RIGA TECHNICAL UNIVERSITY

Kalvis KRAVALIS

RESEARCH OF THE PUMP WITH ROTARY PERMANENT MAGNETS FOR TRANSPORTATION OF LIQUID METAL

Doctoral Thesis

Industry: Mechanical Engineering

Sub-sector: Engineering Technology

Riga 2013

RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Mechanical Engineering
Institute of Mechanical Engineering Technologies

Kalvis KRAVALIS
The doctoral program "Production Engineering" PhD

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Scientific advisor
Dr. sc. Ing., Assoc. professor
G. BUNGA
Dr. Phys., A leading researcher
I. BUCENIEKS

Riga 2013

UDK 621.67(043.2)
Kr 280 r

Kravalis K. Research of the Pump
with rotary permanent magnets
for transportation of liquid metal.
Doctoral Thesis.
R.: - RTU 2012th 30 pages.

Printed in correspondence with
2011th 21. of April protocol
No. 4/11 of MTI Institute

This work is supported by the European Social Fund project "Support to the RTU doctorate in the implementation”

DOCTORAL THESIS
NOMINATED FOR DOCTORAL DEGREE GRADUATION AT RIGA TECHNICAL UNIVERSITY

Doctoral Thesis for Scientific Degree on the public is being defended in 12th of March 2013. at Riga Technical University Faculty of Transport and Mechanical Engineering, Ezermalas Street 6, the 405th auditorium.

OFFICIAL REVIEWERS
Dr.sc.ing. professor Algirdas Bargelis
Kaunas University of Technology, Lithuania

Dr.phys., Leading researcher Juris Zvirgzds
University of Latvia

Dr.sc.ing., Professor Juris Krizbergs
Riga Technical University

APPROVAL

I certify that I have developed this thesis, submitted at Riga Technical University for production of PhD at engineering sciences (or other). This thesis has not submitted at any other university for degrees production.

Kalvis Kravalis .... (Signature)
Date: 06.11.2012.

Thesis written in Latvian, consists of 4 chapters and its volume is 133 pages. It contains 70 files, 7 tables and 4 appendixes. The paper uses 60 literature sources.

CONTENTS

GENERAL DESCRIPTION OF THE PHD THESIS

Topicality

Pilot plants, which use liquid metals, are increasingly being applied in various nuclear energy, nuclear fission and metallurgical process research. Different types of pumps are being used to create liquid metal movement, including the disc-type electromagnetic pumps with rotating permanent magnets. Disc-type electromagnetic induction pumps with rotating permanent magnets have not been studied a lot. Only generalized correlations for calculation of this type of pump design parameters can be found in literature. The calculation methodology for the induction pumps with electrical inducement and the cylindrical permanent magnet pumps is described. So far they have been used only in small power plant because of a small flowrate and developed pressure. To use electromagnetic pumps in high power liquid metal pumping technological equipment, improvement of the output parameters - pressure - flowrate and their calculation methodology must be done so allowing doing more accurate calculations.

The goal of thesis

To develop magnetic systems parameters calculation model of disc-type permanent magnet pumps and to improve the liquid metal pumping process using electromagnetic induction pumps with rotating permanent magnets and to carry out experimental approbation of the model.

Investigated problem

It is very difficult to predict output parameters (flow rate, developed pressure) of disc-type permanent magnet pumps, since there is no precise methodology for calculating the pump parameters. To do that you have to very precisely calculate magnetic field generated by magnetic system. Permanent magnet pump non-magnetic gap is large, and therefore the calculation methodology which is used in electric machine magnetic field induction division and construction parameters calculation can not be used because of its complicated magnetic field distribution. Due to active sections difficult geometric configuration, it is necessary to describe simplified models, which describe only one of the studied parameters (magnet height, width and pole step, the distance between the magnet arrays).

Goals to achieve

1) Develop a pumps magnetic system parameters calculation model and use the model for PM pumps magnetic systems structural parameters calculation. Analyze the various magnetic systems parameters influence on magnetic induction value at pump channel area.

2) Calculate the PM pump pressure - flowrate parameters and velocity distribution at the channel.

3) Produce disc-type pump with permanent magnets and do magnetic field induction distribution measurements at the active zone of the pump.

4) Produce liquid metal loop for pumps pressure-flowrate curves measurement.

5) Compare experimental results with data obtained by the calculation model data to verify the applicability of the model for calculation of this type of pumps and pump efficiency compared with analogue.

The research methodology

Mathematical model has been designed to make it possible to analyze the pump magnetic system parameters influence on the magnetic induction value in the channel area. Magnetic field induction distribution analysis is with help of the model is carried out with the MS Excel program. To do the experimental part of the work, disc-type permanent magnet pump and liquid metal circulation circuit is made. In the experimental part author makes pump magnetic system field induction distribution measurements with gaussmeter *Lakeshore Model 475 Gaussmeter.* Pressure – flowrate characteristic measurements were done using Venturi tube flow meter and differential manometer. Mathematic analysis of the characteristics is carried out with help of linear regression. To check the model, comparison of calculated values and measurement results are made.

Scientific novelty and main research results

Novelty is associated with a new calculation model used for disc-type permanent magnet pump magnetic system parameter calculation. For creating a model author uses calculation methods which are not common in electric inducement electric machines because there are permanent magnets and pump canal in permanent magnet pump non-magnetic gap. Main attention in the model is directed to magnetic field induction calculation in pumps active section. For experimental part disc-type pump and also a liquid metal circuit was made. Theoretical calculations are compared with experimental data.

Practical Application

Disc-type permanent magnet pumps are used in liquid metal pumping technologies, in the concrete, experimental devices and metallurgy needs for metals that are not aggressive to stainless steel canal. Theoretical and empirical results of this thesis are used in IPUL produced permanent magnet pumps, which are delivered to several customers in whole of the world, which includes scientific institutions and manufacturing organizations.

Electromagnetic pumps with permanent magnets are provided to use in same liquid metal Technologies – metallurgy, nuclear energy and the experimental devices.

Author defends work

A new type of permanent magnet magnetic pump system calculation model disc pumps with rotating permanent magnets that are used in liquid metal pumping technologies is being defended.

Approbation

On the main findings and results reports at following conferences and seminars are made:

1. K. Kravalis, G. Bunga. Magnetohidrodinamiskā sūkņa ar pastāvīgiem magnetiem parametru analīze. Rīgas Tehniskās Universitātes 45. starptautiskā zinātniskā konference. Rīga. 14 – 16. oktobris 2004.

2. K. Kravalis, G. Bunga. Elektromagnetisko sūkņu ar rotējošiem magnētiem īpašības un pielietojums. Rīgas Tehniskās Universitātes 46. starptautiskā zinātniskā konference. Rīga. 13 – 15. oktobris 2005.
3. K.Kravalis, G. Bunga. Mazgabarīta kontūrs ar elektromagnētisku indukcijas sūkni ar rotējošiem pastāvīgajiem magnētiem materiālu dzesēšanai ar dzīvsudrabu. Rīgas Tehniskās Universitātes 47. starptautiskā zinātniskā konference. Rīga. 12 – 14. oktobris 2006.
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9. K. Kravalis, G. Bunga. I. Bucenieks Šķidru metālu sūknēšanas tehnoloģijas analīze. Rīgas Tehniskās Universitātes 51. starptautiskā zinātniskā konference. Rīga. 11 - 15. oktobris 2010.
10. I. Bucenieks, K.Kravalis. Efficiency of EM Inducton Permanent Magnets Pumps. 8th International PAMIR Conference on Fundamental and Applied MHD. Borgo, France,.5. – 9. September 2011.
11. I. Bucenieks, K.Kravalis R.Krishbergs. Pressure – Flowrate Characteristics of the Pumps with Permanent Magnets. 8th International PAMIR Conference on Fundamental and Applied MHD. Borgo, France. 05. – 09. September 2011.

Publications

Results and development of the research have been published in seven scientific articles:

1. K. Kravalis. Magnetohydrodynamics and the influence of the magnetic field on various mediums// Rīgas Tehniskās Universitātes zinātniskie raksti. 6. Sēr., Mašīnzinātne un transports. - 14. Sēj. (2004), 62 - 64. lpp.
2. K. Kravalis, G. Bunga Elektromagnētisko sūkņu ar rotējošiem pastāvīgajiem magnētiem salīdzinājums ar pārējiem elektromagnētisko sūkņu veidiem// Rīgas

Tehniskās Universitātes zinātniskie raksti. 6. Sēr., Mašīnzinātne un transports. 19. Sēj. (2005), 50 - 54 lpp.
3. Krisbergs R., Kravalis K. e.t.c. Magnetic field distribution in the rotor of permanent magnets// Proceedings of the Joint 15th Riga and 6th pamir International Conference of Fundamental and Applied MHD, June 27 – July 1 2005. - Riga: IPUL, 2005. - pp 73 – 76.
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Doctoral thesis volume and structure

The thesis is written in Latvian. The doctoral thesis consists of four chapters and conclusions and its volume is 130 pages, it contains 70 figures, 7 tables and 4 appendixes.

Summary of the Dissertation

Introduction.

` Introduction deals with topicality of the chosen subject, investigated problem, aim of the work, and goals to achieve. Short description of research methodology is given, also scientific novelty, main goals of research, implementation possibilities of research results are viewed.

1. THE USAGE OF ELECTROMAGNETIC PUMPS AT LIQUID METAL TECHNOLOGY AND EXISTING METHODS FOR PERMANENT MAGNET PUMPS PARAMETERS CALCULATION

This chapter outlines the liquid metal pumping technology usage historical development and existing methods of permanent magnet pump parameters calculation. It should be noted that this technology today is very important because the metals in the liquid are being used more extensively. As the main problem to be investigated liquid metal flow assurance is defined. The main metal pumping process parameters are developed pressure p and the flowrate Q. This work dealt with the liquid metal flows provided by pumps, in this case with rotating permanent magnets. As the main objective of work is the permanent magnet pump efficiency improvement. This can be done by improving the pumps magnetic systems characteristics. Liquid metal pumping is a complex problem, because the metal pumping characteristics depend on the pumped metal properties. Scopes and goals are quite different, so each time you have choose carefully the pump and circuit design and material. The main application areas are nuclear energy production, metallurgy, and experimental devices. Pump channel is usually made of stainless steel and it determines the range of pumped metals. These are the alkali metals (Na, K, Li) and their eutectics, heavy metals (Hg, Pb) and their eutectics, as well as other metals which are in liquid state at the allowed range of temperatures for stainless steel and are compatible with stainless steel. This chapter reviews the main parameters and considerations determining the design of the pump.

The second part of the chapter deals with literature dedicated to PM pumps magnetic field distribution and the output parameters calculation methods. Different methodologies for negative width and thickness end effects calculation, which does not always give accurate results are viewed. Literature deals with only a small number of electromagnetic induction pumps with rotating permanent magnets. Only a limited number of cases referred to the calculation methodology are described.

Japan current JSNS neutron spallation source target cooled by mercury uses a cylindrical rotating PM pump with drive power 90 kW. H.Kogawa and authors of a collective article [15] are dealing with heat losses depending on the channel wall thickness and rotation speed of the magnetic system. Electromagnetic pressure distribution along the channel thickness and the occurrence of backflow is also considered. Pumps pressure - flowrate curves were measured and low vibration levels, compared with a mechanical gear pump were measured.

Permanent magnet pump calculation methods are described in T.Kalnina and co-authors works [7 - 11].

Mainly cylindrical pumps are viewed. Recommendations for the negative end effect calculation and several pump construction analysis is given. I.Bucenieka work [1 – 5] deals with disc induction pumps with rotating permanent magnets, the design features and application possibilities. He outlined the difficulty of the numerical evaluation of pumps output parameters and the magnetic pump systems created magnetic field induction calculation.

There are no calculation models for disc-type pump parameters calculation found in literature. There is only some general theory for permanent magnet machine calculation available. It does not allow doing precise calculations of the magnetic system-generated magnetic flux density, which results with insufficient precision in pump output parameter calculation. Therefore we have to create a calculation model that takes into account directly disc-type pump's geometry.

Developed pump pressure calculation scheme. Typically electromagnetic pressure which develops the pump, as machines with unmarked poles, as well as machines with marked poles is expressed in the form $p_e = p_o k_{oc} k_b k_\mu k_p$, $p_o = \sigma\tau s f L_{kan} B_\delta^{\ 2}$, where the coefficients describing the impact of various factors on the pump developed pressure are calculated and analyzed with a variety of complexity of mathematical physics solutions or empirical coefficients [14]. The ideal pumps developed pressure - p_o, B_δ - magnetic field induction in the air gap, L_{kan} – length of the channel, f -frequency, s - slip, τ - pole pitch, σ - liquid metal electrical conductivity. As shown, the magnetic induction in this formula is in the second stage, and this parameter has a significant impact on the pump parameters.

Existing PM magnetic field calculation methods. Lets take closer look at the magnet substitution with equivalent point-shape currents. The method of calculation is based on a rectangular parallelepiped type magnet replacement by an equivalent linear current density layer, or an equivalent amount of power [18]. Therefore we have to know the magnetic field generated by a point current located in the air, point current above the ferromagnetic plate with magnetic permeability μ=∞, point current between two ferromagnetic plates with μ=∞.

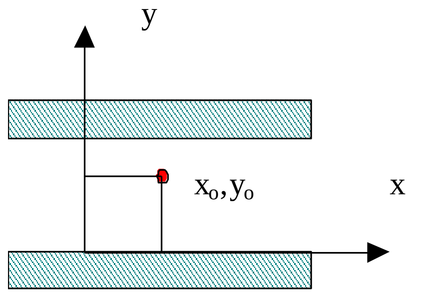


Fig.1.1. Point current between two ferromagnetic plates

Plates are infinite in width and length, relative magnetic constant of the magnet μ_{rpm}=1. Point current magnetic field is calculated by Maxwell's equations.Using the mirror theory, in this case, it should be noted that the field is reflected periodically in the upper and lower plate, so we calculate the sum of the mirror image. As a result, we obtain formulas 1.1 and 1.2:

$$B_{xI2p}(x,y)=\frac{\mu_o I}{4d}\left(\frac{\sin\frac{\pi(y-y_o)}{d}}{\cosh\frac{\pi(x-x_o)}{d}-\cos\frac{\pi(y-y_o)}{d}}+\frac{\sin\frac{\pi(y+y_o)}{d}}{\cosh\frac{\pi(x-x_o)}{d}-\cos\frac{\pi(y+y_o)}{d}}\right) \tag{1.1}$$

$$B_{yI2p}(x,y)=\frac{\mu_o I}{4d}\left(\frac{\sinh\frac{\pi(x-x_o)}{d}}{\cosh\frac{\pi(x-x_o)}{d}-\cos\frac{\pi(y-y_o)}{d}}+\frac{\sinh\frac{\pi(x+x_o)}{d}}{\cosh\frac{\pi(x-x_o)}{d}-\cos\frac{\pi(y+y_o)}{d}}\right), \tag{1.2}$$

where d – distance between ferromagnetic plates, I – dot shaped current, μ_0 – magnetic permeability in the gap between ferromagnetic plates.

Calculation results give a large dispersion of data. This can be explained by the fact that the formulas are semi-empirical. To get more precise data improved calculation methods must be created.

2. DEVELOPMENT OF CALCULATION MODEL FOR PERMANENT MAGNET PUMPS MAGNETIC INDUCTION DISTRIBUTION

This chapter deals with magnetic induction density distribution model. Analysis of the magnetic induction density distribution for disc type permanent magnet pump is done using above mentioned model.

2.1. Disc-type permanent magnet pump magnetic induction distribution calculation model

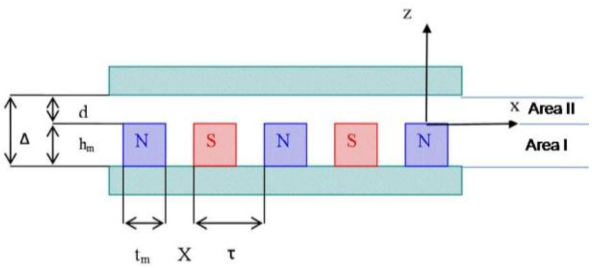


Fig. 2.1. Calculation model for disc-type PM pumps magnetic field distribution in the active zone of the pump

Let us consider calculation model for the magnetic induction density distribution at the air gap seen at figure 2.1. In contrast to the previously viewed model for cylindrical pumps viewed at polar coordinates, the solution here is found at Cartesian coordinates.

Lower magnetic yoke with permanent magnets moves to the x-axis direction. PM oriented with variable polarity are attached to yoke. The distance between magnets in X, τ - pole pitch, distance from yoke to the magnet surface (air gap) is d, the magnet height - h_m, magnet width - t_m. So $X=\tau-t_m$. The distance between ferromagnetic yokes isΔ. Let's find a solution in two areas I and II. Permanent magnets are located at area I, at area II the channel with the liquid metal is situated. Both areas are separated from the top and bottom with ferromagnetic yokes having electric conductivity $\sigma = 0$ and magnetic constant $\mu = \infty$. We assume, that magnetization vector M is homogeneous and equal for all magnets. We need a solution for the area I, solution for area II is necessary to meet the boundary conditions.

$$B_z = \frac{4M_o}{\tau}\sum_{m=1}^{\infty}\frac{\sin(\alpha_m \frac{t_m}{2})}{\alpha_m}\frac{\sinh(\alpha_m h_m)}{\sinh(\alpha_m \Delta)}\cosh(\alpha_m(z-\Delta+h_m))\cos(\alpha_m x), \qquad (2.1)$$

where $\alpha_m = \frac{\pi}{\tau}(2n-1)$.

Let us transform the expression using:

$$\cosh(\alpha_m z - \alpha_m(\Delta - h_m)) = \cosh(\alpha_m(\Delta - h_m))\cosh(\alpha_m z) - \sinh(\alpha_m(\Delta - h_m))\sinh(\alpha_m z), \qquad (2.2)$$

which gives

$$B_{om} = \frac{4M_o}{\tau} \frac{\sin(\alpha_m \frac{t_m}{2})}{\alpha_m} \frac{\sinh(\alpha_m h_m)}{\sinh(\alpha_m \Delta)}, \quad (2.3)$$

$$B_{cm} = B_{om} \cosh(\alpha_m (\Delta - h_m)) \ , \quad B_{sm} = B_{om} \sinh(\alpha_m (\Delta - h_m)), \quad (2.4)$$

$$B_z(x,z) = \sum_{m=1}^{\infty} (B_{cm} \cosh(\alpha_m z) - B_{sm} \sinh(\alpha_m z)) \cos(\alpha_m x). \quad (2.5)$$

The resulting expression (2.5) will be used to analyze pumps active zone parameters influence on the magnetic flux density distribution along the air gap of the pump.

2.2. Magnetic field induction distribution analysis of disc-type permanent magnet pump

Using the developed model we will analyze the active section parameter influence on the induction distribution along the pole surface. Let's look at how induction distribution affects the pole pitch τ, height of magnet h_m , magnet width - t_m, air gap between the magnet surface and the ferromagnetic yoke d. The main calculations will be taken from the pole surface $z = d / 2$, because it is a midpoint of an air gap and there is a liquid metal layer.

Let's evaluate the effect of the curve shape on the magnetic field spectral distribution. In the developed model there are four parameters that determine the geometry of the active section - pole pitch τ, air gap d, magnet height h_m, magnet width t_m. Transition to dimensionless variables will reduce the number of parameters to three. Let's introduce variables: $t_m^* = t_m/\tau$, $h_m^*=h_m/\tau$ and $d^*=d/\tau$. Assuming that $\alpha_n = \pi(2n-1)$, we will get expressions (2.6), (2.7), (2.8) and (2.9):

$$Bo_n = 4Br \frac{\sin(0.5\alpha_n t_m^*)}{\alpha_n} \frac{\sinh(\alpha_n h_m^*)}{\sinh(\alpha_n (d^* + h_m^*))}, \quad (2.6)$$

$$Bc_n = Bo_n \cosh(\alpha_n d^*), \quad (2.7)$$

$$Bs_n = Bo_n \sinh(\alpha_n d^*), \quad (2.8)$$

$$Bz = \sum_{n=1}^{N} (Bc \cosh(\alpha_n z^*) - Bs \sinh(\alpha_n z^*)) \cos(\alpha_n x^*), \quad (2.9)$$

where coordinates $x^*=x/\tau$ and $z^*=z/\tau$.

Lets look at the case when h_m*=0.1 and d*=0.1. Magnet width relation to pole step is very important parameter and will be changed from t_m*=0.25 to t_m*=1.

Magnetic field induction distribution along the channel thickness. Let us consider qualitatively different magnetic system size effects on the magnetic induction distribution along the air gap. The figure shows the distribution of magnetic induction along the magnet width (`x-coordinate) depending on the distance from the magnet surface along the air gap (`z-coordinate) at different magnet heights h_m`, magnet widths $t_m$` and air-gap thicknesses d `.

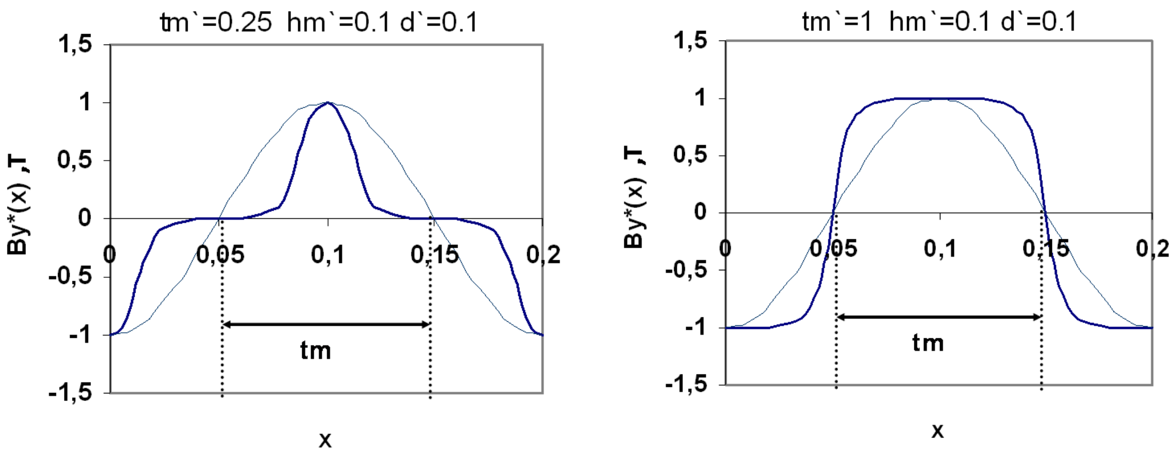


Fig. 2.2. Magnetic field distribution at the air gap of PM disc-type pump depending on the magnet width – light blue line – ideal distribution, dark blue line – calculation data

The first series of calculations are done at h_m`= 0.2, d = 0.2`, t_m`= 0.2 and 0.8 can be seen at figure 2.2. The relation of the magnet width and pole pitch influences significantly the field form distribution along the magnet width.

t_m`=0,2 $t_m$`=0,8

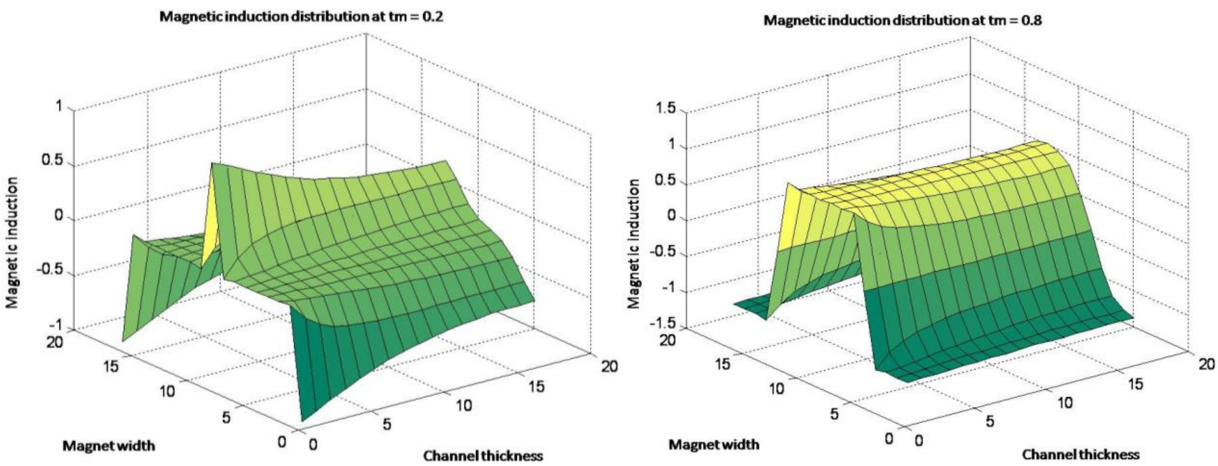


Fig. 2.3. Magnetic field distribution in T of PM disc-type pump in the air gap at different ratio of magnetic pole width against pole pitch t_m = 0,2 and 0,8

Magnet height relation to pole pitch and an air gap relation to pole pitch have low impact on field distribution form along the magnet width.

Series of calculations for h_m\`= 0.2, d = 0.2\`, h_m\`=0.2 and 0.8, are shown in Figure 2.3. We can see that magnet width relation to the pole pitch has a strong impact on field distribution along the magnet width. Near the magnet magnetic field shape distortion can be seen, away from the magnet surface distortion decreases.

3. DISC-TYPE PERMANENT MAGNET PUMP EXPERIMENTAL RESEARCH

3.1. Production of disc-type pump with rotating permanent magnets

To check if the model is precise, we have to produce disc-type PM pump and test its characteristics. For testing the pump it is necessary to take the pressure - flowrate (p - Q) curves and measure pumps driven electric power parameters.

Disc-type induction pump structure forming components can be seen in fig. 3.1. The pump consists of a channel 1 along which rotates on an axis 2 located magnet blocks 11. Pump channel is welded construction, which usually consists of two sides and inner and outer wall. The channel has a rectangular shape. Internal and external wall is usually thicker than the side walls. The channel is curved in the shape of semicircle. Pump channel cross-section - 10 x 54 mm, the channel wall thickness 3 mm.

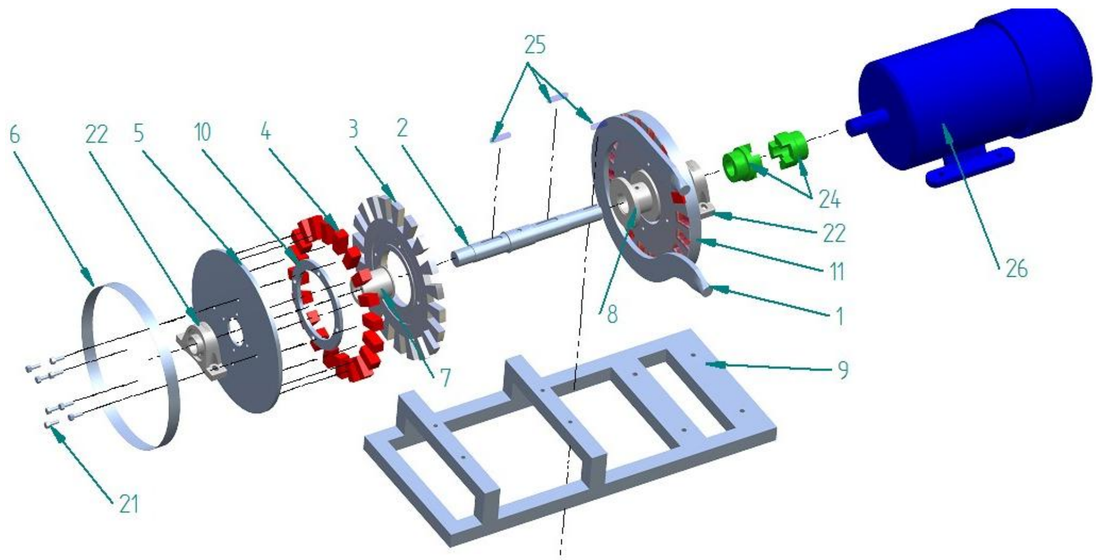


Fig. 3.1. Construction of disc-type induction pump

At the rectangular part of the channel diffusers are welded to ensure the transition to the diameter of pipe circuit. The task of diffuser is to ensure a smooth transition with minimal hydraulic resistance. Sometimes there are flanges welded to diffusers. In the accountable structures flanges are not used and the channel is welded to the circuit. Magnet blocks located on the axis has following structure – on the disc-type ferromagnetic construction steel base 5 we locate magnets 4 (or magnet blocks) with the poles facing the channel side and pole orientation changes alternately on the principle of S - N - S - N - S. The choice of magnet type is determined by the operating temperature. If the magnet operating temperature does not exceed 120° C, we use neodymium - boron magnets, but if the temperature is higher – then we use samarium - cobalt magnets. Diameter of rotating disc is 300 mm. The outer diameter of magnetic system - 302 mm, number of magnetic blocks - 16, block size - 20 x 30 x 60 mm. In each block there are four permanent magnets. Manufacturer of permanent magnet is Universal Magnetech Co., type YXG - 26m. Count of poles is always even number, so that magnetic field lines can be concluded in the active part of the pump.

3.2. Creation of the experimental device for parameter measurements of permanent magnet pump

In order to measure the characteristics of PM pump InGaSn experimental circuit was made. Experiments were performed on the liquid metal circuit. Working environment - InGaSn eutectic (metal ratio by weight percentage: 20.05 In-, Ga - 67, Sn - 12.5). Melting temperature of the eutectic is 10.5 ± 0.1°C. During the experiment Reynolds number varied from 0 to $4*10^5$, but magnetic Reynolds number from 0.02 to 0.6.

InGaSn eutectics heat capacity at 20°C is 428.651 J/kg*^{o}C. Eutectic expansion coefficient while hardening is 1.38% from volume. Eutectic is not explosive, it is fireproof and non-toxic [13].

Liquid metal loop is shown in Figure 3.2. and its principal scheme depicted in Figure 3.3, whert the main components of the loop are outlined:

1 - electromagnetic induction pump with rotating permanent magnets 9;

2 – differential manometer 10 for measuring pumps developed pressure;

3 – tarred Venturi pipe for measuring pumps flow rate;

4 – differential manometer 3 for measuring pressure difference in Venturi pipe;

5 - adjustable hydraulic resistance - ball-shaped valve 13 for regulating the pressure drop in the loop;

6 - liquid metal container 5 for filling loop with liquid metal and drainage;

7 – heat exchanger 11 for controlling liquid metal temperature - heat exchanger type - liquid metal - water, constructive solution - pipe in the pipe. Constant temperature rate is maintained, controlling adequate water flow through the heat exchanger. The outer diameter of the heat exchanger - 100 mm;

Fig.3.2. Experimental InGaSn circuit for testing electromagnetic induction pump with rotating PM

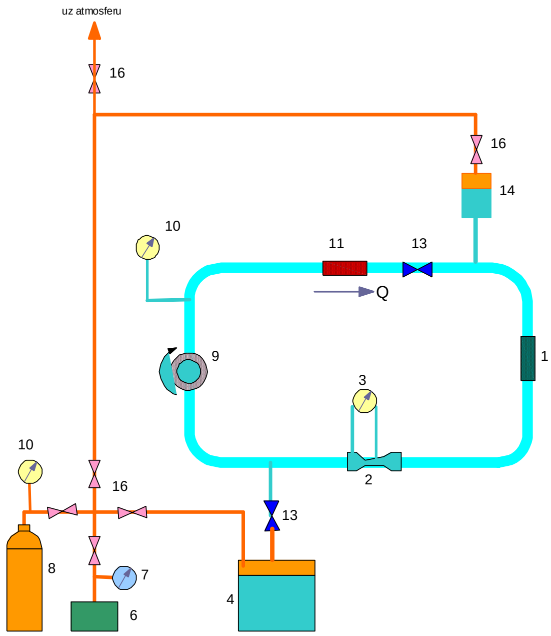


Fig.3.3. Principal scheme of the loop

Outer diameter of the loop - 38 mm, wall thickness - 1.5 mm. Various loop elements connected to each other with flanges, which are packed with rubber packing. Total length of the loop is 5.2 m.

3.3. Disc-type permanent magnet pump magnetic distribution measurements

Measurements were performed with gauss meter Lake Shore Model 475 Gaussmeter equipped with measuring probe HMMT - 6J04 - VR. Probe is placed on a movable table, which is driven along the Y axis by the help of micrometer screw. The measurement scheme is shown in Figure 3.4.

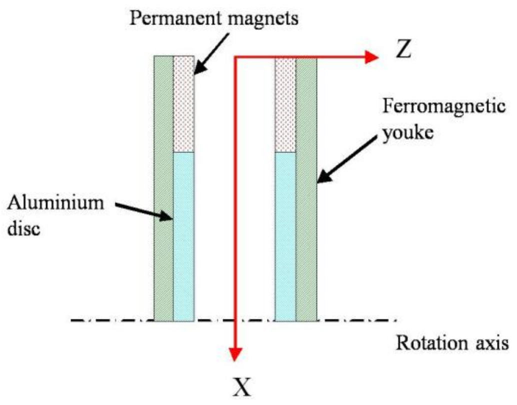


Fig.3.4. Magnetic field induction measurements in the active section of disc pump

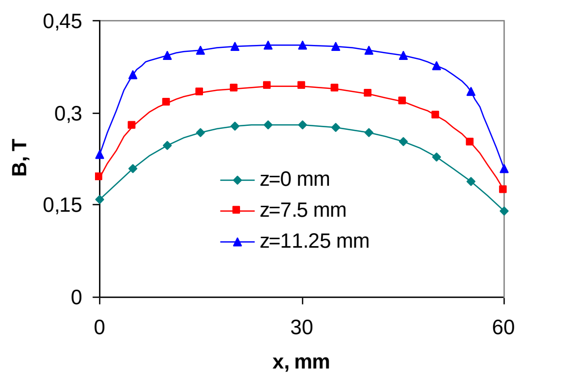


Fig.3.5. Magnetic field induction normal component Bz (x) measurements at different distances Z, from the surface of the pole. Z = 0 mm, 7.5 mm; 11.5 mm at disc-type pumps active section X = 0, Y = 0, d = 30 mm

The results of measurements at a distance between disks d = 30 mm can be seen in Figure 3.5. As we can see, with increasing distance between the disks, magnetic induction decreases. And, towards the surface of the magnet, it grows proportionally. In addition, towards the magnet surface and moving along the X axis, magnetic field induction increases more rapidly than if there is a larger distance from the permanent magnet surface.

Measurements demonstrate how important the spacing between magnetic blocks is. It is extremely important for the proper choice of pumps design, pumps channel construction and pumps output characteristics calculation.

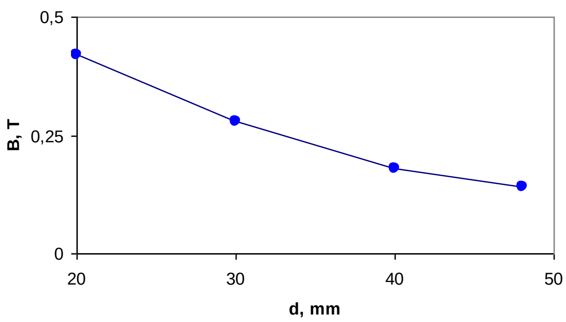


Fig.3.6. Magnetic field induction average value dependence on the magnet block distance in the disc-type pumps active section

After the collected data we can determine the average magnetic field induction value dependence on the distance between the magnet blocks. It is graphically depicted in Figure 3.6. Further we will notice that the pump pressure dependence from magnetic induction B is in second order – so it is very difficult to overrate its impact. Therefore, the liquid metal must be placed as close to the magnets as possible.

The channel walls should be as thin as possible, observing the conditions of strength. It is necessary to reduce the distance between the magnets and the channel walls. In the case of high temperature it is necessary to make the magnet cooling or protect them with heat reflective screens or coatings. If none of those options are possible, you can then increase the spacing between the magnets and the channel (non-magnetic gap), which necessarily reduces the pump efficiency.

3.4. Measurements of disc-type permanent magnet pump pressure – flowrate characteristics

With the help of experimental device, described in the previous chapter, we were able to take the disk-type PM pump p(Q) characteristic measurements. Afterwards we summarized measurement results and processed them, so we could compare them with theoretically acquired results. Measurements were performed by help of differential manometers, which were added to pressure measurement locations at the inlet and outlet of the pump for measuring developed pressure and to the Venturi tube fluid flow speed measurement exits. During the measurements we changed distance between the magnet blocks from 48 to 30 mm and the magnet block rotation frequency from 288 to 1440 r / min.

Pumps developed pressure p and flowrate Q measurements were performed to assess both of the main pump characteristics and their interdependence.

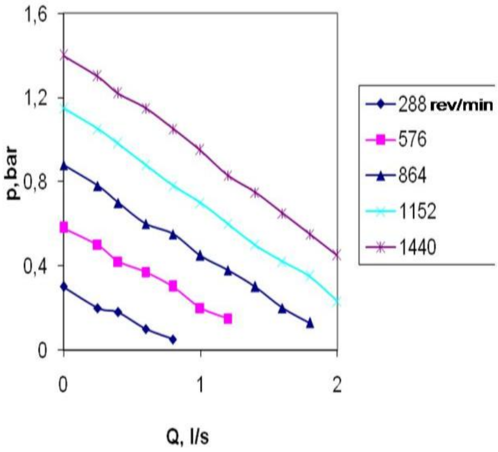


Fig.3.7. Experimentally obtained p (Q) curves at the distance between the magnet blocks d = 48 mm

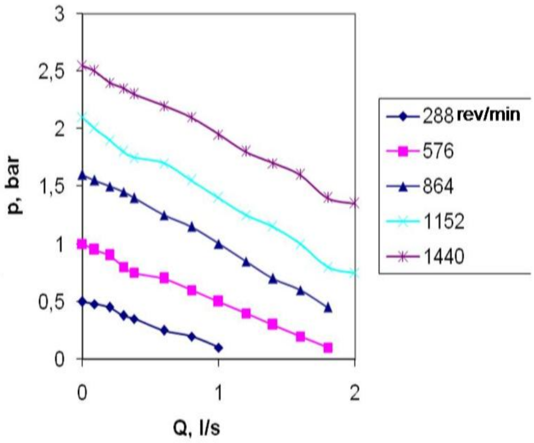


Fig.3.8. Experimentally obtained p (Q) curves at the distance between the magnet blocks d = 40 mm

These parameters determine pumps utilization possibilities, necessary security measurements, allow to assess the efficiency of the pump and to choose the rest of the hydraulic and mechanical components of the loop.

Pumps productivity and developed pressure are associated with a close connection. The higher pressure pump develops, the lower is the flowrate. It may also be formulated as follows: - the higher resistance of rest of liquid metal loop, the lower the flowrate of the pump at the constant structural parameters of the pump. During the measurement process, distance d between the pump magnet blocks was changed, in order to assess the impact of this parameter on the pressure – flowrate parameters.

As we can see in previous chapters, when increasing distance between the pumps permanent magnet blocks, magnetic field induction reduces significantly in the active part, where channel with the liquid metal is situated.

4. COMPARISON OFCALCULATION AND MEASUREMENT RESULTS

4.1. Disc-type permanent magnet pump magnetic induction measurement comparison with calculation results

To assess the magnetic field induction calculation model, we compare experimentally measured data with model calculation data. According to the measurements we have obtained the magnetic field induction value profile (map), which appears in Figure 4.1. Both measurement and calculation results shows tendency of magnetic field decrease when distance d between the magnet blocks increases. Magnetic field value in the middle of the magnet falls from 0:41 T at distance d = 20 mm, to 0:13 at T d = 48 mm when measured directly in the middle between the two magnet blocks (z = 0). Comparing the results of measurements with calculations we can see that the calculation results describes results better directly in the middle of the magnet and at z = 0 – there difference between measured and calculated results does not exceed 3%. At the magnet walls data varies more - up to 17%. As we approach the surface of the magnet difference between measured and calculated results is growing – up to 28% at d = 20 and z = 7.5 mm (16.5 mm from the surface of the magnet). Increasing the distance between the magnet blocks, compatibility between the results of measurements increases. At z = 0 and d = 48 mm in the middle of the magnet difference does not exceed 1.5%, approaching the edges, difference increases to 4%. Asymmetric picture is observed because of uneven magnetization of the magnet. Moving closer to the surface of the magnet, difference at the edges of magnet between calculation and measurement results grows up to 12%.

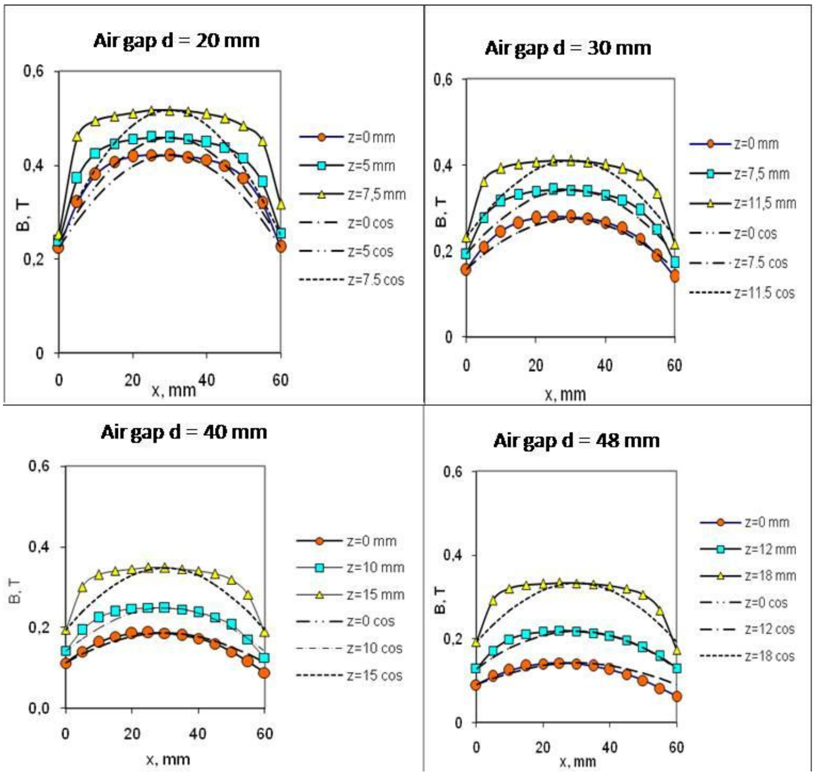


Fig.4.1. Magnetic field induction normal component distribution along the magnet length comparison at the different air gaps d = 20, 30, 40, 48 mm at various distances from the magnet surface (with broken lines for comparison induction distribution of cos law is shown)

If the channel is located in the middle of the magnet and the liquid metal layer is located at certain distance from the magnet surface, where the difference between calculation and measurement results are not too large (no more than 7%), then we can say that the calculation model describes sufficiently magnetic induction distribution in liquid metal zone and can be used in pump output parameter calculation.

4.2. Disc-type permanent magnet pump pressure - productivity characteristic measurement result comparison with the calculation results and speed distribution in the channel analysis

We compare the pressure productivity calculation and measurement results at different distances between the magnet blocks and the different rotational frequencies. The first series of measurements were carried out at the 48 mm spacing between magnet blocks. The obtained characteristics we can see in figure 4.2.

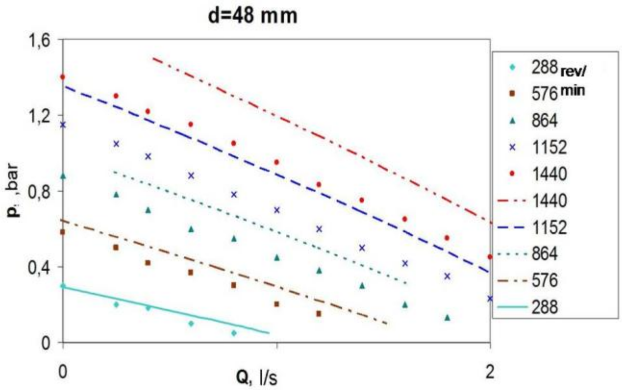


Fig.4.2. p (Q) characteristics at d = 48 mm and various disk rotational speeds, n = 1440, 1152, 864, 576 and 288 r / min

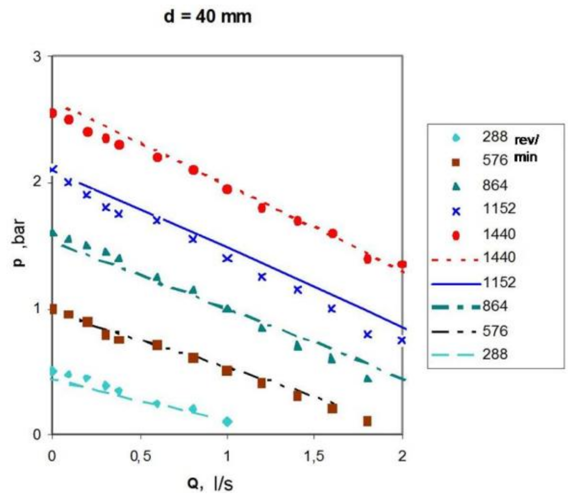


Fig.4.3. Characteristic at d = 40 mm and various disk rotational speeds, n = 1440, 1152, 864, 576 and 288 r / min

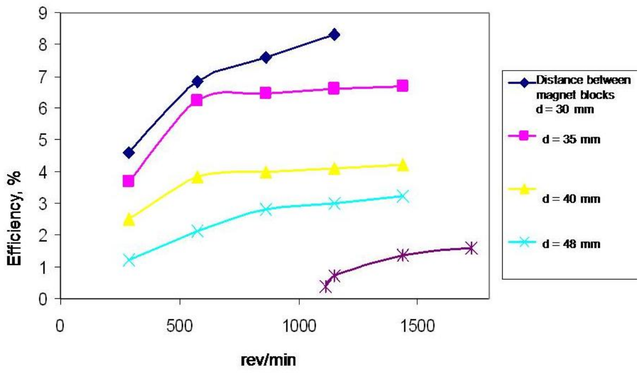
The measurement results are shown with colored points, the estimated correlations plotted as a curve. As we can see the measurement results of the connection is linear. Comparing the results of measurements with the calculation results we can observe that the calculation results of the characteristic across all of the p - Q-range match with results of measurements points sufficiently. The biggest difference does not exceed 15.2%. This is explained by the fact that the calculation model assumes a constant pole pitch, which does not change along the pump diameter, because permanent magnets are arranged in radial direction.

Difference between calculation results of the experiments reaches 8.2% at the pump maximum pressure developed. Thus we may conclude that the calculation model better describes characteristics of the pump at the smaller distances between magnet blocks. To assess the effects of an experimental model of the pump efficiency was compared with the other disc type pump.

For comparison disc type pump for InGaSn eutectic pumping at 300°C temperature is selected. Its magnet block outer diameter is 300 mm, number of pole pairs - 6, but the magnet dimensions are 15 x 60 x 10 mm. Both pumps magnet inductance value is the same. Pumps channel internal cross-section is 60 x 10 mm. The pump selected for comparison because of similar characteristics. The distance between the magnet blocks for this pump is 46 mm.

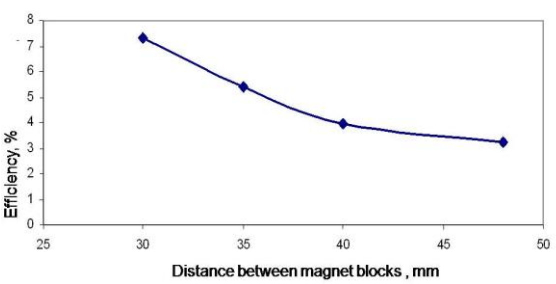
Efficiency coefficient dependence of pump rotation speed and distance between magnet blocks can be seen in figure 4.4.

Here you can see that the pump efficiency increases with rotation speed increase and decreasing the distance between the magnet blocks. Comparison shows that distance reduction between the magnet blocks from 48 to 30 mm gives efficiency coefficient increase three times. Comparing these data with another pump, which also is used for InGaSn eutectic, we see that at a similar distance between the magnet blocks (48 and 46 mm), efficiency is three times higher for the pump, which magnetic system parameters are calculated with the mathematical model viewed at the work.

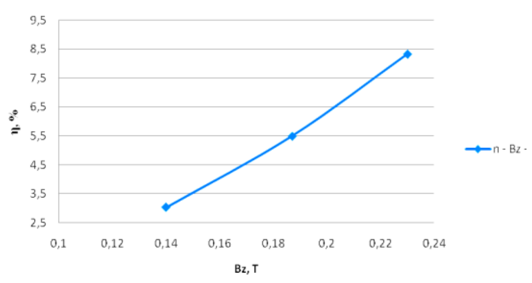


4.4. Fig. Efficiency coefficient dependence of pump rotation speed and distance between magnet blocks compared with the high-temperature pump efficiency

This suggests that balanced magnetic pump system parameters allow to increasing pumps efficiency and improving the output parameters - pressure and flowrate. At figure 4.5. the efficiency coefficient dependence on the distance between the magnet blocks is shown. The increase of the distance between the magnet blocks gives an efficiency decrease. Therefore minimal possible distance between the magnet blocks should be ensured. This sets special requirements for the pump channel and the manufacture of insulating materials, if any, are used.



4.5. Fig. Efficiency coefficient depending on the distance between the magnet blocks



4.6. Fig. Efficiency coefficient depending on value of magnetic field induction normal component Bz

In Figure 4.6. the relationship between the magnetic field induction value of the normal component Bz and pump efficiency shows that the increase in magnetic induction increases efficiency. This again emphasizes the considerable value of the magnetic field effect on pump efficiency and output parameters.

CONCLUSIONS

1. At this work disc type permanent magnet pumps magnetic systems created magnetic induction calculation model is developed. With the developed mathematical model, it was observed that increasing the pump active zones height, the magnetic field in the zone decline. If the magnet pole width, height or pole step magnetic field increases, magnetic field induction initially increases rapidly, but continuing to further increase these parameters, the growth rates are falling and reach a certain "saturation". These structural parameters have sufficient effect on the magnetic field at the pump core, but must be carefully balanced at the optimization of parameters and comply with all structural requirements to meet the required pump output parameters and constraints to make its construction is reasonable and harmonious. For the pump viewed at the work selected permanent magnet height is 20 mm, width 20 mm and the average pole pitch 26 mm.

2. Pumps output parameters - pressure and flowrate calculation using the model from literature [9] was done. Calculations were performed at different distances between the magnet blocks (30, 40 and 48 mm) and at different rotational speeds of the magnet blocks. There is a linear regression - increasing pressure will reduce the pump output capacity. Increasing the pump rotational speed of magnet blocks will increase the pumps developed pressure and flowrate. Liquid metal velocity distribution calculation at the pump channel was carried out at the magnet block distance of 40 mm and a rotation speed of 1440 r/min. Observed that at low pressure of fluid in the pump channel power moves in the direction of magnet block rotation, but when the back pressure increases back flows occur, which lowers the pump efficiency.

3. Disc type permanent magnet pump was made. Pumps magnetic systems magnetic field induction measurements showed that the magnetic field increases three times, if the distance between the magnet blocks is varied from 20 to 48 mm. This suggests that using the

pump at high working temperatures, thermal insulation and heat reflective screen use can significantly reduce pump output characteristics.

4. An experimental device for pumps pressure - flowrate performance measurement was made. Pumps pressure - flowrate measurements at different distances between magnet blocks and rotational speeds were done. It is observed that distance reduction between the magnet blocks from 48 to 20 mm gives pump developed pressure increase more than 7 times. At the same time the magnetic field increases 3 times by reducing the distance between the magnet arrays from 48 to 20 mm This allows to talk about the square relationship between the pressure characteristics and the magnetic induction value, which coincides with the theoretical data.

5. Comparison of data obtained by mathematical model with measurement results is done. Both measurement and calculation results show the trend of increasing magnetic field when the distance d between the magnet blocks is decreased. The developed mathematical model describes well the magnetic field induction of the magnet along the middle surface of the magnet, along the edges of the magnet data differ more.

Comparing the results of measurements with the calculation results we can observe that the calculation results of the curve across the p - Q-range sufficiently consistent with the results of measurements points. The biggest difference does not exceed 15.2%. This is explained by the fact that the calculation model assumes a constant pole step - permanent magnets are arranged in radial direction so pole step varies along the magnet length.

Using the findings for output parameters - pressure - flowrate calculation we managed to get a good match with experimental data, which suggests that this model is useful for use in calculations. Comparing the results of measurements with the calculation results we can observe that the calculation results of the curve across the p - Q-range sufficiently consistent with the results of measurements points. Thus we may conclude that the calculation model better describes the characteristics of the pump at the smaller distances between the magnet blocks.

Comparing the pumps magnetic systems magnetic field induction and the same pumps pressure – flowrate measurements the relation between the magnetic field induction values and pumps output parameters was observed. Comparing the maximum pump pressure developed across the revolution range at different distances between the magnet blocks, magnetic field, reducing the distance between the magnet arrays from 48 to 20 mm increases by 3-fold. By contrast, the maximal pumps developed pressure changing the distance between the magnet arrays from 48 to 20 mm, increased by more than 7 times. This allows talking about a significant magnetic field induction influence on the pumps developed pressure. This correlation is close to square, which generally coincides with the theoretical data.

Comparing pump viewed at the work with earlier produced PM disc type pump can be seen that balancing the magnetic systems characteristics allow to increase pump efficiency. Similarly pumps efficiency depends on the magnet blocks rotation speed and the distance between them. Reducing the distance between the magnet blocks from 48 to 30 mm, can increase pump efficiency almost twice. Choose a suitable pump operating regime to allow the pump work at the highest efficiency.

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