PARAMETERIZATION OF ACTUATING ELEMENTS OF PUMPING ELECTROMECHANICAL CONVERTERS

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ABSTRACT

The question of validity of the choice of an actuating element of heat-generating pumping devices with blade structures is considered. These devices are characterized by low hydraulic resistance of a working channel, absence of support and sealing parts, a wide range of design modifications of increased efficiency. Their feature is that the supporting element is not the traditional shaft, but the outer surface of the actuating element. The article shows what parameters of the elements used ensure modeling and control of heat transfer processes.

Keywords: *transport power system, heat-generating transfer device, actuating element, parameters, 3D model, independent control.*

Background. *Pumping devices with blade actuating elements are widely used in industrial and transport power systems. Traditionally, they are represented by centrifugal, axial or diagonal pumps, fans and compressors, aggregated with adjustable drive motors. However, despite such advantages as a significant reduction in hydraulic resistance of the working channel, the lack of supports and sealing parts, an expanded range of design modifications of increased efficiency, only in a small part of blade devices a bearing element is not a traditional shaft, but the outer surface of the actuating element. And this became possible only after the appearance of a fundamentally new type of functionally combined pumping electromechanical converters (PEC), in which the actuating element is an integral part of the drive mechanism [1–3].*

Objective. *The objective of the authors is to consider parameterization of actuating elements of pumping electromechanical converters.*

Methods. *The authors use general scientific and engineering methods, simulation, comparative analysis.*

Results.

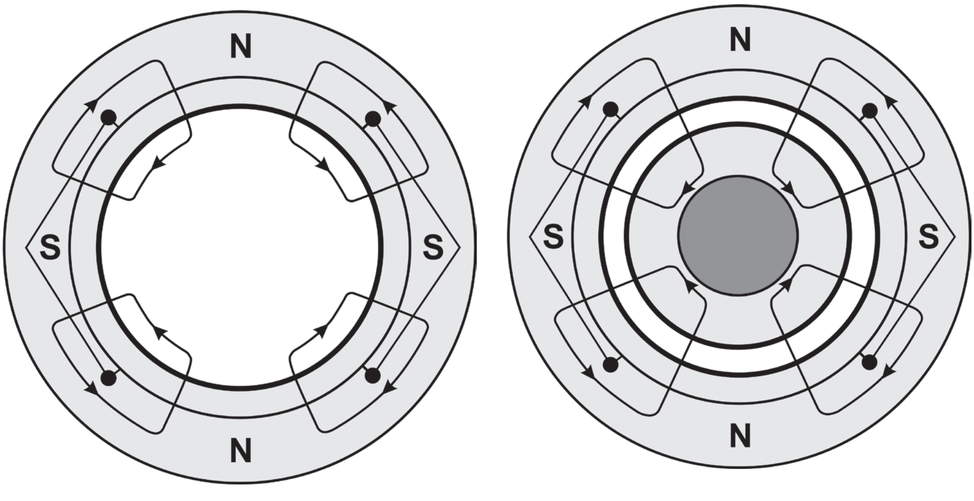
From general to specific

The main feature of PEC as a device for transfer of the heated medium is an extremely low hydraulic resistance due to the lack of a shaft and classical bearing assemblies. At the same time, such a design, in the absence of an internal ferromagnetic conductor, is characterized by a significant magnetizing reactive current and power consumption, leading to heating of the hermetically sealed stator of PEC, which is associated with an increased magnetic resistance of the magnetizing circuit and distribution of the electromagnetic field in which a large part of its power lines passes through a non-magnetic section inside the device. Pic. 1 shows for comparison, the distribution of the magnetic field in the inner region of PEC (a) and the induction motor (b) for a four-pole version.

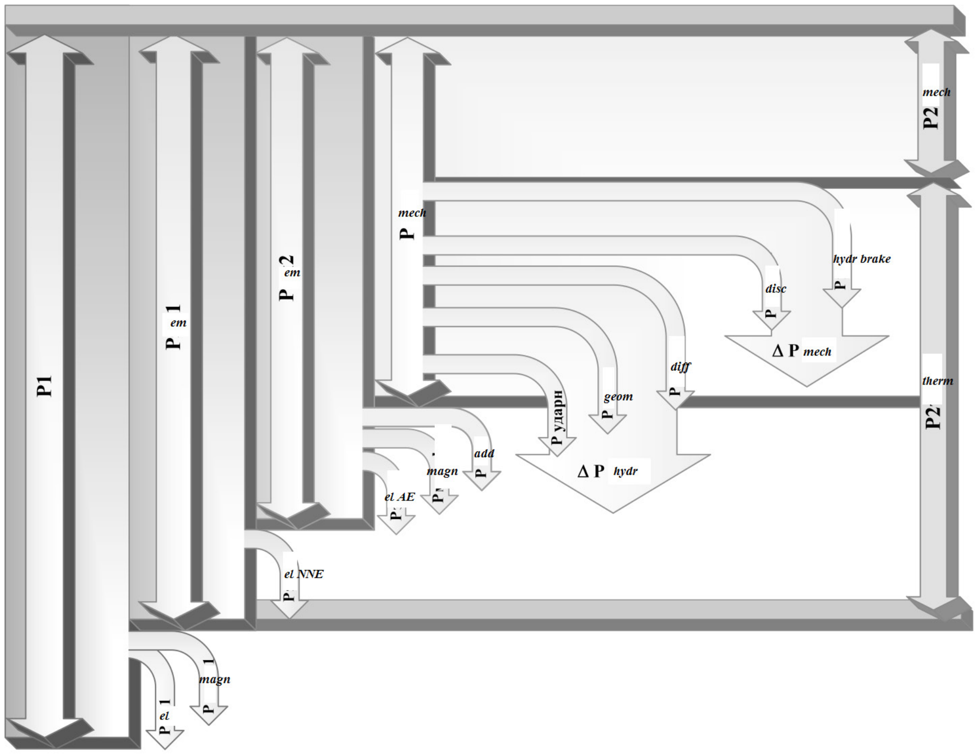
The principle of PEC operation, which explains energy conversion in the considered combined device, is based on the analysis of processes typical for traditional electromechanical converters.

Pic. 2 shows the energy diagram of PEC, which illustrates conversion and distribution of power with allocation of all components of losses that determine efficiency of the device.

It can be seen from the diagram that the output power of PEC represents the sum of thermal and mechanical powers and is determined by power consumption P_1. In this case, the power going to move and heat the working medium is the difference between P_1 and all losses, except for electrical losses in the primary winding P_{el1} and magnetic losses in the



Pic. 1. Field lines of the magnetic field in absence (a) and presence (b) of the internal ferromagnet.

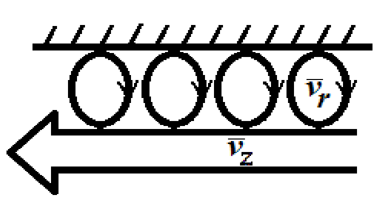


Pic. 2. Energy diagram of PEC.

steel of the tight magnetic core P_{magn1}. Mechanical power P_{2mech} provides movement of a working environment with the set parameters of pressure and productivity, and thermal P_{2therm} – its heating to the demanded temperature. In steady-state operation modes at a speed of rotation of the actuating element close to synchronous (n_1), the thermal parameters of PEC will be determined mainly by the parameters of the stationary heating element, while the actuator reflects productivity (flow rate) and pressure (head).

Pumping electromechanical converters constructively integrate drive, transmission and actuating mechanisms and at the same time do not have mechanical transmissions, reducers, multipliers, variators and seals. The combination of the functions performed by them without deteriorating the performance characteristics makes them promising for reconstruction and replacement of existing equipment.

Analysis of scientific sources [4–8] shows that the main research of PEC is aimed at comprehensive maintenance of their operational reliability, and the issues of designing and optimizing the parameters of the direct actuating elements (AE) of converters remain in the background because of the lack of adequate mathematical models of mass transfer processes with an interconnected accounting for electromagnetic, hydraulic, thermal, mechanical effects.



Pic. 3. Combined heat and mass transfer model.

Algorithm of identification

Parameterization of actuating elements, which allows to establish their basic geometric relationships, involves several stages:

1. Preliminary determination of configurations and volumes of zones with different types of fluid flow based on the theory of the boundary layer.

2. Parameterization of the model, which simultaneously ensures the accuracy of mapping of thermal and hydraulic processes and limits the complexity of mathematical representations necessary for its analysis.

3. Construction of a three-dimensional geometric solid-state parametric model.

4. Assignment of initial and boundary conditions, constraints-equalities, constraints-inequalities, optimization criteria.

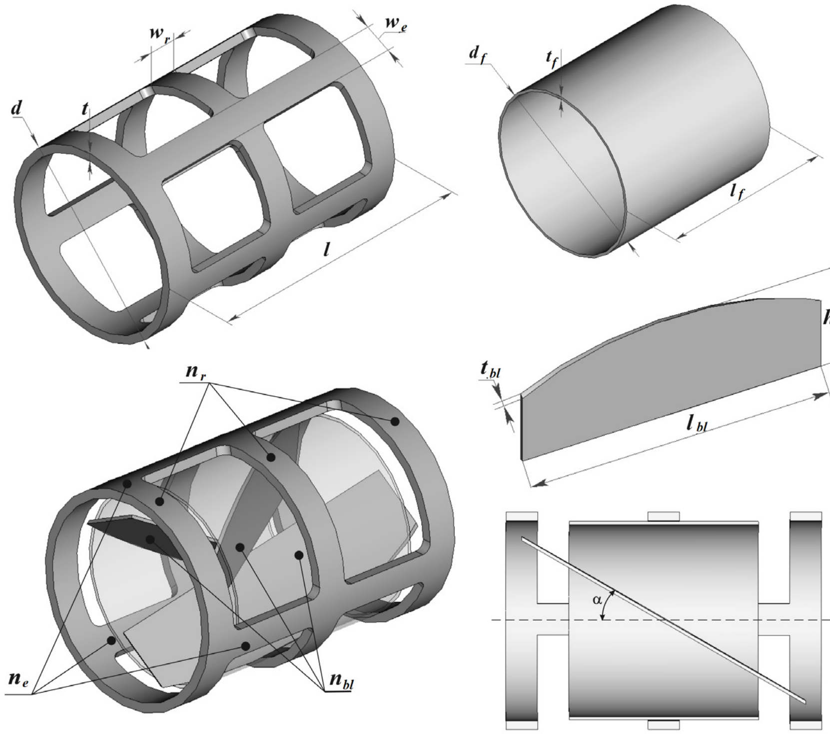
5. Ensuring the possibility of organizing an iterative computational experiment on the basis of expert assessments of the suboptimal parameters of the actuating element.

6. Conducting a computational experiment on the basis of a virtual three-dimensional model.

7. Determination of the weight coefficients of design parameters.

8. Testing the adequacy of the model by comparing the results of computational and full-scale experiments.

Analysis of the hydrodynamic conditions with respect to the actuating elements of PEC shows that



Pic. 4. To a selection of design parameters of AE of PEC.

the a priori specification of the exact initial and boundary conditions is impossible because of the complexity of the distribution of the flow elements of the pumped medium due to the unevenness of the flow velocity profile, its turbulence, the formation of unrecognizable discontinuous currents, stagnant zones, and associated currents, interphase heat and mass transfer processes.

Parameterization of the actuating element can be performed using a mixed model describing a set of interconnected flow areas with different characteristics [9–11]. The model is applicable both for simple idealized flow regimes (mixing, displacement, displacement with diffusion), and for complex (partially immiscible, back-circulating, jet streams). The main condition for using the ideal mixing model is that the required mixing intensity is provided automatically due to the presence of a rotating actuating element. The model of ideal displacement presupposes the piston nature of the flow of the medium and the absence of flow mixing. In this case, the time of motion of the medium is determined by the ratio of the volume of the internal channel of PEC to the volumetric flow, as in tubular heat exchangers in the turbulent flow of a fluid with a uniform velocity profile.

Identification of characteristic heat and mass transfer target areas, shown in Pic. 3, is made on the basis of the analysis of the processes of ideal mixing (the intensity of the circulation of the flow leads to uniform mixing of the incoming and channeled medium with radial velocity $\overline{v}_r$) and ideal displacement (the flow consists of particles of the transported medium moving uniformly at the same axial velocity $\overline{v}_z$).

The mixed model allows to consider two conditionally independent processes: heating and displacement of the medium, the process of displacement being the determining factor for both the intensity of the heat removal from the channel wall and the performance of PEC.

Selection of design parameters of AE

Preliminary selection of the basic design parameters of the actuating element that characterize the mass transfer process in PEC can be done with the help of the model of an idealized single-flow and single-stage mechanical power source having an infinitely large number of flat blades of a single thickness that move the physical medium. Such a model corresponds to a design in the form of a set of two static end rings connecting the pressure blades, with a variable number of blades, a variation in the geometric dimensions, and the angles of inlet / outlet of the flow.

At this stage, the technique for determining the velocities of the same type of technical devices for moving liquids and gases is based on the use of the Euler equation, which makes it possible to calculate the pressure characteristics of a blade device from the known speed distribution in the working channel:

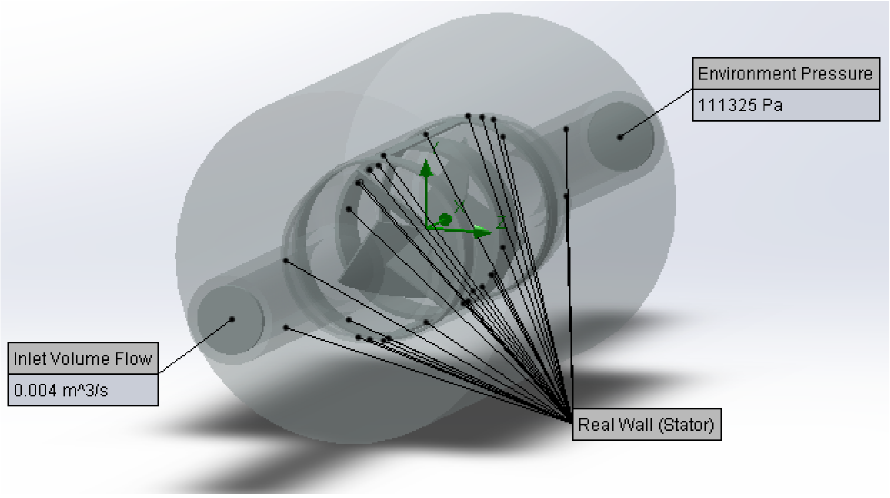
$$gH = u_2\upsilon_{2u} - u_1\upsilon_{1u},$$

where g – acceleration due to gravity, m/s²; H – head, m; u_1 – tangential velocity at the blade inlet, m/s; u_2 – tangential velocity at the output of the element – blade of AE, m/s; υ_{1u} – tangential component of the absolute velocity at the input, m/s; υ_{2u} – tangential component of the absolute velocity at the output, m/s.

To go to the real element, it is necessary to take into account:

• the number of AE blades, which depends on the functional purpose of PEC (low-, medium-, high-pressure) and for low-pressure devices it is no more than 10–12;

• design parameters: outer diameter of AE – d; length of AE – l; thickness of AE – t; number of rings



Pic. 5. Setting of boundary conditions.

of AE – n_r; number of edges of AE n_e; width of the ring of AE – w_r; width of the edge of AE – w_e; blade length – l_{bl}; blade thickness – t_{bl}; blade height – h_{bl}; number of blades – n_{bl}; blade angle – α; the diameter of the internal ferromagnetic conductor (FM) – d_f; the length of FM – l_f; thickness of FM – t_f (Pic. 4);

• volumetric, hydraulic and mechanical losses.

Creating a 3D Model

Preliminary selection of design parameters of AE allows to proceed to the stage of creation of a three-dimensional solid-state parametric model of AE. The absence of a priori information on significance of individual parameters necessitates the study and evaluation of their influence on its output characteristics on the basis of the theory of experimental design.

Finding a suboptimal version of AE requires the creation of its flexible variational geometric model. This task is solved using the technology of parameterization based on the computer-aided design system T-FLEX CAD.

The implementation of the parametric 3D model project begins with 3D fragments of the individual AE parts. The modeling process is divided into two stages:

1. Creation of the geometry of the projected object (profile construction, 3D modeling operations, positioning of parts in the assembly model).

2. Specification of parameters of the projected object (linear, angular dimensions, number of elements) and their values (numbers, variables, expressions).

The model of the «actuating element» assembly unit includes the fragments: the body of AE, the ferromagnetic conductor, the blade and allows to control the geometric shape of the assembly elements in T-FLEX CAD. Parameter values are transferred using the external variables of the fragment (for example, diameter, length, thickness of the body of AE, diameter, length, thickness of FM, length, blade height); the number of assembly elements (for example, the number of edges and rings of the body of AE, the number of blades); position of the assembly elements (for example, the angle of inclination of the blades).

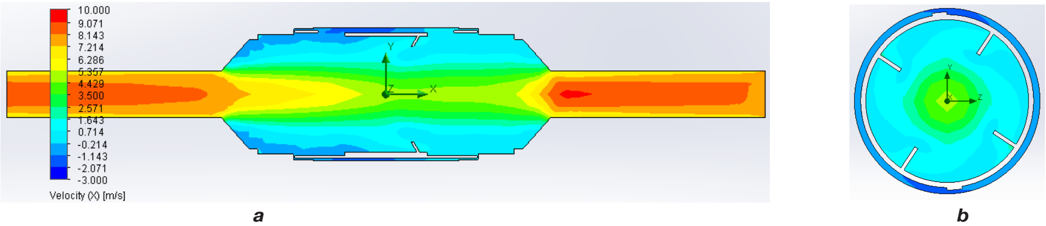
The design parameters for parameterization of the elements of the assembly model of AE are divided into two groups. The group of basic variables include: outer diameter – d; length – l; thickness – t; number of rings – n_r; number of edges – n_e; width of the ring – w_r; width of the edge of AE – w_e. The group of auxiliary variables of the body of AE includes: pocket angle – alfa_karm and ejection length – dl_vyt.

When forming a three-dimensional assembly parametric model of AE, the external variables (3D fragments) are linked with the variables of the assembly unit. Thus, the parameters of the assembly unit automatically change the parameters of the 3D fragments depending on the values of the input data. Parameterization allows obtaining various constructive variants of AE and proceeding to an assessment of the influence of dimensional relationships on the process of heat and mass transfer in the target areas.

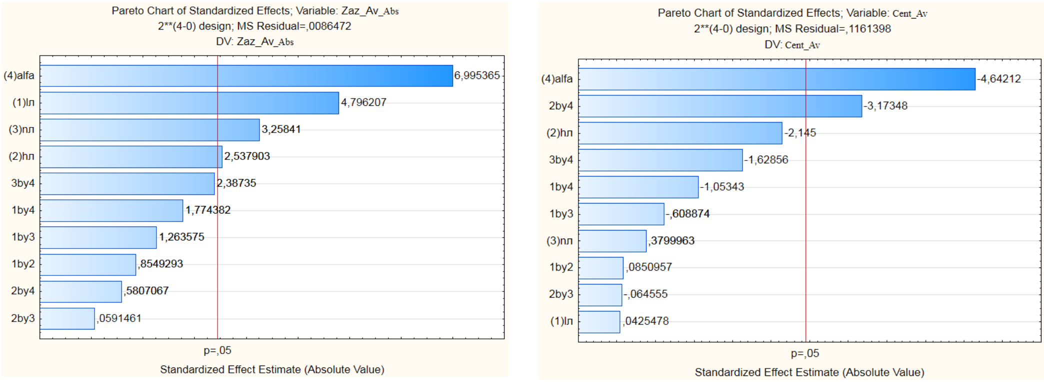
Boundary conditions and constraint conditions

The factors limiting the choice of AE parameter values are determined by the set of processes occurring in the PEC and its design features. Analysis of the processes of heat and mass transfer shows that the criteria for selecting parameters can be:

• for electromagnetic processes – the permissible current density and the permissible value of induction in the elements of the magnetic circuit, determined

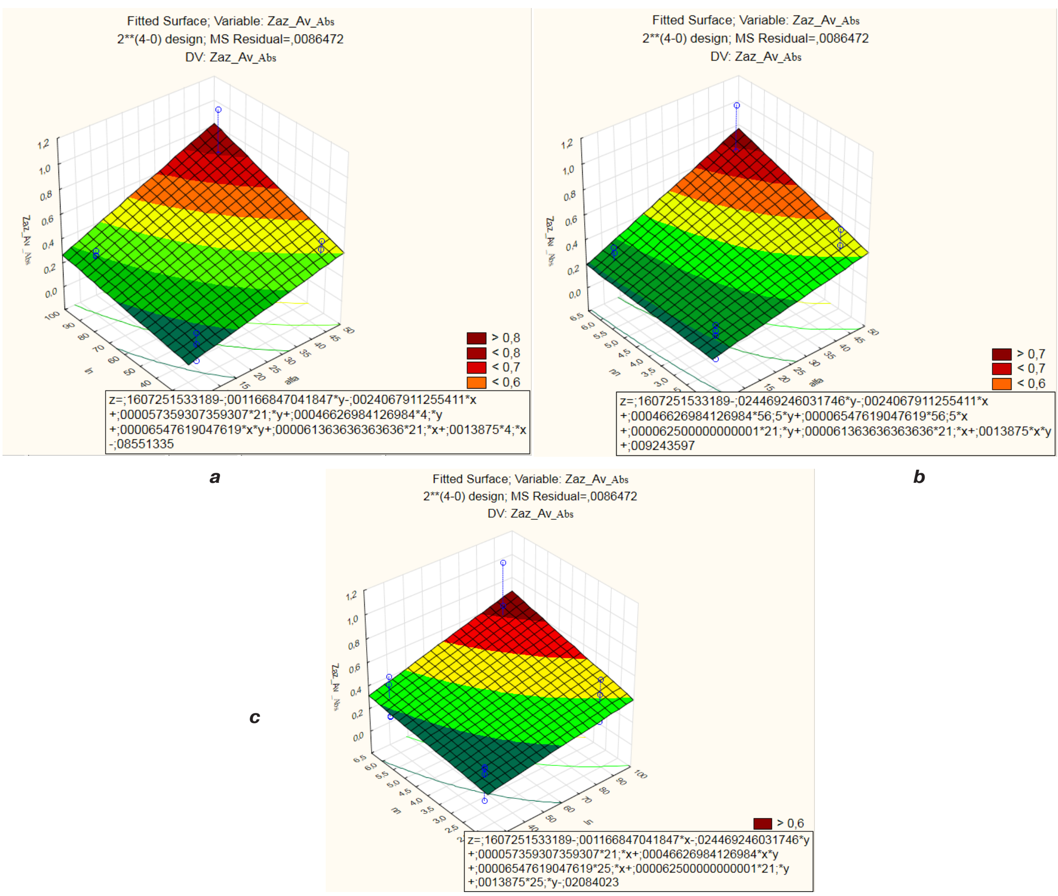


Pic. 6. Visualization of the result of calculating the velocity field in the longitudinal (a) and cross sections (b) of the channel.



a ***b***

Pic. 7. Pareto diagrams.



Pic. 8. Response surfaces for significant design parameters.

taking into account the conditions of heat exchange with the working medium;

• for mechanical processes – the ultimate strength of structural elements in static and dynamic modes;

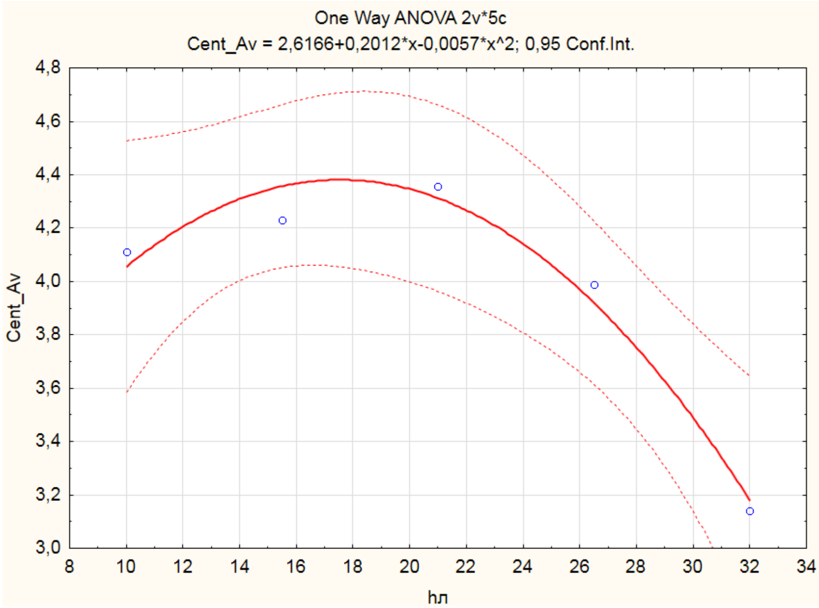
• for hydraulic processes – the minimum hydraulic resistance created by the actuating element;

• for thermal processes – ensuring the permissible values of the temperature of the working medium at the outlet of the channel.

The input volumetric flow is set as the boundary conditions (Invlet Volume Flow 0.004 m^3/s) and the outlet pressure (Environment Pressure 111325 Pa); for the channel (Stator), the boundary condition is Real Wall (Pic. 5).

Based on the configuration of the modeling areas and recommendations given in [1], it is possible to limit the ranges of variation of individual AE parameters.

Thus, the outer diameter and length of AE are selected from the following conditions:



Pic. 9. Dependence of the axial component of the velocity of the working medium on the blade height.

$d < D_1$; $l < l_1$,
where D_1, l_1 – internal diameter and length of the channel.

The thickness of AE is determined by the conditions of the minimum hydraulic resistance and the necessary mechanical strength:
$0 < t \ \ k_r \cdot t_{add}$,
where k_r – coefficient of reliability, taking into account the design features and technology of production of AE, adopted by general machine-building techniques and is 1,1–1,2 for a solid cylinder; t_{add} – minimum thickness of AE, obtained taking into account the limits of mechanical strength.

The number of end rings of AE is assumed to be n_r = 2, based on the condition of shorting the secondary current of PEC. If it is necessary to increase the mechanical strength of AE and to ensure the possibility of placing pressure blades, n_r can be increased, but this should not lead to a deterioration of the heat transfer conditions when the working medium moves relative to the channel wall.

The widths of the edges w_e and rings w_r of AE are chosen from the permissible current density in forced convection conditions, taking into account mechanical loads and the results of hydraulic calculation.

The number of edges n_e is chosen from the condition:

$$n_e = \frac{M_2}{(l - 2w_r)w_e t \cdot \sigma_{add}}$$

where M_2 – torque applied to AE; σ_{add} – permissible ultimate strength of the material.

The length of the blade l_{bl} is limited by the value of the installation angle α and the internal diameter of the FM and is selected in the range $0 < l_{bl} \leq l_{bl.max}$.

The range of variation of the blade angle α – 0–45°.

The thickness of the blade is selected in accordance with the minimum hydraulic resistance and the necessary mechanical strength:
$0 < t_{bl} \leq k_r \cdot t_{add}$,
where t_{add} – minimum thickness of the blade, obtained taking into account the strength limits of the material and the results of the mechanical calculation of the blade.

The height of the blade is limited by the internal diameter of the FM $h_{bl} < 0,5d_f$.

The outer diameter and length of the FM must satisfy the conditions $d_f < d\text{-}t$; $0 < l_f < l - 2w_r$.

The thickness of the internal ferromagnetic conductor, which determines its internal diameter and, accordingly, the hydraulic resistance of the flowing part, is preliminarily selected equal to the minimum width of the stator tooth $t_f = b_z$.

The minimum number of blades is chosen from the symmetry condition $n_{bl} \geq 2$.

Modeling the velocity field

The process of modeling the movement of the working environment is visualized as a velocity field using the CFD (computational fluid dynamics) of technologies based on the SolidWorks Flow Simulation module [12]. Variations in the geometry of AE are carried out automatically by the program for parametric modeling. The values of the parameters are determined from the plan of the full-factor experiment. The number of files obtained corresponds to the number of tests in the experiment. Parameter files are used when updating the geometry model of AE.

An example of the results of calculating the velocity field in the longitudinal (a) and cross sections (b) for the target zone of ideal channel displacement is shown in Pic. 6.

For a preliminary assessment of the effect of the design parameters of AE on the average velocity of the medium moving, a weighted average velocity value is taken from the graphical display of the velocity field.

Based on the Pareto diagrams, significant factors are determined: for the target zone of ideal mixing, the blade mounting angle α, blade length l_{bl}, number of blades n_{bl}, blade height h_{bl} (Pic. 7a); for the target zone of ideal displacement – the angle of installation of the blade α and the joint influence of α and h_{bl} (Pic. 7b).

Pic. 8a, b, c show the response surfaces for significant factors α, l_{bl}, n_{bl} in the target zone of ideal mixing.

Analysis of influence of significant parameters

Represented in the form of response surfaces in Pic. 8 the results of the simulation allow us to analyze the influence of significant design parameters on the magnitude of the axial component of the displacement velocity of the working medium.

The main significant parameter is the height of the blade h_{bl}, nonlinearly related to the axial component Cent_Av (Pic. 9, constructed for the confidence interval).

The initial increase in speed is explained by the increase in the area of the blades and the insignificant overlapping of the working channel by the blades. The choice of values of h_{bl}, exceeding the critical value (18 mm) leads to a decrease in the speed and a decrease in the performance of PEC.

The next important is the angle of the blade a, which simultaneously influences the heat and mass transfer processes, which does not allow it to be used for separate control of the output parameters of the converter.

To a less extent, the mass exchange process is influenced by the length of the blade l_{bl}, which turns out to be the third most important parameter.

The number of blades n_{bl} at the main stage of the study turned out to be an insignificant parameter, however, with further simulation, the joint calculation of the number of blades and the inclination angle of the blade n_{bl}+a made the parameter the fifth most important. With an angle of 45°, the number of blades n_{bl} became the fourth in the parametric rating.

The thickness of the body of AE t was the most significant parameter for the ideal mixing zone, in which the parameter t and the axial velocity component are inversely correlated.

On the whole, the analysis of the influence of significant parameters shows that for separate control of the output parameters of the PEC it is possible to use: in the zone of ideal mixing – t, l_{bl}, n_{bl}, in the zone of ideal displacement – h_{bl}.

Conclusions.

1. The area of research of pumping electromechanical converters can be represented by two unconnected sub-areas: ideal mixing and ideal displacement.

2. The axial velocity component in the channel is a functional for determining the capacity of the converter and its thermal state.

3. A priori, the main design parameters of the actuating element are its outer diameter, length and thickness, the number and width of the rings and edges, length, thickness, height, installation angle and number of blades, and the dimensions of the internal ferromagnetic conductor.

4. The parameters of the actuating element in terms of their significance are distributed as follows: blade height, installation angle, blade length, number of blades, body thickness.

5. Independent control of the process of heat transfer is provided by the parameters – t, l_{bl}, n_{bl}, the process of displacement – h_{bl}.

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