LIQUID METAL FLOW INDUCED BY COUNTER-ROTATING PERMANENT MAGNETS IN A RECTANGULAR CRUCIBLE

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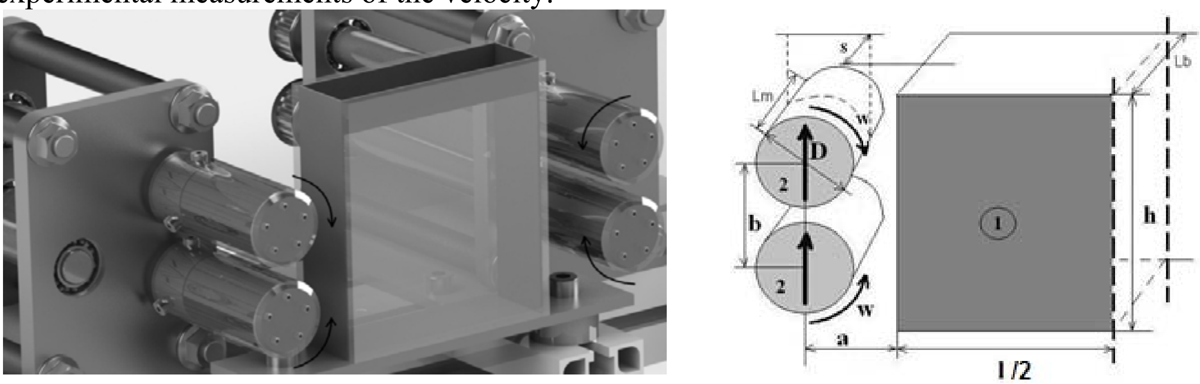
Abstract: The present paper reports the first step of research project, which contains a fundamental numerical investigation of the flow of liquid gallium in the system of 4 counter-rotated cylindrical magnets and an innovative neutron radiography experiment. The design of the experimental set-up is reported. Numerical aspects of the modeling of such a system as well as preliminary results are demonstrated.

1. Introduction

The paper will consider the flow of liquid metal, which is induced by a system of four counter-rotating cylindrical Nd-Fe-B magnets (see fig 1). A liquid metal stirrer based on rotating permanent magnets has been proposed by A. Bojarevičs & Beinerts [1]. The mentioned reference contains an analytical expression for a magnetic field and an iterative solution for the flow velocity in the limits of a two-dimensional model as well as experimental measurements of the velocity.



(a) (b)

Figure 1: design of the liquid metal stirrer with four counter-rotating magnets. (a) magnets and a liquid metal vessel; (b) scheme for mathematical modeling (1 – rectangular liquid metal container, 2 – cylindrical magnets).

Generally, the proposed electromagnetic (EM) system produces in a rectangular crucible the flow of a topology that is similar to that in an induction crucible furnace (ICF) that is widespread in metallurgy for melting and stirring of secondary metals. The classical approach is used in such stirrers: alternative current in a solenoidal inductor around a crucible induces current in a melt and a magnetic field that results in a Lorenz force that moves the liquid metal and forms counter-rotating vortices. Permanent magnet systems are very rare in industrial metallurgical applications due to the temperature limitation imposed by the magnets; however, recent and still unpublished A. Bojarevičs' and Beinerts' inventions found also an industrial use of such a technology for stirring of aluminum. Moreover, an application of rotating cylindrical magnets for pumping of aluminum is reported [2,3] and liquid metal pumps with magnets integrated in a single rotating cylinder or a double disk is also well-known (see, e.g., [4]).

Homogenization of solid inclusions in the ICF as an application of a stirrer is of industrial interest. Such processes were simulated using Large Eddy Simulated (LES) method by Ščepanskis et al. [5]. However, an experimental investigation of particles in turbulent flow of liquid metal is an extremely complicated challenge and only last year the first attempt to measure a particle concentration field in a small ICF has been done [6]. Nevertheless, the mentioned experiment was able to measure the concentration field only at the dynamically equilibrium stage.

Therefore, an experiment using neutron tomography technology (see, e.g., [7]) is proposed now. Unfortunately, due to technical limitations an ICF is not suitable for such an experiment. So, we decided to use the aforementioned permanent magnet system to produce the motion of liquid metal like in the ICF and to investigate the particles there. Such a permanent magnet system can also represent some other metallurgical application for stirring and pumping of liquid metal. The experiment is planned to be carried out on 25-27 of July, 2014 at Paul Scherrer Institute (Switzerland), while the present paper will demonstrate a design of the experimental set-up and numerical investigations of the flow in the rectangular vessel highlighting relevant numerical aspects.

2. Design of the stirrer

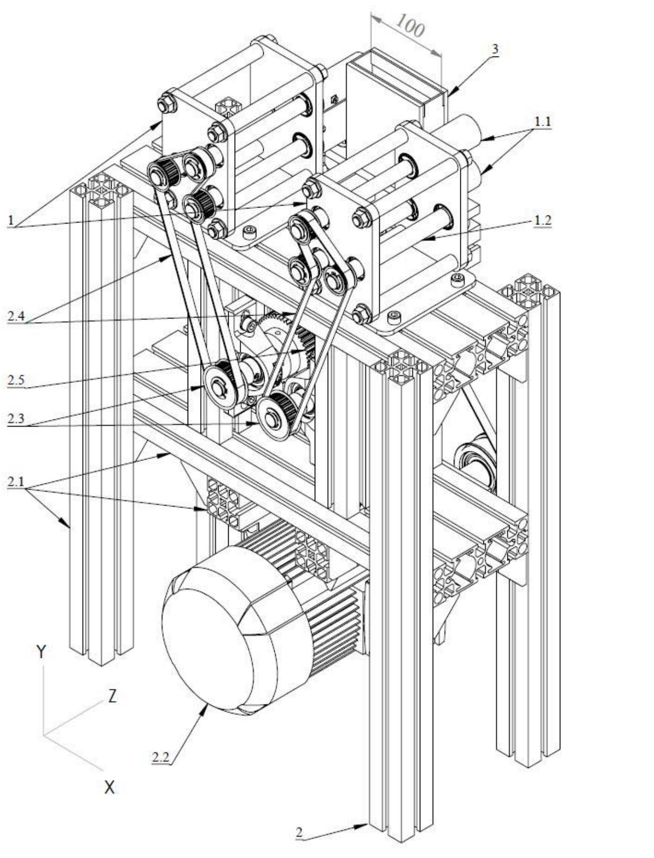


Figure 2: A sketch of the experimental set-up.

The stirrer consists of the three main units: 1) a block of shafts with rotating magnets on one side and belt pulleys on the other side; 2) a frame with a motor and driving elements, gears and pulleys; 3) a rectangular vessel with glass walls on the front and the back sides, a small heating element on the bottom. The mentioned units are marked on fig 2.

A rectangular vessel for liquid metal (marker 3 on fig 2) is made out of quartz which is a transparent material for neutrons. Inside dimensions of the vessel are 100 x 100 x 30 mm. The stirrer is constructed in such way that nothing disturbs the neutron beam, it only has to pass 2 mm thick glass.

Gallium is expected to be used for the experiment because of its relative transparency for neutrons. It is also important that no radioactive waste is expected after the limited irradiation of the gallium by neutrons. The melting temperature of this metal is 30°C, therefore, a very simple heater is integrated in the construction below the vessel of the liquid metal.

The blocks 1 (fig 2) hold shafts with the cylindrical permanent magnets (1.1) that are magnetized as it is shown on fig 1b (arrows). The magnets are covered with stainless steel cups and bolted to the common shafts. Each shaft is supported by two bearings and ends with a pulley. The third shaft (1.2), which also holds an additional pulley, is necessary for the belt connection. The whole block is moveable in the X direction (see fig 2) to carry out different experiments. Most parts of the mentioned details, including the bearings, are made of stainless steel.

The unit 2 (see fig 2) consists of aluminum and stainless steel profiles (2.1), an electric motor (2.2), shafts in the middle level of the construction (2.3) that are necessary to drive both double-sided belts (2.4). These shafts have pulleys on each side and spur gears (2.5) to change the direction of rotation of the paired shaft.

Sizes of the different element of the set-up (see marking on fig 1b) are as follows: 1) due to neutron radiography limitations the sizes of the liquid metal vessel are l = 10 cm, h = 10 cm, L_b = 3 cm; 2) the available magnets have D = 3 cm, L_m = 5 cm; 3) positions of the magnets are optimized so that b = 5 cm, a = 4 cm (subject to change in a case of necessity), s = 0.

3. Numerical simulation

A block diagram of a general algorithm, which is implemented in the present investigation, is shown on fig 3. The EM field of the system and, consequently, the Lorenz force distribution

$$\mathbf{f}=\mathbf{j}\times\mathbf{B}\ ,$$

in the liquid metal are calculated non-stationary and then averaged during a turnover period of the magnets. Generally, current density j is defined as follows: $\mathbf{j}=\sigma(\mathbf{E}+\mathbf{v}\times\mathbf{B})$, where σ, $\mathbf{v}$, $\mathbf{E}$ and $\mathbf{B}$ denote here conductivity of material, velocity of conductive liquid, an electric field and magnetic flux density. The magnetic Reynolds number Re_m << 1; therefore, an induction term ($\mathbf{v}\times\mathbf{B}$) can be neglected, while E is determined by a changing magnetic field of the rotating magnets described by the Maxwell's equations. Nevertheless, the equations of the EM field to be solved in a frame of the moving liquid and the solution should be corrected by taking into account the velocity field iteratively.

So, it becomes clear that the algorithm, which is illustrated on fig 3, have a couple of purely numerical degrees of freedom that have to be carefully investigated to avoid their influence on the result.

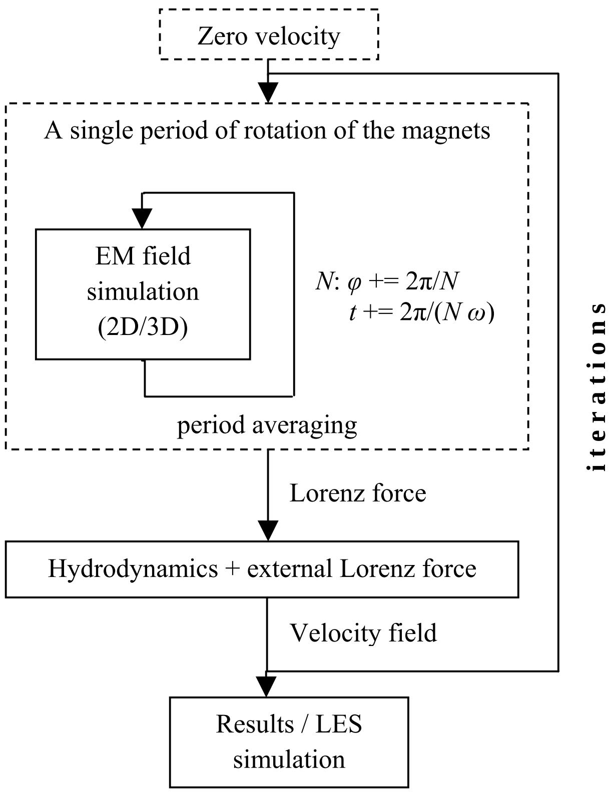
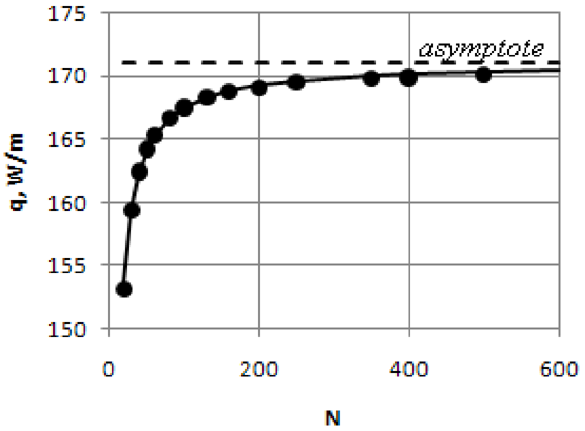


Figure 3: The block diagram of the numerical algorithm. N denotes a number of time steps within the turnover period; φ, t, ω are the rotation angle, time, angular velocity.

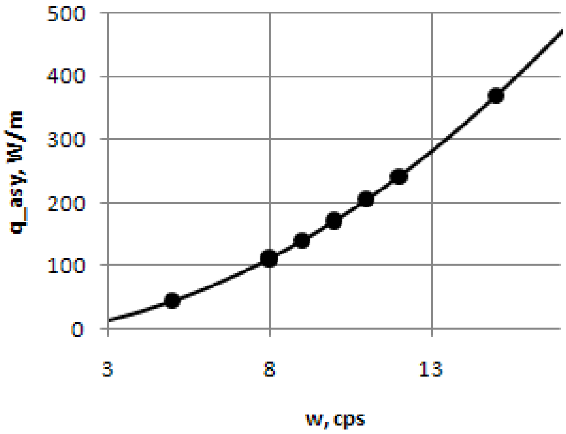
First of all, it is N – the number of time steps within the single period of rotation of the magnets, which is the most important numerical parameter. Fig 4 shows Joule heat induced in the melt as a function of N in the case of a 2D simulation (the results are shown for a case of zero velocity field – an initial step of the iterative algorithm). It is clear from fig 4a that the induced power per length unit of the restricted third direction increases monotonously with increasing N and can be described with an exponential function (see the curve on fig 4a):

$$q(N) = q_{asy} e^{-k/N}, \quad (1)$$

where q_{asy} is the asymptotic value that is in fact the real induced heat value; k is a convergence parameter that depends on the rotation speed ω. Since the functional dependence $q(N)$ is known, the asymptotic (real) value can be reconstructed from only few points at low N using the least square method in order to avoid very long calculations in a 3D case. Fig 4b shows a quadratic dependence of the induced heat q_{asy} on ω that is theoretically expected. The influence of other numerical parameters is insignificant in the case of enough resolution.



(a)



(b)

Figure 4: results of the 2D modeling of the system that is shown on fig 1b; (a) induced heat power in the melt as the function of the numerical parameter N, (b) asymptotic value (see left figure) of the induced heat depending on the angular speed of the magnets.

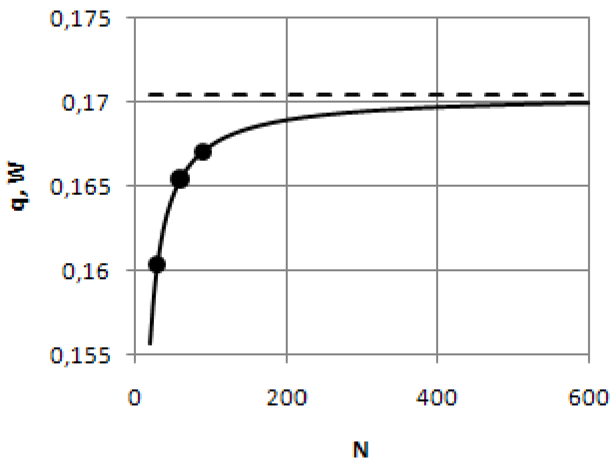


Figure 5: reconstruction of the real value of induced heat according to the function (1) in 3D case; ω = 10 cps.

Fig 5 demonstrates the results of 3D calculations (the geometric parameters of the system used in this calculation are mentioned at the end of the Section 2) for ω = 10 cps. It seems to be unrealistic at first glance that the induced heat in the 3D case is less than 4% of that in the 2D case multiplied by the length of the 3rd direction L_b = 3 cm (compare asymptotic values on fig 4a and fig 5). However, taking into account the small thickness of the vessel L_b, it becomes clear that the induced current in the thin layer of liquid metal is hard to close without significant loses. Therefore, this case dramatically differs from the 2D case that in fact means current closure at infinity. Increasing L_b and L_m 10 times we obtained the result for the 3D case to be approximately 80% of that in the 2D case. Thus the previously mentioned result for the 3D case seems to be reliable.

Another numerical parameter, which definitely influences the result, is the number of iterations that take into account the reduction of the induction effect in a movable metal (see the scheme on fig 3). This part of numerical simulation is still in progress since 3D calculation is very time consuming.

Therefore, we can demonstrate now only the velocity distribution in liquid metal in the quasi-2D case that, however, significantly overestimates the force and, consequently, the velocity of the induced flow as it was already discussed. The quasi-2D denotes here LES 3D hydrodynamics based on 2D EM calculation. Fig 6 demonstrates the topology of the time-averaged flow but the magnitude is not shown because of the discussed overestimation of the 2D case. The figure shows an interesting structure of the flow, which consists of 3 vortices instead of the expected 4 eddies. We suspect it can be a result of hydrodynamic instabilities, probably characteristic of such a system. A. Bojarevičs experimentally observed the same structure with changing direction of the central eddy along two diagonals sequentially with a period of several minutes (unpublished results). Therefore, the averaging for a 70 s long period, which is demonstrated on fig 6, cannot represent the mentioned changes.

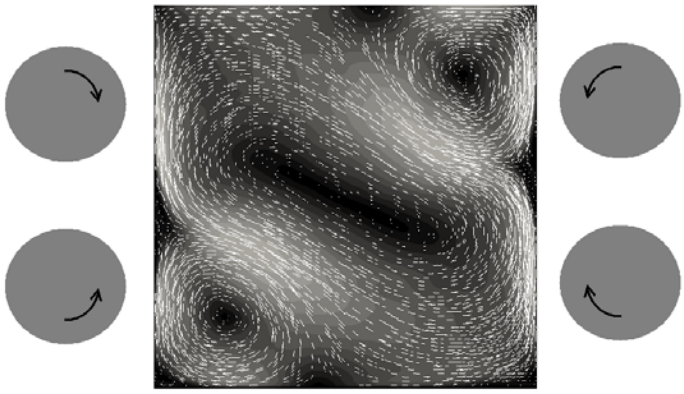


Figure 6: Topology of the time-averaged flow of liquid gallium in the system of four counter-rotated cylindrical magnets.

4. Conclusions & further plans

The experimental set-up of the four counter-rotated cylindrical magnets is designed to represent the multi-eddy structure of liquid metal flow like in wide-spread metallurgical applications.

At the beginning of the numerical investigation of such flows the significance of 3D EM calculation and the number of numerical steps of transient calculation within the single period of the magnet rotation were recognized. Fundamental numerical research of the flow including full 3D LES simulation of turbulence and the innovative neutron radiography measurements are the next steps.

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6. References

[1] Bojarevics, A.; Beinerts, T.: Experiments on liquid metal flow induced by a rotating magnetic dipole. Magnetohydrodynamics. 46 (2010) no. 4 333-338.

[2] Beinerts, T.; Bojarevics, A.; Gelfgat, Yu.; Bucenieks. I.: Linear permanent-magnet pump and stirrer for molten aluminium. J. Iron Steel Res. Int.. 19 (2012) suppl. 1 528-530.

[3] Bojarevičs, A.; Gelfgats, J.; Beinerts, T.; Bucenieks, I.: Metāla sakausējuma sūknē□anas un maisī□anas peņēmiens un iekārta tā realizē□anai. Patent LV 14404 B, 20.10.2011 (in Latvian).

[4] Bucenieks, I.; Kravalis, K.: Efficiency of EM induction pumps with permanent magnets. Magnetohydrodynamics. 47 (2011), no. 1 89-96.

[5] Ščepanskis, M.; Jakovičs, A.; Nacke, B.: Homogenization of non-conductive particles in EM induced metal flow in a cylindrical vessel. Magnetohydrodynamics. 46 (2010), no. 4 413-423.

[6] Ščepanskis, M.; Jakovičs, A.; Baake, E.; Nacke, B.: Solid inclusions in an electromagnetically induced recirculated turbulent flow: simulation and experiment. Int. J. Multiphase Flow, in press (2014), doi: http://dx.doi.org/10.1016/j.ijmultiphaseflow.2014.04.004.

[7] Tremsin, A.S.; McPhate, J.B.; Vallerga, J.V.; Siegmund, O.H.W.; Bruce Feller, W.; Lehmann, E.; Kaestner, A.; Boillat, P.; Panzner, T.; Filges, U.: Neutron radiography with sub-15 μm resolution through event centroiding. Nuclear Instr. Meth. Phys. Res. A. 688 (2012) 32-40.