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Numerical and experimental study of liquid metal stirring by rotating permanent magnets

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Abstract

In this work, we study liquid gallium stirring by rotating permanent magnets. We demonstrate possibility of easily creating different flow patterns by rotating permanent magnets, which can be industrially important for controlling heat and mass transfer processes in the system. Unlike the typical approach of simulating magnet rotation as a transient problem and time-averaging the Lorentz forces, we solve the magnet rotation as a harmonic (frequency domain) problem, which leads to forces equal to time-averaged ones and decreases the simulation time considerably. Numerical results are validated using qualitative flow structure results from the neutron radiography visualization of tracer particles and quantitative data from Ultrasound Doppler velocimetry.

Keywords: magnetohydrodynamics, liquid metal stirring, neutron radiography, UDV, numerical modelling

Introduction

In metallurgy, melt stirring is used to intensify heat and mass transfer processes, as well as chemical reactions, to improve final product quality. Different methods of stirring can be employed, such as gas bubble flow [1] or electromagnetic stirring [2]. Among electromagnetic stirring techniques, moving permanent magnet systems have advantages over, for example, travelling magnetic fields provided by AC inductors, since no heat is lost to coil heating and different field configurations can be achieved with simpler and smaller setups.

Nowadays, numerical modelling is an important part of industrial process design and improvement, as it can help understanding phenomena and system characteristics that are difficult to study experimentally or theoretically, such as melt flow instabilities. However, numerical models usually require experimental validation. Recently, application of neutron radiography for liquid metal flow visualization has been reported [3]. This opens up new possibilities of numerical model validation, as two-dimensional (or three dimensional with specific configurations of neutron beams) images of flow structures can be obtained, unlike with conventional flow measurement methods, such as Ultrasound Doppler velocimetry (UDV).

In this work, we concentrate mostly on numerical modelling of liquid metal stirring by rotating permanent magnets, trying to obtain flow structures as seen in the neutron experiments. Different possible flow configurations are demonstrated. Since Particle Image Velocimetry (PIV) analysis of tracer particles is not in a good agreement with numerical results [4], we perform Ultrasound Doppler Velocimetry measurements for quantitative validation.

System description and numerical model

The scheme of main liquid gallium stirrer under investigation is shown in Fig.1. It consists of 10x10x3cm glass container with gallium (density 6080 kg/m^3, viscosity 1.97 mPa·s, conductivity 3.7 MS/m) and four cylindrical permanent magnets (remanence 1.4 T) attached to electric motor. The magnets are cylinders magnetized perpendicular to their axes. Magnet positions are fixed relative to the vessel, but their direction of rotation and gallium level in the vessel can be changed. This system was used in the neutron radiography experiments. Basically, the experimental procedure was neutron beam striking the vessel perpendicular to its plane and transmitted neutrons being detected behind the vessel. The acquired data was shadow images of contrast particles entrained in the gallium flow. Further details of the experiments and methodology can be found in [3].

The system shown in Fig.2 is used only for quantitative validation against UDV measurements.

The numerical model contains liquid gallium volume, the magnets and air around them. The fluid is driven by Lorentz force:

$$\vec{f_L} = \vec{j} \times \vec{B} = \sigma\left(-\frac{\partial \vec{A}}{\partial t} + \vec{v} \times \vec{B}\right) \times \vec{B} \tag{1}$$

where $\vec{j}$ – current density, $\vec{B}$ – magnetic flux density, $\vec{A}$ – magnetic vector potential, $\vec{v}$ – fluid velocity.

The electromagnetic part of the simulation is performed in *Elmer* [5], which solves the Maxwell's equations in potential formulation using the finite element method, but fluid dynamics in *OpenFOAM* [6], which solves the Navier-Stokes and k-ω SST turbulence model equations using the finite volume method. The coupling is achieved with the an open-source code *EOF*-Library [7], which effectively transfers data between *Elmer* and *OpenFOAM*.

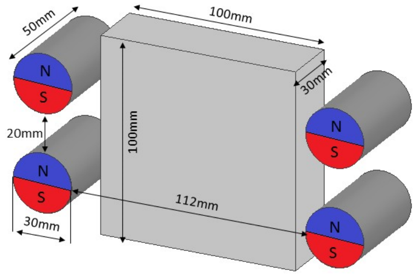

Fig. 1: Main stirrer under investigation

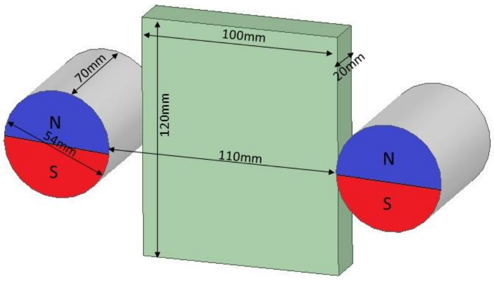

Fig. 2: Stirrer for UDV validation

In this work, we consider the magnet rotation in quasi-stationary approximation (frequency domain), where permanent magnet rotation is modelled by setting real and imaginary parts for magnetization components. It was tested that in such a way obtained Lorentz force is equal to time-averaged one. This approach considerably decreases simulation time compared to transient magnet rotation computation and performing time-averaging.

The $\vec{v} \times \vec{B}$ term is computed directly in *Elmer*, with velocity field imported from *OpenFOAM*. The coupling algorithm used to obtain velocity coupled Lorentz force is shown in Fig.3, where superscript *i* designates coupling iteration. Usually, no more than three coupling iterations are needed to achieve converged force distribution.

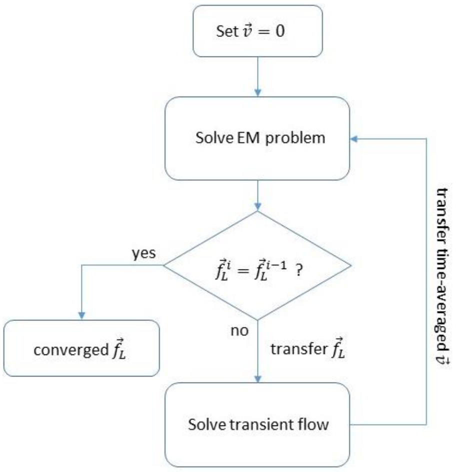

Fig. 3: Algorithm to compute velocity coupled Lorentz force

Electromagnetics mesh consists of 240422 elements, but fluid dynamics of 37500 elements. No-slip boundary condition is applied to all walls, free surface is fixed (modelled as a wall) and standard wall functions are used for boundary layer resolution. For the main system under investigation (Fig.1) two gallium filling levels are considered – 100mm and 75mm with two magnet rotation configurations as shown in Fig.4. The second system (Fig.2) is used only for comparison to UDV measurements, in which case the gallium level is 120mm and the magnets are counter-rotating (left one clockwise, the right one counter-clockwise).

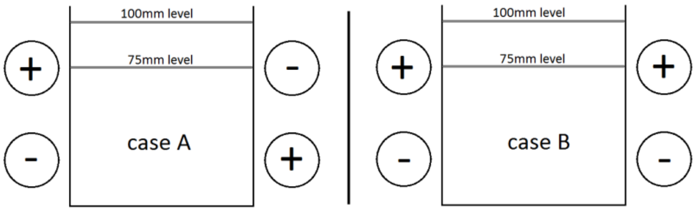

Fig. 4: Considered cases; “+” means clockwise, “-“means counter-clockwise

Results

One of the goals of the current study is to validate numerical models, both qualitatively and quantitatively. Quantitative validation cannot be achieved using PIV analysis of neutron radiography of tracer particle movement [5], therefore we resorted to traditional methods of measurement. The measurements were performed in system shown in Fig.2. Simulation results in comparison to UDV measurements on a vertical line near the vessel side wall (where velocity has maximum) for magnet rotation frequency 3.18Hz are shown in Fig.5. Quantitatively, the results agree well. The curve shape disagreement can be due to instabilities – vortex transitions in permanent magnet stirred flows have been reported in the past [8] and the lifetime of some specific vortical configuration can be longer than the time UDV measurements were averaged over.

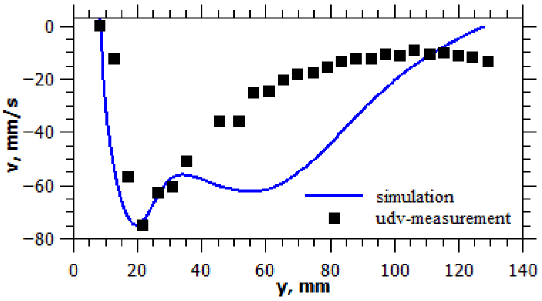

Fig. 5: Velocity on vertical line near vessel side wall

Another goal of the current work is demonstrating, by neutron radiography and numerical simulation, different stirring regimes achieved by rotating permanent magnets. The following figures contain simulated velocity vectors in vertical cross section in the middle of the vessel and still frames from the neutron radiography. Since the still neutron images don’t reveal flow structures, vortex directions are indicated as arrows (the flow can be seen in videos shown in presentation), although the flow direction near the surface can be deduced from particle distribution (darker areas).
Fig.6 and 7 are results of 100mm filling level for magnet rotation case A, Fig.8 and 9 is with 75mm filling for case A. To demonstrate other possible flow structures, Fig.10 and 11 shows simulated velocity results for case B (Fig. 4) with 100mm and 75mm gallium level, respectively. Magnet rotation frequency for all cases is 21Hz.

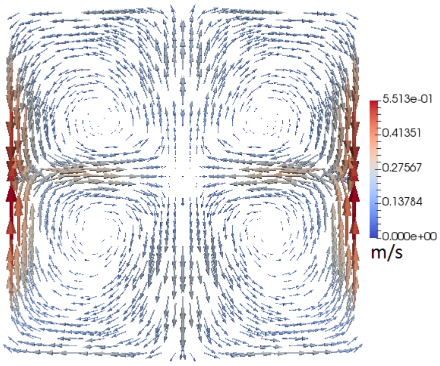

Fig. 6: Case A, gallium level 100mm, simulation

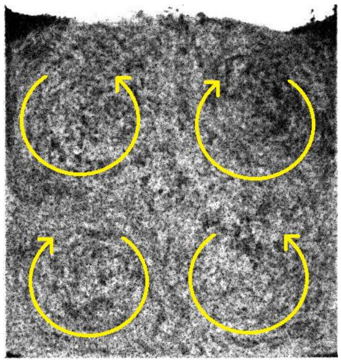

Fig. 7: Case A, gallium level 100mm, neutron radiography

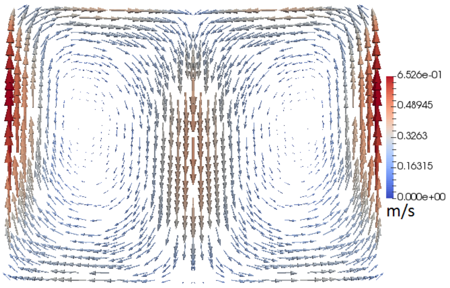

Fig. 8: Case A, gallium level 75mm, simulation

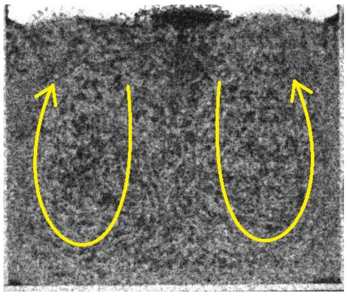

Fig. 9: Case A, gallium level 75mm, neutron radiography

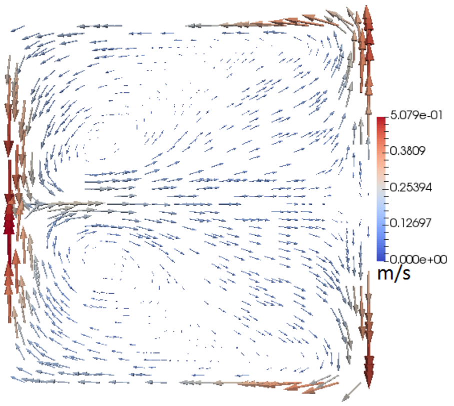

Fig. 10: Case B, gallium level 100mm, simulation

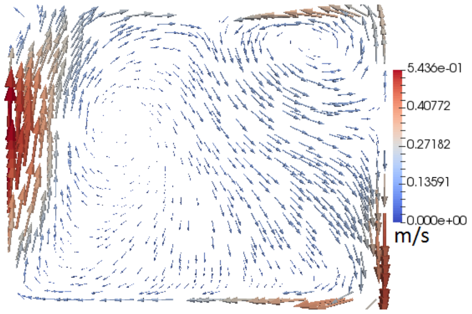

Fig. 11: Case B, gallium level 75mm, simulation

Such simple four magnet system can obviously provide many different flow patterns. Compared to EM stirring by fields produced by inductor coils, permanent magnet systems are more energy efficient and flexible regarding setup and desirable magnetic field distribution. For industrial applications, it means that if flow field can be easily controlled, so can other parameters, such as temperature and inclusion concentration distribution. However, although high Curie point materials exist, usage of permanent magnets for stirring high temperature melts is still limited.

Conclusions

This paper is concerned with numerical simulation of liquid metal stirring by means of rotating permanent magnets. Qualitative validation was done using images from neutron radiography of tracer particles entrained in gallium flow and velocity magnitude validation was achieved using UDV measurements.

An improvement of simulation time was achieved by modelling the magnet rotation in quasi-stationary approximation, that is, solving the EM problem in frequency domain, which leads to Lorentz force density identical to time-averaged one. Even more advantages are provided by using free open-source software, which does not have any license limitations and therefore can be run on large computer clusters.

Different flow configurations easily achievable by rotating permanent magnet system were demonstrated numerically and by neutron radiography visualization of tracer particles. For industrial applications, the ability to easily and controllably create different flow patterns can be useful in controlling process parameters, for example, temperature and concentration distributions.

References

1. J. Wannasin et al., Scripta Materialia 55 (2006) pp. 115–118
2. S. Eckert et al., Metallurgical and Materials Transactions B, Vol. 39 (2008), pp. 374–386
3. M. Scepanskis et al., Metallurgical and Materials Transactions B, Vol. 48 (2017), pp. 1045-1054
4. V. Dzelme, et al., Proceedings of XVIII International UIE-Congress, Hannover, Germany, 2017, pp. 362-367
5. ElmerFEM, https://www.csc.fi/web/elmer
6. OpenFOAM, https://openfoam.org
7. EOF-Library, https://eof-library.com
8. V. Dzelme et al., Proceedings of the 10th PAMIR International Conference, Cagliari, Italy, 2016, pp. 252-256