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Numerical Simulation of Double Side Linear Induction Pump for Liquid Magnesium

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Abstract

The development and survey results of magnetohydrodynamic pump for liquid magnesium are given in the paper. The analysis of pump flow and head-capacity characteristics and metal velocity distribution in its canal is conducted. The article considers the flow-rate pressure characteristics for special induction pumps. The counter flow is investigated in the three-dimensional problem by SST model.

Introduction

Induction pump is an electrotechnologic installation intended for liquid conducting metal transport. The first installation with similar operating principle was patented in 1920 [1,2]. To date the induction pump invention is supposed to belong to Albert Einstein and Leo Szilard [2,3]. This pump type is often applied in metallurgy industry, biomechanics and at nuclear power stations. There are alternatives to induction pump such as conductive or mechanical pumps for example. However, it is impossible to make a conclusion about what pump type has the best indices. Pump applicability of certain design should be analyzed for each case individually.

The study of magnetohydrodynamic pump (MHD) has been relevant for many years. It is because of peculiarities connected with the application of these devices in different branches of industry. Specific nature of pump constructions intended for different purposes makes it impossible to develop a general theory of induction electromechanical converters of energy with a liquid-metal secondary element. Successful attempts to describe and arrange current development results in this field was taken in papers of A.I. Voldek [3,4].

The current state of production of magnesium alloys with the use of MHD pumps is defined by quite a high level of reject. It is caused by MHD-pump breakdown in the process of molding due to the fracture of windings’ heat insulation and their future burnout. Induction pump for liquid magnesium equipped with flat coils characterized by a high-temperature capability is studied in the paper.

Special-purpose MHD pump for liquid magnesium (Fig. 1) was developed and implemented at OJSC “Kamensk Uralsky metallurgical plant” [5,6]. Mathematical models allowing us to take into account electromagnetic and hydrodynamic effects occurring due to the specific nature of pump construction are described in the paper.

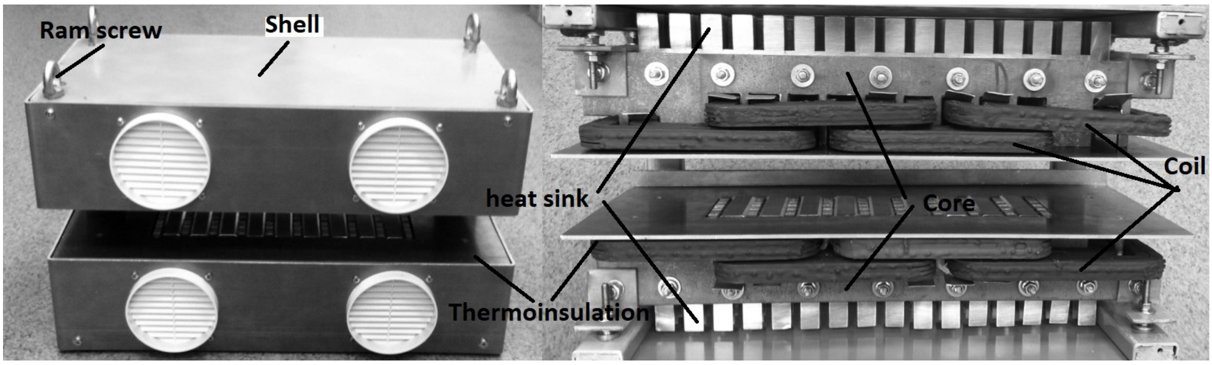

Fig. 1. Picture of the pump being studied in case and without case

2. Mathematical descriptions

A brief description of mathematical methods employed is given in the chapter. Description of basic mathematical equations and algorithms is given as well. Electromagnetic approximation with the aid of detailed magnetic equivalent circuits (DMEC) in 2-D is used for calculation of flow and head-capacity characteristic. Three-dimensional problem of magnetic and hydrodynamic fields is solved by using of finite element method (FEM) in Comsol 5.3. module.

2.1. Detailed magnetic equivalent circuits

With the use of DMEC energy characteristics and forces under stationary statement required for calculation of flow and head-capacity characteristic taking into account an impact of material properties changes due to thermal and edge effects by applying Bolton's coefficient are defined in the paper. The method is not new, its implementation for this pump is described in works [5,6], detailed algorithm is given in the following works [7-10].

2.2. Flow and head-capacity characteristic

Flow and head-capacity characteristic is an important tool for determination of pump operating point. Pump parameters defined by using of flow and head-capacity characteristic can be expressed in terms of integral parameters of its analog, namely linear induction machine with a solid secondary element. Pressure losses in the result of liquid friction on the channel walls should be considered. The loss can be expressed in terms of cross-section and liquid flow velocity in the pump channel:

$$Q = V \cdot S \,, \tag{1}$$

where, V — velocity, S —canal section.

The head in ist turn is composed of pump pressure and pressure loss caused by liquid friction in channel

$$P = \frac{F}{S} - \Delta P_f \,, \tag{2}$$

where F — pulling force in channel, ΔP_f —pressure losses due to friction.

Head in this characteristic is expressed in meters of liquid column:

$$H = \frac{P}{\gamma \cdot g} = \frac{F}{S \cdot \gamma \cdot g} \,, \tag{3}$$

where γ — density of medium pumped; g - gravitational acceleration.

Head loss is measured in meters and can be defined according to formula, [82],

$$\Delta H_f = \lambda \frac{l_k \cdot V^2}{D \cdot 2 \cdot g}, \tag{3b}$$

where V — metal flow velocity, $\lambda = \frac{0.3164}{\sqrt[4]{\mathrm{Re}}}$ — pressure loss coefficient, Re — Reynold's number; l_k — length of channel; $D = \sqrt{\frac{4 \cdot S}{\pi}}$ — nominal inside diameter of the channel, where S — canal section.

2.3. Mathematical description by finite element method

Simulation of MHD-pump by finite element method is implemented in Comsol Multiphysics. We consider a link of magnetic task with hydrodynamics through a transfer of forces calculated by means of Lorenz Force (4) built-in function in task of computational dynamics of fluid. Magnetic field is calculated in quasi-steady setting of a task. Hydrodynamics task can't be solved by means of laminar models due to backward flows caused by high compression forces occurring near canal's walls. In view of the above SST turbulent model was chosen.

$$F = \frac{1}{2} \mathrm{Re}\left(J \times \overset{*}{B} \right). \tag{4}$$

It should be noted as well that because of symmetry of the task it is reasonable to consider a half model only with the use of the certain conditions indicated at Fig.2. in order to save computing resources. Optimized grid of the model intended for results calculation is shown at Fig. 2 as well. Extended grid for more precise calculation of metal velocity field is constructed in the channel. The grid can be relieved with a view to magnetic task solving as a rule.

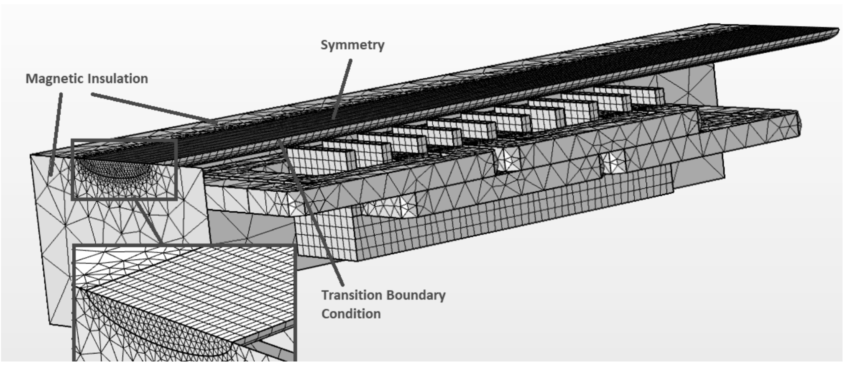

Fig. 2. Model's grid and boundary conditions

In the following we briefly describe boundary conditions on account of which the symmetry of the task is performed. Magnetic Insulation condition is established for all boundaries of computational domain with exception of the canal area (5). This boundary condition is characterized by zero value of normal component of magnetic inductance vector near this border. Symmetry condition is used for magnetic task (6) and for hydrodynamics as well (7). The equation (6) represents the requirement that normal flow of magnetic field passes through the area of boundary condition. The equation (7) describes the symmetry of flow velocity.

$$\mathbf{n} \times \mathbf{A} = 0, \tag{5}$$

$$\mathbf{n} \times \mathbf{H} = 0, \tag{6}$$

$$\mathbf{u}\times\mathbf{n}=0,\ \ \mathbf{K}-\left(\mathbf{K}\times\mathbf{n}\right)\mathbf{n}=0, \tag{7}$$

where $\mathbf{K}=\mu\left(\nabla\mathbf{u}+\left(\nabla\mathbf{u}\right)^T\right)\mathbf{n}$, $\mathbf{n}$ – normal vector, $\mathbf{u}$ – velocity vector, $\mathbf{H}$ – magnetic field vector, $\mathbf{A}$ – magnetic vector potential.

Transition boundary condition (8) is applied for simplifying of electromagnetic parameters calculation in metal walls of the channel. By applying the condition mentioned above we can establish boundary condition equivalent to the domain.

$$J_{s1}=\frac{Z_S\mathbf{E}_{t1}-Z_T\mathbf{E}_{t2}}{Z_S^{\ 2}-Z_T^{\ 2}};J_{s1}=\frac{Z_S\mathbf{E}_{t2}-Z_T\mathbf{E}_{t1}}{Z_S^{\ 2}-Z_T^{\ 2}} \tag{8}$$

where $Z_S=\dfrac{-j\omega\mu}{k}\dfrac{1}{\tan(kd)}$; $\quad Z_T=\dfrac{-j\omega\mu}{k}\dfrac{1}{\sin(kd)}$

$k=\omega\sqrt{\left(\varepsilon+\left(\sigma/(j\omega)\right)\right)\mu}$; $\varepsilon-$ relative permitivity; $\mu-$relative permability; $\sigma\ -$ electrical conductivity d – surface thickness

3. Simulation results of flow and head-capacity characteristic

Mathematical calculation results of characteristics for various performance of induction pump with flat coils are given in this chapter of the paper. Three types of pump design are considered, their characteristics are given in Tab.1. Design №1 – operating pump for liquid magnesium with linear load of 36.5 A/mm and current density of 2.93 A/mm^2 installed at OJSC KUMZ. Pump №2 with linear load of 50 A/mm and current density of 2 A/mm^2 is designed for replacement of the operating pump №1 (pump construction is described in Chapter 1). Pump №3 is an ideal case of Pump №1 (limiting technical characteristics). Consideration of various pump types makes it possible to compare capabilities of pumps of different design and analyze constructions of pumps.

Tab. 1. Main parameters of HDM-pumps

Parameter	Codification	Unit of measure	№1	№2	№3
Frequency supply	f	Hz	50	50	679
Number of phases	m		3	3	3
Number of poles	$2p$		6	2	2
Pole pitch	τ	mm	60.0	180.0	180
Width of statos pack	L_I	mm	100.0	85.0	85.0
Yoke height	h_A	mm	35.0	40.0	40.0
Tooth pitch	t_Z	mm	20.0	40.0	40.0
Slot width	b_Π	mm	12.0	30.0	30.0
Tooth width	b_Z	mm	8.0	10.0	10.0
Tooth height	h_Z	mm	40.0	58.5	97.8
Number of slots	z_I		18	9	9
Number of slots per one pole and phase	q		1	1.5	1.5
Number of turns in one slot	w_K		2	16	16

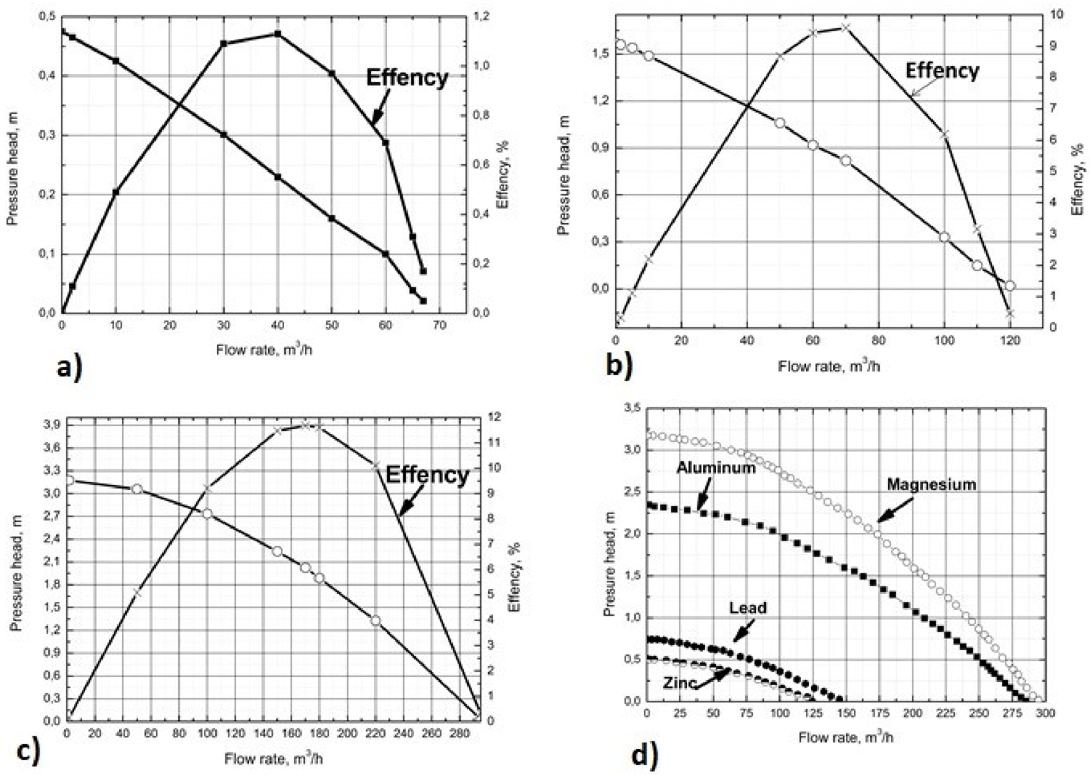

Fig. 3. Flow and head-capacity characteristics of: pump №1 (a), pump №2 (b), pump №3 (c) and flow and head-capacity characteristic for different materials of pump №3(d).

As we can see from the fig.3 the head of HDM pump №3 is 6 times higher than the head of HDM-pump №1 provided that feeding mode of all pumps described is the same. It makes it possible to use this pump for heavier metal such as zink and plumbum. Flow and head-capacity characteristics of HDM-pump №3 for aluminium, zink and plumbum are indicated at Fig.3, d.

Results obtained with electrodynamical approximation do not allow us to take canal's shape, counterflows in the pump passage and a number of other effects into account well. As it follows from Fig.4 heavy backward flows in near wall regions of metal canal are obtained in the process of task solution. This is due to relatively high pressing forces values occurring near canal mouth. Mean value of outlet flow rate provided that average velocity is 1-2m/sec on frequencies of 50 Hz and 679 Hz is equal to10-20 m^3/h.

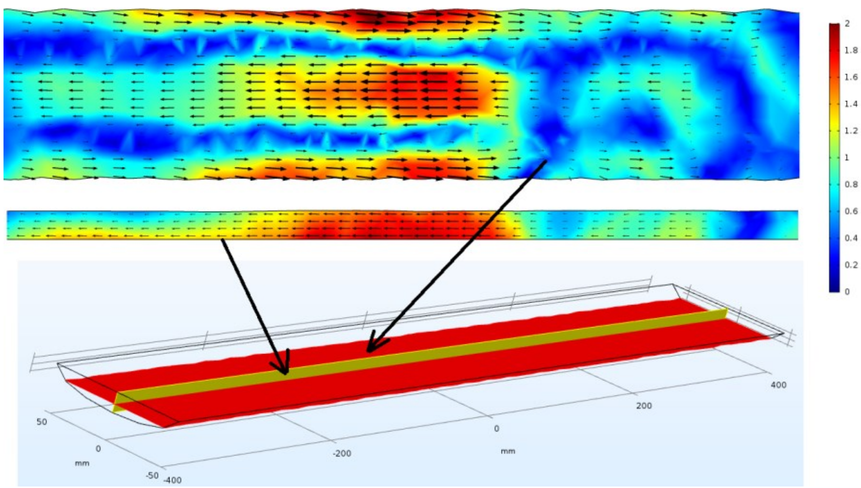

Fig.4. Velocity field in cross-section of canal

Conclusions

Calculation of flow and head-capacity pump characteristic with electromagnetic approximation makes it possible to evaluate integral characteristics quickly, enough for engineering computations. Design features and various effects connected with features of induction units with liquid-metal secondary element should be taken into account which requires simultaneous solution of magnetic field task and computational dynamics of fluid task. Results described in the paper show that backward flows of liquid metal are rather heavy that is why reverse speed of liquid metal flow should be considered in the process of magnetic task solution (calculation of forces in a canal).

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