV technique, placing the ultrasound transducer outside the cylinder perpendicular to the container's wall so that the transducer axis points radially to the center of the cylinder at a height of 5 mm from the bottom of the GaInSn layer, and allows to measure the radial velocity component as function of space and time.

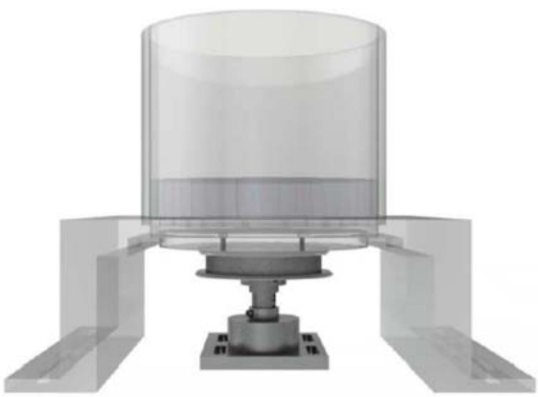

Figure 1: Sketch of the electromagnetic stirrer in cylindrical configuration.

3. Results

The measured signal of velocity shows repetitive patterns and, under certain conditions (i.e. characteristic rotation frequencies) oscillations of the free surface appear. In order to determine the characteristic frequencies of such phenomena, the Fast Fourier Transform

(FFT) analysis was applied to the velocity signal at every measured point. With these results we were able to find not only the characteristic frequencies, but also to discern approximately the global flow patterns. Although not presented here, the observed patterns indicate that during some time intervals the flow goes to the center of the cylinder and in a later time interval the fluid is driven to the cylinder walls [15]. Figure 2 shows the maximum value of the power spectra for all the analyzed penetration depths (i.e. positions along the ultrasound beam) corresponding to the flow generated by two magnets located at 42.2 mm from the cylinder axis, rotating at a frequency of 1.75 Hz. In this figure, the results of five different experiments are superposed so we can assure experimental reproducibility. A similar behavior was observed for the different magnet arrays and rotation frequencies explored. It is important to mention that experiments 4 and 5 in Figure 2 were performed without the hydrochloric acid solution layer. We observe that this layer does not affect significantly the dynamics of the flow. The experiments for all the explored magnet configurations and rotation frequencies show velocity patterns whose characteristic frequencies are always smaller than 0.6 Hz. In addition, it was observed that under certain experimental conditions the system resonates and its surface begins to oscillate at frequencies higher than 1 Hz. In order to distinguish all the characteristic frequencies of the flow, the plots were divided in two sections: one from 0 to 0.65 Hz approximately, where the bulk flow frequency (BFF) and its harmonics appear, and from 0.65 to 7 Hz, corresponding to the free surface oscillation (FSO) frequency. In Figure 2, the first peak corresponds to the bulk flow frequency while the second one represents its first harmonic. In turn, the peak in the second section of the plot (frequencies > 0.5 Hz) corresponds to the free surface oscillation frequency (FSOF). As we are only showing the maximum of the power spectrum along the whole penetration depth, it must be pointed out that the bulk flow frequency is not observed nor in the central region of the container (80 - 120 mm) neither close to the cylinder walls (0-30 mm and 170-200 mm); while the FSOF is observed all along the measured line since a backward and forward movement is produced.

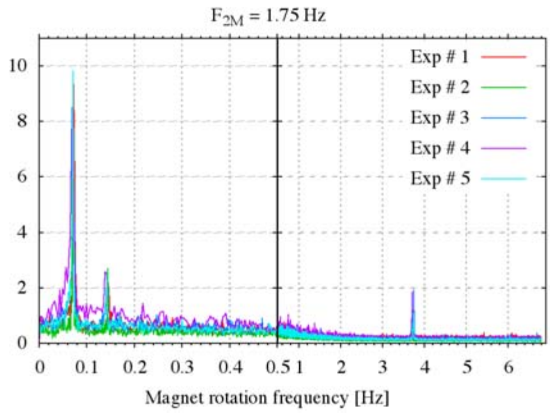

Figure 2: Maximum values of power spectra for the experiments performed with two magnets rotating at a frequency of 1.75 Hz. Note that the frequency axis was shrunk in order to show the peak at 3.8 Hz.

Figure 3 shows the bulk flow frequency and free surface oscillation frequency as a function of the magnet rotation frequency for all experiments with all magnet arrays when magnets are placed at 42.2 mm from axis. We observe an increase in the characteristic bulk flow frequencies as the magnet rotation speed is increased. We notice that as we increase the number of magnets the BFF does not grow linearly. This can be seen by defining the normalized frequency as the BFF divided by the number of magnets. For a magnet rotation frequency (MRF) of 6.06 Hz and one magnet, the normalized frequency is 0.115 Hz, and it decrease for two magnets to 0.093 Hz. This value increases to 0.136 Hz when three magnets are used and diminishes up to 0.105 Hz for five magnets. Then for an array of two magnets, we have a local minimum and for three magnets a maximum. The latter can be considered as a global maximum due to the fact that if we increase the number of magnets and all of them have the same orientation, the distribution of the total magnetic field will tend to diminish the inhomogeneities in the direction of rotation of the array (the resulting magnetic field will tend to that produced by a ring shaped magnet) and eventually a more homogeneous and less intense motion will be produced. We should remember that the maximum number of magnets that we can use is limited by the shape, size and arrangement of the magnets, as well as the rotation radius. Finally, if we use a disordered array of magnets (that is, with not equidistant location and unsorted magnetic pole orientation), the resulting bulk flow frequencies will be smaller than the corresponding values obtained with an ordered array. In addition, if the magnets are close to each other the resulting effect will be similar to the produced by a smaller number of magnets. When we look at the FSO frequencies produced by this disordered array, we observe that depending on the MRF the free surface oscillates at frequencies that follow the tendency lines of other ordered arrays, in this case arrays of 1, 2 or 4 magnets (see Figure 3).

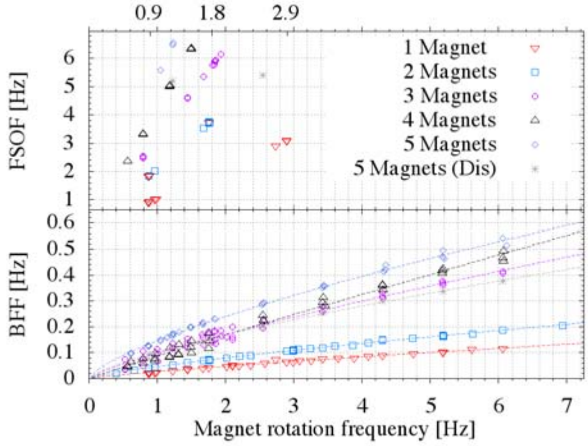

Figure 3: Bulk flow frequency (BFF) and free surface oscillation frequency (FSOF) as a function of magnet rotation frequency for all magnets arrays rotating at 42.2 mm from the axis. The notation (Dis) corresponds to the disordered array of 5 magnets.

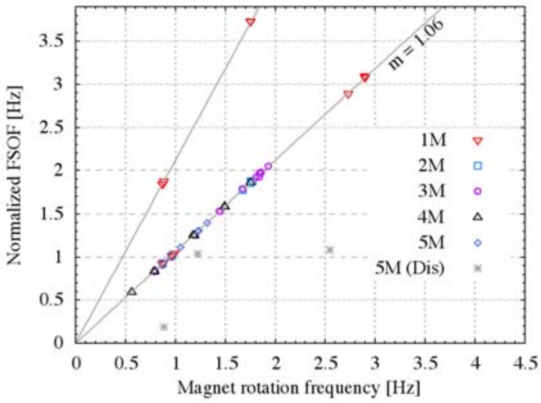

Figure 4: Normalized free surface oscillation (FSO) as function of magnet rotation frequency. Linear fitting lines correspond to $y = mx$, and $y = 2mx$, where $m = 1.06$ is the slope of the fitted line.

Figure 4 shows the normalized FSOF as a function of the magnet rotation frequency. We observe that the majority of the normalized frequencies corresponding to ordered arrays, adjust to a linear fitting with a slope $m = 1.06$. Additionally, it is found that for the explored rotation radius of 42.2 mm only one harmonic appears when one magnet is used. It is important to notice that as the number of magnets is increased the maximum MRF at which

FSO occurs decrease. So, in general we can say that as MRF is increased, the characteristic bulk frequencies also grow. But bulk frequencies do not grow linearly as the majority of the FSOFs do. From Fig. 4, we may conclude that most of the experiments in which oscillations of the free surface occur have a linear behavior in the sense that when we plot the normalized FSOF of all experiments, if exist, they fit to the same tendency line.

4. Conclusion

The experimental analysis of an electromagnetic stirring device based on a rotating localized magnetic field was carried out. The flow takes place in a cylindrical container where a shallow liquid metal layer is driven by Lorentz forces induced in the fluid by the rotation of different arrays of small permanent magnets. The goal of this study was, on the one hand, to explore if small perturbations produced by the rotation of localized magnetic fields can produce a global stirring of the liquid metal and, on the other, to characterize the flow quantitatively. Fast Fourier Transform analysis of the velocity signals obtained with the UDV along a diameter of the cylindrical container was used to determine characteristic frequencies of the flow structures. These experiments showed that the motion of localized magnetic fields in different configurations is able to produce a global perturbation on the bulk and free surface of the liquid metal. Future work will be focused on the characterization of the flow patterns produced by the different arrays of magnets and to determine the characteristic flow regions where energy is mainly transferred.

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5. References

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