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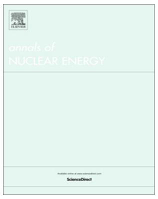

3D numerical modeling of liquid metal turbulent flow in an annular linear induction pump

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ABSTRACT

3D numerical simulation of the liquid metal flow affected by electromagnetic field in the Annular Linear Induction Pump (ALIP) is performed using modified ANSYS package. ANSYS/EMAG has been modified to take into account arbitrary velocity field at the calculation of the electromagnetic field and has been unified with CFX to provide integration of all the system of magnetohydrodynamic (MHD) equations defining dynamics of the conductive media in the variable electromagnetic field. The non-stationary problem is solved taking into account the influence of the metal flow on the electromagnetic field. The pump performance curve and the dependence of the pump efficiency on a flow rate are obtained.

1. Introduction

MHD ALIPs are the most perspective types of pumps for circulation of molten metals in fast breeder atomic reactors (FBRs). Although commonly used centrifugal pumps are more effective than existing ALIPs, the last ones have a number of advantages over the centrifugal pumps such as absence of moving parts and therefore high reliability, low noise and vibration level, simplicity of the flow rate regulation, easy maintenance and so on. Therefore, one of the basic problems in design of the ALIPs is the increase of their efficiency. It is expected that due to this the ALIPs will greatly simplify design and improve industrial safety and efficiency of the FBRs.

ALIPs have been widely investigated in Kim and Lee (2012), Kwant and Boardman (1992), Namba (1978) and Yang and Kraus (1983). The characteristics of ALIPs were calculated in the model of MHD pump with narrow annular channel type. This type of pumps has been analyzed using an electrical equivalent-circuit method explored conventionally for induction machines. The relation between the developed pressure and the flow rate for various pump parameters has been obtained from the balance equation for the circuit (Baranov et al., 1978). However, such an approach can not be applied in some important cases.

A lot of efforts have been devoted to develop ALIPs (see, for example, Andreev et al., 1978; Andreev et al., 1988; Kliman, 1979; Karasev et al., 1989; Rapin et al., 1989) with large flow rate. The most significant problem that we are faced at the design of a large-scale pumps is the magnetohydrodynamic (MHD) instability. The instability arises when the Reynolds magnetic number exceeds one (Gailitis and Lielausis, 1975). Kirillov et al. (1980) and Karasev et al. (1989) experimentally exhibited that the magnetohydrodynamic instability is accompanied with a low frequency pulsation of the pressure and flow rate, azimuthal non-uniformity of the velocity and magnetic field, vibration of the pump and heat carrier loop, and fluctuation of the winding current and voltage. The conventional electrical methods does not help in this case. The numerical simulation becomes the only reliable method of design of the large scale ALIPs. A lot of efforts were made to perform a computer modeling of the metal flow in the MHD pumps (Kirillov and Obukhov, 2003; Galanin and Rodin, 2012; Araseki et al., 2004; Bergoug et al., 2007). Nevertheless, all these attempts dealt with simplified models of the pumps, basically two dimensional. The most advanced attempt was made in the work (Kirillov and Obukhov, 2003). However, the impact of the velocity of the metal on the electromagnetic field has not been incorporated into the code of this work. This approach did not allow to calculate the most important characteristics of the pump: P-Q characteristic and efficiency of the pump.

Our main objective is development of a technology of computer design of ALIPs with high mass flow rate taking into account all the relevant physical processes. In this work we solve the particular problem of development of a technology of numerical modeling of the metal flow in the channel of the pump based on the commercial numerical packages ANSYS/EMAG (ANSYS, 2007) and

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ANSYS CFX (2007) temporally neglecting the impact of the magnetic field on the turbulence. On this reason we limit our work by low magnetic Reynolds numbers.

ANSYS CFX provides calculation of hydrodynamics. We use ANSYS/EMAG to calculate transient electromagnetic fields in realistic physical conditions and in 3D geometry. ANSYS CFX by itself allows us to solve MHD problems for low values of the magnetic Reynolds numbers. However, the original version of CFX does not allow us to model MHD flows in the necessary for our problem physical conditions and geometry. Therefore, we unified ANSYS CFX and ANSYS/EMAG into unique complex which allows us to model the flow of the metal in the conditions when the metal affects on the electromagnetic field and the electromagnetic field affects on the metal.

The paper is organized as follows. In Section 2 we present the modifications of the ANSYS/EMAG and ANSYS CFX which were made for modeling of the MHD problems. Then in Section 3 we describe the computer model which was used to demonstrate the method. In Section 4 we present the basic results.

2. Modifications of CFX and ANSYS/EMAG

The basic requests to the numerical codes for solution of the industrial MHD problems are:

- ability to reproduce real geometry;
- ability to calculate eddy electromagnetic field in the conducting and in the surrounding media with different physical properties;
- ability to solve the problem of non stationary MHD flow of the conducting media;

None of the numerical codes satisfy to these requests. To minimize the work, we took the solution to modify one of the existing codes. The commercial package ANSYS is the most appropriate for this because it demands smallest modifications.

The package ANSYS/CFX solves the hydrodynamical part of the problem while ANSYS/EMAG solves the electromagnetic part. Due to our modifications the Lorentz force was included into the system of hydrodynamical equations in ANSYS CFX and ANSYS/EMAG was modified to take into account the impact of the velocity of the electrically conducting media on the electromagnetic field. The impact of the velocity on the Lorentz force was taken into account as well.

In order to unify ANSYS CFX and ANSYS/EMAG into one software complex we developed a technology of synchronization of these packages and data exchange between them.

2.1. Basic equations

The system of hydrodynamical equations includes the continuity equation

$$\frac{\partial \rho}{\partial t} + div\rho\mathbf{v} = 0. \tag{1}$$

and the Navier-Stokes equation

$$\rho\frac{\partial v_i}{\partial t} + \rho v_k\frac{\partial v_i}{\partial x_k} = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ik}}{\partial x_k} + [\mathbf{j}\times\mathbf{B}]_i. \tag{2}$$

Here $\mathbf{v}$ is the velocity vector with components v_i and v_k, ρ – density, P – pressure, τ_{ik} is the tensor of viscous stresses which includes molecular and eddy stresses. The last term in Eq. (2) is the Lorentz force.

We used standard models of turbulence available in CFX. The impact of the magnetic field on the hydrodynamical turbulence is neglected in this work. The equations for turbulence are omitted here. They can be found in the manual for CFX (ANSYS CFX, 2007).

Electromagnetic field is calculated in ANSYS/EMAG in terms of vector potential $\mathbf{A}$ and electric potential ϕ integrated over time. The equations for $\mathbf{A}$ and ϕ are as follows

$$\nabla\times\nu\nabla\mathbf{A} - \nabla\nu_e\nabla\cdot\mathbf{A} + \sigma\left(\frac{\partial\mathbf{A}}{\partial t} + \nabla\frac{\partial\phi}{\partial t} - [\mathbf{v}\times[\nabla\times\mathbf{A}]]\right) = 0. \tag{3}$$

$$\nabla\cdot\left(\sigma\left(\frac{\partial\mathbf{A}}{\partial t} + \nabla\frac{\partial\phi}{\partial t} - [\mathbf{v}\times[\nabla\times\mathbf{A}]]\right)\right) = 0. \tag{4}$$

Here ν is the reversed magnetic permeability, σ is the electric conductivity. The Coulomb gauge $div\mathbf{A} = 0$ (Landau and Lifshitz, 1987) is used for $\mathbf{A}$. The last terms in Eqs. (3) and (4) appear due to motion of the electrically conducting media.

2.2. Dependence of the electromagnetic field on the flow velocity.

Simulation of the eddy electromagnetic field is available in ANSYS/EMAG using finite element method (Langtangen et al., 2003). Vector $\mathbf{A}$ and electric ϕ potentials are specified at the nodes of the elements SOLID97 of ANSYS (2007). Vector potential is interpolated in the finite element in the form $A_i = \sum_p N_p(\mathbf{r})A_i^p$,with summation over the nodes of the finite element. $N_p(\mathbf{r})$ are the shape functions of the element. The electric potential has a form $\phi = \sum_p N_p(\mathbf{r})\phi^p$. Galerkin method of discretization gives the following discrete equations: $\hat{C}\dot{u} + \hat{K}u = \hat{J}$. Here vector $u = \{A_x, A_y, A_z, \phi\}$. $\hat{C}$ is damping matrix which doesn't depend on the velocity. Stiffness matrix $\hat{K}$ has the following structure

$$\widehat{K} = \begin{Bmatrix} K^{AA} & 0 \\ K^{\phi A} & 0 \end{Bmatrix}. \tag{5}$$

Matrix element K^{AA} has a form

$$K^{AA} = K_0^{AA} - \int [N_A]\sigma([\mathbf{v}\times\nabla\times[N_A]^T)d\Omega, \tag{6}$$

where integration $d\Omega$ is performed over the volume of the finite element. K_0^{AA} is the matrix element corresponding to zero velocity of

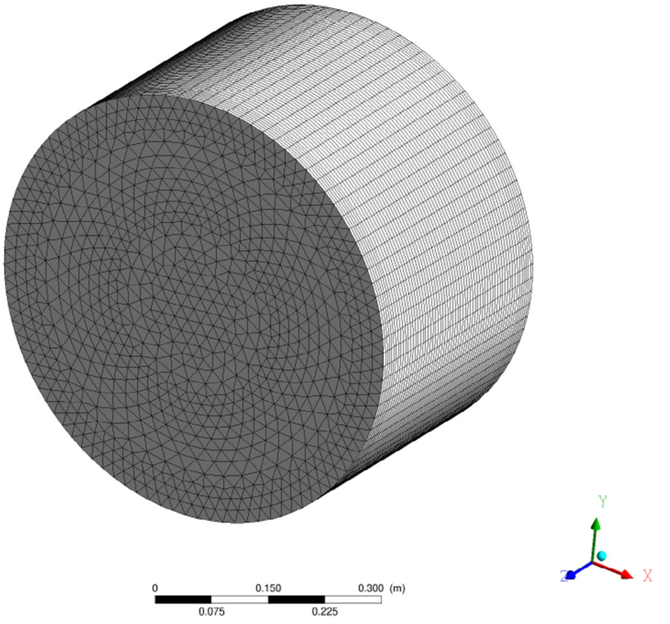

Fig. 1. Mesh of the test model.