Numerical modelling of liquid metal electromagnetic pump with rotating permanent magnets

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Abstract

In this work, we study rotating permanent magnet based liquid metal pump. Full 3D model of the pump is created and different approaches to electromagnetic force computation are investigated. First, we seek a possibility to model the permanent magnet block consisting of many separate magnets as a single block with equivalent analytically prescribed magnetization. Second, different approaches regarding coupling of electromagnetic field to fluid dynamics simulation are considered. Main results show that for pump integral parameter calculation, time-dependent coupling is not necessary, although it can lead to different velocity and turbulent structure distribution in the channel.

Keywords: magnetohydrodynamics, liquid metal pump, simulation

Introduction

For liquid metal transportation, electromagnetic pumps (EMP) have an advantage over mechanical pumps in channel hermetization and the absence of moving parts in the melt. Among EMPs, permanent magnet based ones have an advantage over, for example, linear induction or conduction pumps regarding setup flexibility, the absence of electrodes or windings and overall pump efficiency [1].

Generally, pump performance is described by $p-Q$ characteristics, which are curves showing the relation between developed pressure difference $\Delta p$ and flow-rate $Q$. Previous studies of electromagnetic pumps are mostly analytical estimations and experimental measurements of those integral parameters [1, 2]. Such approaches, although usually giving reasonably correct $\Delta p$ and $Q$, do not give specific information about velocity distribution, turbulence and instabilities. Numerical modelling, on the other hand, can give information about pump operation and flow field, leading to greater understanding of various processes and instabilities and consequently to improvements of pump design and operation.

There have been efforts in EMP numerical modelling, but, as pump setups are usually quite complex, simulations are heavily limited by computer resources, requiring many simplifications to be made. Rotating permanent magnet EMP simulation in 2D was performed in [3], which could correspond to pumps with very high aspect ratios of channel width to height. Liquid metal flow driven by travelling magnetic field in a straight channel was investigated numerically in 3D in [4], showing good developed pressure agreement to analytical estimations. More realistic 3D simulations of a disk-type permanent magnet pump are found in [5], using an iterative electromagnetics – fluid dynamics coupling algorithm to acquire time-average velocity distribution. The iterative algorithm is quite time consuming and it would be virtually impossible to apply it to time-dependent coupling.

In this work, we study rotating permanent magnet based liquid metal pump numerically in 3D. First, we seek a possibility to model the permanent magnet block consisting of many separate magnets as a single block with equivalent analytically prescribed magnetization. Second, different approaches regarding coupling of electromagnetic field to fluid dynamics simulation are considered.

System description

The pump is located at the Institute of Physics, University of Latvia in Salaspils, Latvia. It is used for research purposes and smaller commercial pump testing. Picture of the active part is shown in Fig. 1.

Melt in the channel is Pb-Bi eutectic at 523K (relevant material properties are given in Tab.1). Channel walls, magnet rotor core, shell around the rotor and other parts are made of stainless steel. Below the channel is a laminated iron yoke with relative magnetic permeability $\mu=100$. The permanent magnet rotor consists of 20 permanent magnets arranged in a Halbach array (see Fig.3). Each permanent magnet remanence is $B_r=(1.39\pm0.03)$ T.

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Table 1. PbBi properties at 523K

| Property       | Value          |
|----------------|----------------|
| Density, \( \rho \) | 10430 kg/m\(^3\) |
| El. conductivity, \( \sigma \) | 8.6 \times 10\(^5\) S/m |
| Viscosity, \( \mu \) | 2.20 mPa\(\cdot\)s |

**Numerical model**

The electromagnetic pump is a complex multiphysical system that includes electrically conductive fluid flow, time-varying magnetic field and electric currents and the mutual interaction of those phenomena, mainly in the form of Lorentz force density (fluid driving force) and Joule heat. The electromagnetic part of the simulation is performed in Elmer [6], which solves the Maxwell’s equations in potential formulation using the finite element method, but fluid dynamics in OpenFOAM [7], which solves the Navier-Stokes and, in this work, k-\(\omega\) SST turbulence model equations using the finite volume method. The coupling is achieved with the EOF-Library [8], which effectively couples Elmer and OpenFOAM and is an open-source library itself.

Generally, the current density and magnetic field in this system is, respectively,

\[
\mathbf{j} = \sigma \left( -\frac{\partial \mathbf{A}}{\partial t} + \mathbf{v} \times \mathbf{B} \right)
\]

(1)

\[
\mathbf{B} = \mathbf{B}_0 - \mathbf{B}_i - \mathbf{B}_v,
\]

(2)

where \( \mathbf{j} \) – current density, \( \mathbf{B} \) – magnetic flux density, \( \mathbf{B}_0 \) is magnetic field of the permanent magnets, \( \mathbf{B}_i \) is secondary magnetic field created by the \( \sigma \frac{\partial \mathbf{A}}{\partial t} \) current (\( \mathbf{A} \) – vector potential) and \( \mathbf{B}_v \) is magnetic field created by the \( \sigma (\mathbf{v} \times \mathbf{B}) \) term. \( \mathbf{B}_i \) and \( \mathbf{B}_v \) oppose the primary field \( \mathbf{B}_0 \), hence they are subtracted from it.

There are two ways of taking the \( \mathbf{v} \times \mathbf{B} \) term into account. The simplest is to compute electromagnetic problem for static fluid, then transfer current density and magnetic field to flow simulation adding \( \sigma (\mathbf{v} \times \mathbf{B}) \) to the imported current density. This approach leads to neglecting of \( \mathbf{B}_v \) in formula (2) and to underestimation of Lorentz force, as explained in [9]. The correct approach is to solve the electromagnetic problem in its entirety importing velocity from fluid dynamics simulation and iteratively (or every time-step) updating the Lorentz force in fluid flow simulation. Approaches used in this work are summarized in Tab. 2.

| \( \Sigma \) | \( \delta \) | \( \varepsilon \) |
|-------------|-------------|-------------|
| Constant instantaneous \( \mathbf{j} \) and \( \mathbf{B} \); \( \mathbf{v} \times \mathbf{B} \) computed in fluid simulation |
| Time-dependent coupling; \( \mathbf{v} \times \mathbf{B} \) computed in fluid simulation |
| Time-dependent coupling; \( \mathbf{v} \times \mathbf{B} \) computed in electromagnetic simulation |

Numerical model corresponding to active part of the pump was created as shown in Fig. 2, with cross-section in Fig. 3.

In the beginning of the results section it will be shown that the rotating magnet block consisting of many magnets can be equivalently modelled as a single piece with analytically prescribed remanence components:

\[
\mathbf{B}_{rx} = B_r \sin \left( \omega t + (n - 1) \arctg \left( \frac{\mathbf{y}}{\mathbf{x}} \right) \right)
\]

(3)

\[
\mathbf{B}_{ry} = B_r \cos \left( \omega t + (n - 1) \arctg \left( \frac{\mathbf{y}}{\mathbf{x}} \right) \right)
\]

(4)

where \( n \) – periodicity (in this case \( n=5 \)), \( \omega \) – magnet block rotation frequency, \( t \) – time.
Electromagnetics mesh consists of about 3M finite elements in 3D and 200k in 2D simulation. For simplicity channel walls are set the same electric conductivity as the melt (see Tab.1). Fluid dynamics mesh consists of about 220k elements in 3D and 20k in 2D. No-slip boundary condition is applied to all walls, inlet and outlet are openings with set relative pressure difference (the developed pressure) and standard wall functions are used for boundary layer resolution. Fluid density and viscosity as in Table 1.

The main problem with 3D simulations, especially of such coupled type, is computation time. For example, 1 second flow simulation with coupling approach B and C (which recalculate electromagnetics every time-step) takes about 4 days on computer with Intel Xeon E3-1240 3.7GHz 4-core processor with 32Gb RAM. However, the open-source solutions used in this work can be efficiently used on computer clusters, if available.

Results

First of all, Fig. 4 shows instantaneous magnetic flux density vectors in the cross-section of the system, revealing the Halbach array. The instantaneous normal magnetic field component along the channel between magnets and yoke is shown in Fig. 5. The analytical magnetizations are multiplied by a factor of 0.91 to acquire the same amplitude as in the separate magnet case (this is because in the real case there are small gaps between magnets, decreasing magnetic field). Clearly, the magnetic field distribution is completely identical, so further we use only the case of single piece rotor with analytical magnetization.

An example of instantaneous Lorentz force and velocity distribution is shown in Fig. 6 and 7, respectively. Note the nonhomogeneity of force density along the channel width, which causes fluid recirculation and vortices near the channel sides as seen in Fig. 7. This is known as channel end effects and is the main reason why 2D models are incapable of giving reasonable results without introducing some corrections.

Magnet block rotation frequency is taken \( f = 6 \) Hz. We calculate the \( p-Q \) characteristics using approaches A, B and C (see section Numerical model, Tab. 2) and, to show the necessity of 3D simulations, approach A is also applied to 2D model. Results, including experimental measurements, are shown in Fig. 8.
The simple approach A of computing electromagnetic field in static fluid and including $\vec{v} \times \vec{B}$ term only in flow simulation gives results reasonably close to experimental data, with slightly underestimated flow-rate at a given pressure difference. Approach B gives integral results very close to those of case A. As also explained in [9], this is so because the integral force acting on the fluid is constant during the magnet block rotation. The correct coupling approach is C, which is also reflected in the $p$-$Q$ characteristics – the results are closest to experimental data.

**Conclusions**

Realistic 3D model of permanent magnet based electromagnetic induction pump was created and simulated using open-source software and different coupling approaches. From $p$-$Q$ curves the necessity of 3D simulation is obvious, since 2D model remarkably overestimates induced currents and consequently Lorentz force. The 3D model clearly reveals channel side or end effects – electromagnetic force decreases and changes direction near the channel sides, which leads to change of flow direction and vortices in those regions.

Overall, if only integral parameters are of interest, transient coupling is not necessary and approach A of using constant instantaneous forces is as good as transient approaches B and C. Transient coupling is necessary when studying particular flow structures and instabilities, although in that case the choice of turbulence model plays a big part and approach C is recommended, as the forces can be very sensitive to neglecting some part of magnetic field.

The open-source package EOF-Library for coupling Elmer and OpenFOAM proves to be a powerful tool in MHD applications where transient coupling is needed.

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