Electromagnetic separation of impurities in a conductive medium

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Abstract. A numerical study of the flow of an electrically conductive fluid is carried out in a cell under the action of a constant magnetic field. Distribution of electromotive force is investigated as well as the topology of electric current in the cell. The evolutions of velocity field are studied for different parameters. Two large scale unstable eddies are generated in the cell. The characteristic of the flow oscillations are determined using the wavelet analysis. It was found that an increase of current does not lead to the appearance of additional oscillation modes. Asymmetric pressure distribution may appear in the cell. Particle movement are possible due to the asymmetric pressure field.

1. Introduction
In our days, metals and alloys purified from impurities have a high demand. Materials and structures which made of ultrapure metals or alloys have an increased yield strength, better corrosion resistance compared to products from contaminated alloys. Metals and alloys of a high degree of purity are used in construction, in aerospace and high-tech equipment, and many other industries. Also liquid metals (for example, liquid sodium) are used as a coolant at fast neutron nuclear power plants. The degree of purity of the coolant essentially determines the lifetime of the equipment of the nuclear power plant, which is extremely important for the safe operation of the plant. In this regard, the task of detecting impurities in multiphase electrically conductive media, as well as the cleaning of melts from impurities, is one of the most important tasks for research.

There are many different methods for cleaning metals from impurities, for example, flotation methods [1, 2], sedimentation of the ore melt in a liquid [3], etc. Many existing metal cleaning methods require significant energy consumption. In this regard, the electromagnetic (em) method of mixture components separation is attractive in production. The em-method is based on the difference in the electrical conductivity of the metal and impurities. The impurities will either drown in the metal or float to the surface [4, 5] under the action of electromagnetic forces, where they can be easy removed. It depends on the magnitude of the electrical conductivity of the impurities (more or less the electrical conductivity of the metal). The method of applying on the metal the em-force is the least labor-intensive, easily implemented. Additionally it allows not only to separate impurity particles from the metal, but also to detect the impurities in the metal. It may be used in non-destructive testing technique of finished products and structures.

One of the methods for generating the em-force is to apply the external magnetic field co-directionally to the electric current. Such a configuration can be created by placing the studied
cell in the solenoid. This method is the easiest to implement. The superimposed external magnetic field is significantly more intensive than the own magnetic field of the electric current.

In the cell the em-force is generated due to distortion of electric current streamlines near the impurities. The distortion appear due to difference in the electrical conductivity between the impurities and liquid metal (current distortion cases are shown in Fig. 1. Obviously, if there are no impurities in the metal, then there is no reason for the appearance of em-force.

Thus, the common aim of the investigation is to study numerically the behavior of an ensemble of impurity particles in a liquid metal under the influence of em-forces. It is necessary in the frame of mathematical model to formulate a constitutive relation for parameters describing the electrical and mechanical properties of the phases and interphase interactions. In the first stage, described in the paper, the study of em-force, current distribution and velocity field behavior is carried out for single inclusion. In the second stage, the calculations to an ensemble of impurity particles will be provide in our future work.

2. Mathematical statement

The mathematical model is based on the equation of magnetohydrodynamics. It is used the non-induction approximation, which is valid for small magnetic Reynolds numbers, this allows you to explore the electrodynamic and hydrodynamic parts of the problem separately [6]. We consider a cell of liquid metal, which is a cube, with side $L$. Inside the cell an spherical electrically conductive particle having radius $R$ is placed in the center (fig. 1).

![Figure 1. Scheme of the problem in the central section (a), electric current streamlines distortion schemes (b)](image)

A potential difference is supplied to the system. The electric current of density $j$ flows through the cell along the X axis. In order to suppress the own magnetic field of electric current ($j = \mu_0 \text{rot} B$), an external magnetic field $B_0$ is imposed to the cell along the X axis. In this case $f^{em} = j \times B_0$.

There are various options for the distortion of electric current streamlines in the cell, depending on the magnitude of the conductivity of the particle (less, equal to or greater than the conductivity of the metal) (fig. 1). A series of numerical experiments for the two most interesting configurations are carried out, the distinguishing feature of which are:

a) metal conductivity is greater than particle conductivity ($\sigma_{Part} = \sigma_0; \sigma_{Me} = k \cdot \sigma_0$),

b) metal conductivity is less than particle conductivity ($\sigma_{Me} = \sigma_0; \sigma_{Part} = k \cdot \sigma_0$).

To describe the motion of a viscous conductive fluid, it is used the Navier-Stokes equation taking into account the electromagnetic forces (1) and continuity equation (2). The (3-6) describe...
the electromagnetic part of the task.

\[
\rho \left( \frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} \right) = -\nabla P + \eta \Delta \mathbf{V} + \mathbf{f}^{em}
\]  

\[
\nabla \cdot \mathbf{V} = 0 \tag{2}
\]

\[
\Delta \phi = 0 \tag{3}
\]

\[
\mathbf{f}^{em} = \mathbf{j} \times \mathbf{B} \tag{4}
\]

\[
\mathbf{j} = \sigma \mathbf{E} = -\sigma \nabla \phi \tag{5}
\]

\[
\mathbf{B} = (B_0; 0; 0) \tag{6}
\]

Electrodynamic parameters: \( \sigma_{part} \) – particle conductivity, \( \sigma_{Me} \) – metal conductivity, \( I \) – current strength, \( B_0 \) – external magnetic field.

Hydrodynamic parameters: \( \rho \) – density, \( \eta \) – dynamic viscosity.

Boundary conditions: \( V|_{\text{bound}} = 0, V|_{t=0} = 0, \frac{\partial \phi}{\partial n} = 0 \). For potential: \( \phi = \phi_1, \phi = \phi_2 \) – on opposite walls \( (x = 0, x = L) \). At the solid boundaries of the cell the non-slip condition is used.

To calculate the viscous parameters, the \( k-\omega \) turbulence model is used. The problem is numerically solved in the Ansys Emag (electrodynamics) and Ansys Fluent (fluid flow) applications.

3. Results and discussion

Calculations were carried out with the following parameters: \( \sigma_0 = 10^6 \) Sm/m – conductivity, \( \mathbf{B} = (10^5; 0; 0) \) – external magnetic field, \( k = 100 \) – coupling coefficient of the conductivity of a particle and a liquid, \( R = 20\)mm – particle radius, \( L = 100\)mm – cell side length.

The most interesting and indicative result is the field of the velocity profile in various sections. On fig.2 the velocity field in cross section \( x=0.07, y=0.05 \) is shown.

![Figure 2. The velocity field in the cross section x=0.07, y=0.05; Velocity profiles](image)

In fig.2 the oscillations (ripples) of the velocity profile are visible at a current strength of \( I=200A \). In order to visually determine the frequencies obtained, a signal analysis was performed with a length of 60s: interval 140-200s.

Using wavelet analysis, two characteristic frequencies of velocity fluctuations can be detected: \( \nu_1=0.15\)Hz, \( \nu_2=0.07\)Hz.

This suggests the coexistence of large-wave oscillations in the system, as well as small-scale pulsations. Thus, the fluid flow has a complex character, but at the same time it has allocated oscillation frequencies.
In this case, it is important to determine the average velocity both at one point under consideration over time and the average velocity in the cross section at a fixed point in time. One of the most indicative criteria for the intensity of the current is the average speed (in time) at a fixed point. The dependence of the average speed at the point (0.07; 0.05; 0.03) on the magnitude of the current is estimated (fig.4). A characteristic increase in the average velocity is visible as the current strength increases. The maximum speed is achieved the value \( V = 0.22 \text{m/s} \) for current strength of \( I = 1000 \text{A} \).

The calculations were performed for currents: 1A, 50A, 200A, 500A, 750A, 1000A. For wavelet analysis of oscillation frequencies, we choose a time interval in the range of 100-200s. This allows us to discard the process of establishing the flow and more accurately identify the frequency. The fig.5 shows that three characteristic frequencies can be detected in the system. The values of the frequencies change slightly with the change in the current strength. Since there are several oscillation frequencies for all currents in the system, there is no need to significantly increase the current strength in order to increase the number of oscillation modes. Thus, the intensity of the flow depends on the magnitude of the current, but does not depends on the number of oscillation modes of the system.

The analysis of the pressure field in the cell around the particle is carried out. The fig.6 presents the density distribution in the plane \((x,0.05,z)\):

It can be seen that the pressure field is not the same in different sides of the particle. It may generate the hydrostatic force which may move the particle. A pressure distribution diagram is
Figure 5. The dependence of the oscillation frequency on the current

![Graph showing frequency vs. current](image)

Figure 6. Pressure field: on the left - in section, on the right - along the center line depending on time

![Pressure field images](image)

prepared along the line passing through the center of the particle along the direction of current flow (fig.7).

The fig.7 is presented their pressure distribution curves near the particle at various time moments. The figure shows that the pressure in the system varies significantly during the process having an oscillatory nature. The pressure gradient at different time moments has different (opposite) directions.

An integral estimate of the mean pressure near the particle is carried out. It was found that on one side of the particle, the time-average pressure is higher than on the other. Thus, it can be assumed that the particle under the action of em-force may shift towards a lower pressure – along the direction of the current strength.
4. Conclusion
The study has shown that the vortex flow with two large-scale eddies is generated near the particle. For small value of em-force the flow is almost stationary. For moderate and large values of em-force the flow is unstable. The average flow the velocity is estimated as a function of current strength. It was found that the velocity increases with increasing current strength by square quadratic law.

A wavelet analysis of the velocity pulsations yields the characteristic oscillation frequencies. It was found that an increase of current does not lead to the appearance of additional oscillation modes. It was found that the pressure in the system is unsteady, however, it was possible to determine the integral pressure gradient. Asymmetric pressure distribution may appear in the cell. Particle movement are possible due to the asymmetric pressure field.

5. References
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