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V. E. DRANKOVSKIY, K. S. REZVAYA, E. S. KRUPA

CALCULATING THREE-DIMENSIONAL FLUID FLOW IN THE SPIRAL CASING OF THE REVERSIBLE HYDRAULIC MACHINE IN TURBINE MODE

One of the stages of a numerical research of water passage of the reversible hydraulic machine in turbine mode was described with program packages. Graphical results in the form of the velocity and pressure distributions in the predetermined modes of operation of reversible hydraulic machine were obtained. On the basis of these data can be obtained average kinematic parameters of the flow, which are determined in the inlet of calculation domain. Analysis of this numerical research was performed.

Key words: numerical research, reversible hydraulic machine, inlet, water passage, spiral casing, stay vanes, turbine mode, calculated mode, pressure distribution, velocity distribution.

Introduction. During the last decades, a huge change has occurred in the solution of problems of applied hydromechanics.

One of the main problems of modern designing of hydraulic machines is the calculation their energy characteristics. This makes it possible at the stage of the calculation to replace real experiment by numerical one.

Currently, there are many software program packages (ANSYS, XFlow, FlowVision, IPMflow, Fluent, etc.), which allow to do the numerical research of spatial flows of viscous fluid in the water passage of the hydraulic machines to a new level. Along with it, systematization of data of average kinematic parameters of the flow and coefficients of the energy loss in the elements of water passage was performed. These data were obtained on the basis of the theoretical and experimental researches of reversible radial-axial hydraulic machines.

Designing of perspective constructions of hydraulic machines and modernization of existing one requires obtaining geometry of water passage. This model must maximally satisfy numerous criteria of quality, such as the maximum average coefficient of performance (COP), the required values of cavitation coefficient, strength limitations, manufacturability, durability and metal consumption [1].

Main part. Increase of the efficiency of in the reversible hydraulic in pumping and turbine modes is an important technical and economic requirement in improving of the energy efficiency of the power system. Its further increase is possible only after careful research of the spatial structure of the flow in all elements of water passage (WP). In designing of water passage is widely used numerical and experimental research methods [1, 5].

One of the important elements of water passage of the high-pressure hydraulic machine in turbine mode is an inlet. Spiral casing (SC) together with the stator is used to for supplying the water to the unit and forming the necessary flow at the inlet to wicket gate (WG). They must ensure the axisymmetric uniform flow of liquid with acceptable values of velocities and angles of attack at the inlet of guide vanes, but the energy losses must be minimal.

The structure of the flow in spiral casing and the stator has a complex spatial form. It depends on the angle of coverage, and forms of cross-sections and accepted velocity distribution law. The study of fluid flow in these elements allows to set the zone of high-energy losses and to find ways for reducing them.

In practice of hydraulic mechanical engineering, in designing of spiral casing different methods are used. They are based on the assumption of the constancy of the velocity moment at any point of the spiral ($V_u \cdot r = const$), the constancy of the average velocity ($V_u = const$), the constancy of the law $V_u/r = \text{const}$ or in combination of these laws.

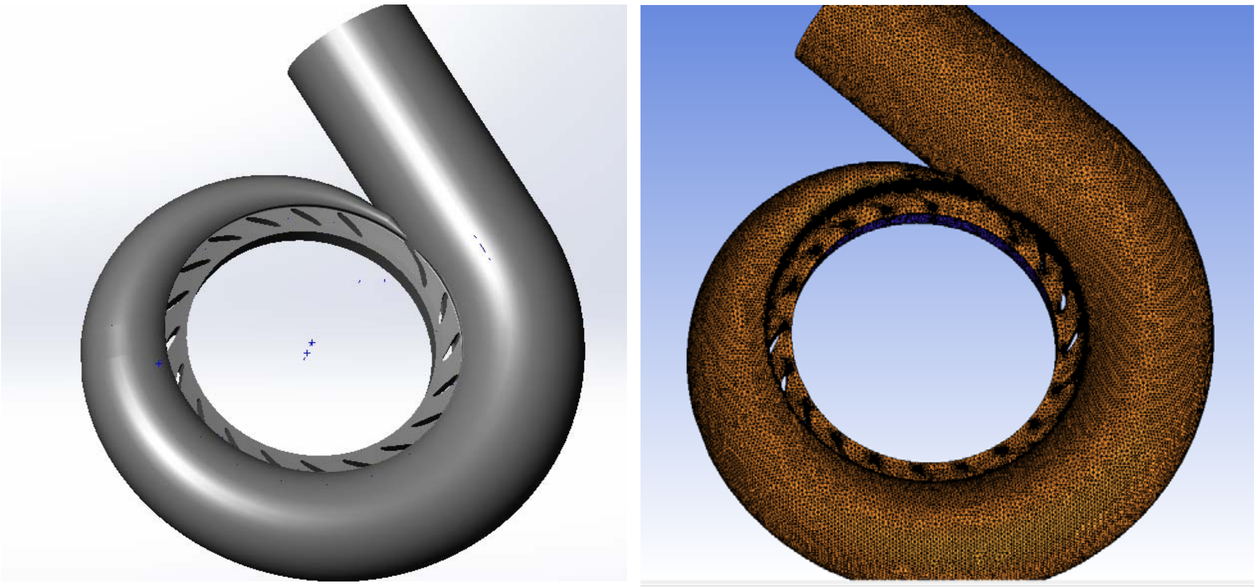
As a result of calculating the three-dimensional flow velocity and pressure fields were obtained. the averaged flow characteristics and energy losses in elements of water passage will be determined on the base of these fields. It is allowing to determine the coefficient of the resistances in elements of water passage and to calculate the energy characteristics, on the base on mathematical models of the working process in hydraulic machines [2].

One of the programs, which allows modeling the three-dimensional steady flow of an incompressible fluid in the channels of hydraulic machines, is software package CFD. The complex CFD has a user-friendly interface that allows performing automatic generation of mesh, choosing a mathematical model of the flow and setting the boundary conditions.

The first stage is to create the geometry of calculation area (fig. 1, *a*), and then it is imported into the program.

The next stage of numerical simulation is to create a mesh. The logic of any numerical simulation suggests partitioning calculation area into elements. In the nodes of the mesh values of the sought variables are determined (mainly velocity and pressure) and boundary conditions of the problem are set. With the design module can be fast enough to break considered area to the elements that make up the so-called unstructured or structured mesh.

In this paper, the investigating spiral casing with the stator columns were divided into prismatic elements of unstructured mesh. The number of cells was about 4,5 million (fig. 1, *b*). Local fragmentation near edges of the stator column was made; the maximum and minimum sizes of the global object were specified. This method is simple and convenient, but the error of performed calculation on this mesh about 5 % higher than the calculation on structured meshes.



a *b*

Fig. 1 – Models of the spiral casing with stay vanes:
a – geometrical model; *b* – finite element model

As the boundary conditions at the numerical research were selected:

- at the inlet to spiral casing – the mass flow rate;
- the outlet of spiral casing – static pressure.

Research of fluid flow was conducted on the head $H = 1$ m and the runner diameter $D_1 = 1$ m. The work of the reversible hydraulic machine in turbine mode at optimal ($Q_I' = Q_{Iopt}'$) and calculated ($Q_I' = 1{,}33Q_{Iopt}'$) points of the universal characteristics was considered. Angle of coverage in the plan $\varphi = 360°$ with circular and elliptical meridian section of the spiral casing, which calculated according to the law of constancy of the average velocity. The stator consists of 20 vanes, uniformly arranged in a circle including spiral casing tooth. In the spiral casing tooth area for reducing limitation of flow one vane is removed. The meridional projection of stator has a conical form to provide acceptable flow characteristics at an input in the spiral casing in pumping mode.

There is the graph of the relative area of the meridian section on the fig. 2. It is defined relative to the input cross-sectional area and depends on the angle of coverage [3].

k-*ε* turbulence model (equation of energy and dissipation rate) was used in calculations. This model makes possible to close the equation of continuity and the Reynolds-averaged Navier-Stokes equation.

$$\frac{\partial}{\partial x_j}\left(\rho \bar{u}_j\right) = 0;$$

$$\frac{\partial}{\partial t}\left(\rho \bar{u}_i\right) + \frac{\partial}{\partial x_j}\left(\rho \bar{u}_i \bar{u}_j\right) + \frac{\partial}{\partial x_j}\left(\rho \bar{u}'_i \bar{u}'_j\right) =$$

$$= -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)\right] + f_i;$$

$$\frac{\partial k}{\partial t} + \bar{u}_j \cdot \frac{\partial k}{\partial x_j} =$$

$$= \frac{\partial}{\partial x_j} \cdot \left[\left(\mu \cdot \frac{\mu_t}{\sigma_k}\right) \cdot \frac{\partial k}{\partial x_j}\right] + \tau_{ij} \cdot \frac{\partial \bar{u}_i}{\partial x_j} - \varepsilon,$$

$$\frac{\partial \varepsilon}{\partial t} + \bar{u}_j \cdot \frac{\partial \varepsilon}{\partial x_j} =$$

$$= \frac{\partial}{\partial x_j} \cdot \left[\left(\mu \cdot \frac{\mu_t}{\sigma_\varepsilon}\right) \cdot \frac{\partial \varepsilon}{\partial x_j}\right] + c_{\varepsilon 1} \cdot \frac{\varepsilon}{k} \cdot \tau_{ij} \cdot \frac{\partial \bar{u}_i}{\partial x_j} - c_{\varepsilon 2} \cdot \frac{\varepsilon^2}{k}.$$

where $i, j = 1 \ldots 3$; $\bar{u}_{j,i}$ – verage velocities over the time; $u_{i,j}$ – pulsating velocity components; f_i – the component that expresses the action of mass forces; μ – dynamic viscosity; μ_t – dynamic coefficient of turbulent viscosity. And empirical constants have next values: $C_\mu = 0{,}09$; $C_{\varepsilon 1} = 1{,}44$; $C_{\varepsilon 2} = 1{,}92$; $\sigma_k = 1{,}0$; $\sigma_\varepsilon = 1{,}3$.

Calculation research of fluid flow are presented graphically using the velocity distribution in the horizontal and meridional sections, the meridional component of the full velocity in meridional cross-sections, the pressure distribution in the horizontal section.

There is distribution of static and total pressures on the fig. 3, *a*–*b* and fig. 4, *a*–*b*. Pressures values in kPa.

Coefficients of energy resistance in the spiral casing with the stator in the turbine mode were determined on the basis of dependence [4]:

$$k_h = g \cdot \frac{\Delta h \cdot D^4}{Q^2},$$

where

$$\Delta h = \frac{\bar{P}_{inlet}^{total} - \bar{P}_{outlet}^{total}}{\rho \cdot g}.$$

For the calculation mode it is equal 0,98 and for an optimal mode – 0,77.

The distribution of full velocity in the horizontal plane passing through the plane of symmetry spiral, and meridional cross-sections for specified modes are shown in fig. 5, *a*–*b* and fig. 6.

From fig. 5 it is seen that the stay vanes considerably effect on the character of the flow at the outlet of spiral casing. Periodicity of changing values of flow parameter (velocity and pressure) is observed along the circumference.

Isolines of full speed almost vertically, its value increases as it approaches to the stay vanes.

Vector illustration of meridional velocity component in the characteristic cross-sections ($\varphi = 0°$, $\varphi = 90°$, $\varphi = 180°$, $\varphi = 270°$) for spiral casing in the optimal mode is given in fig. 6. The flow parameters only in the spiral casing are presented. Reverse vortex motion from the axis to the periphery, which affects the flow at the inlet to the stator, is observed for the meridional section ($\varphi = 180°$).

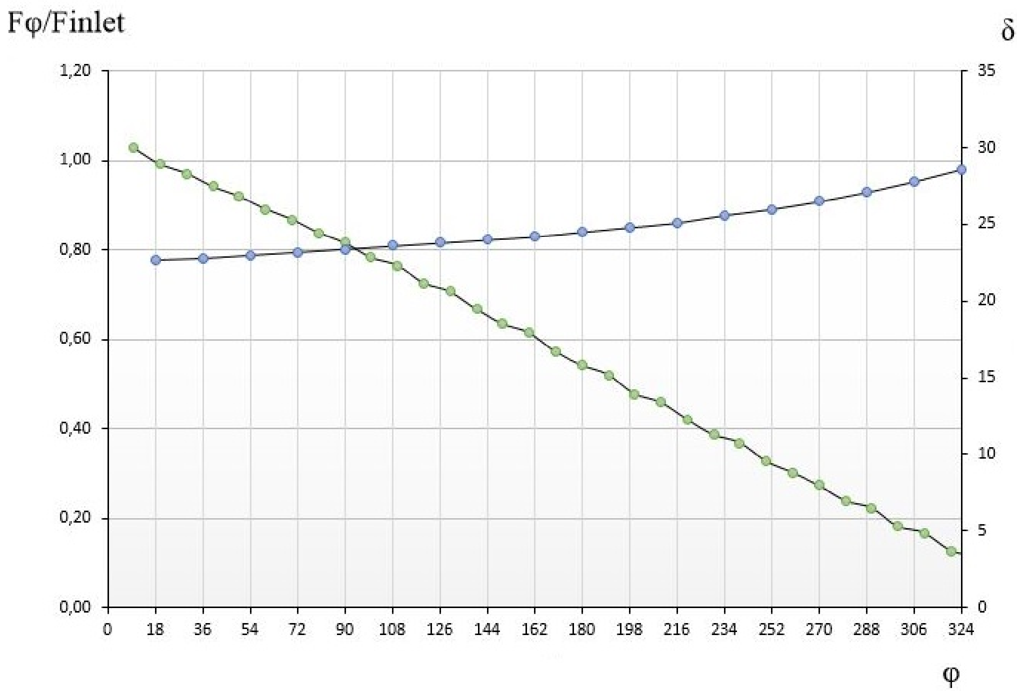
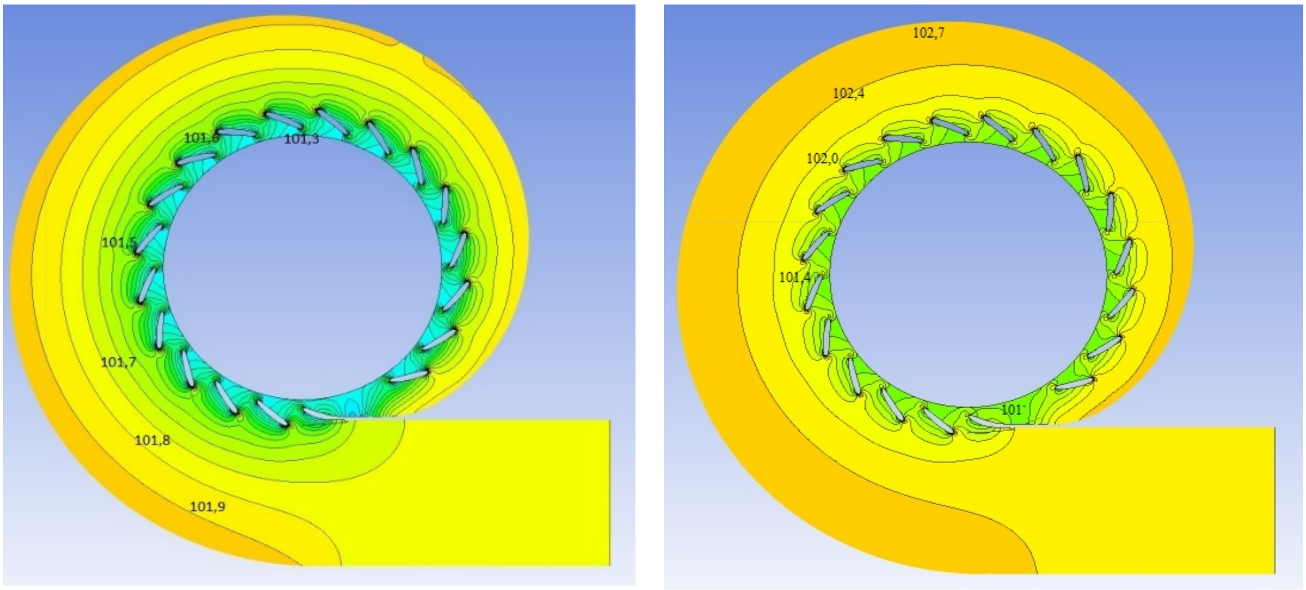
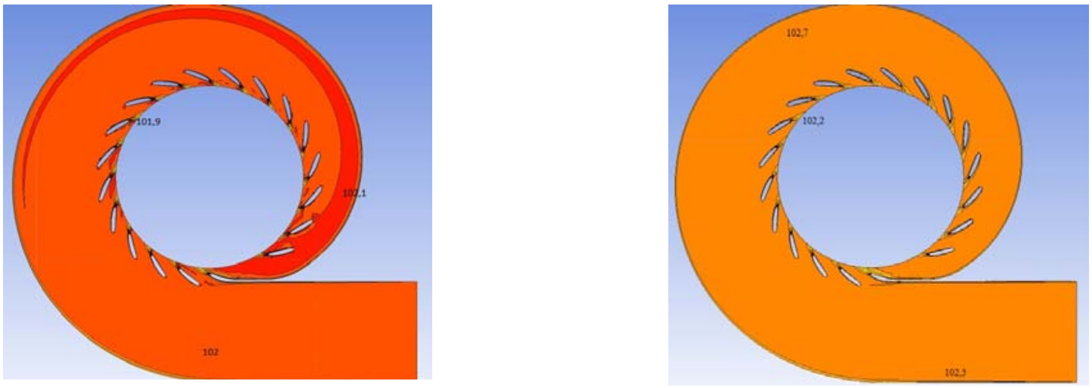


Fig. 2 – The dependence of the relative area of the meridian cross-section



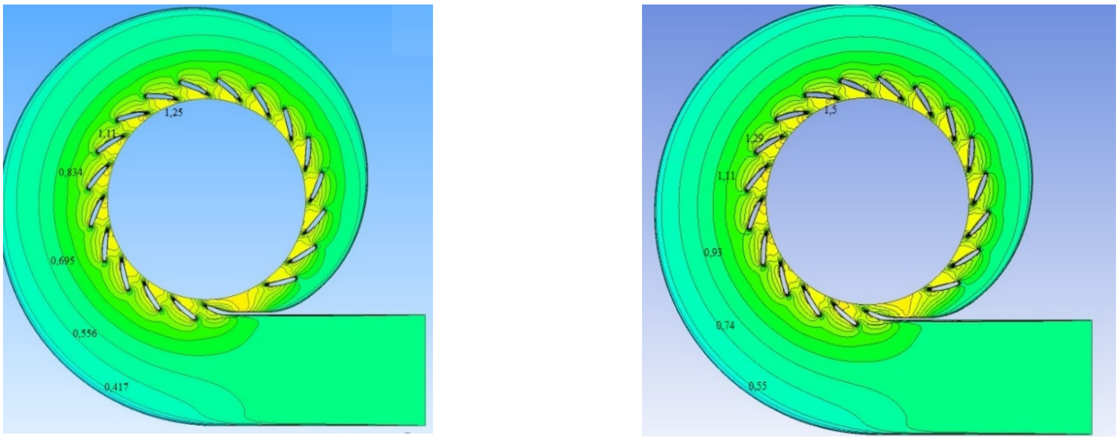
a *b*

Fig. 3 – The distribution of static pressure:
a – optimal mode; *b* – calculated mode



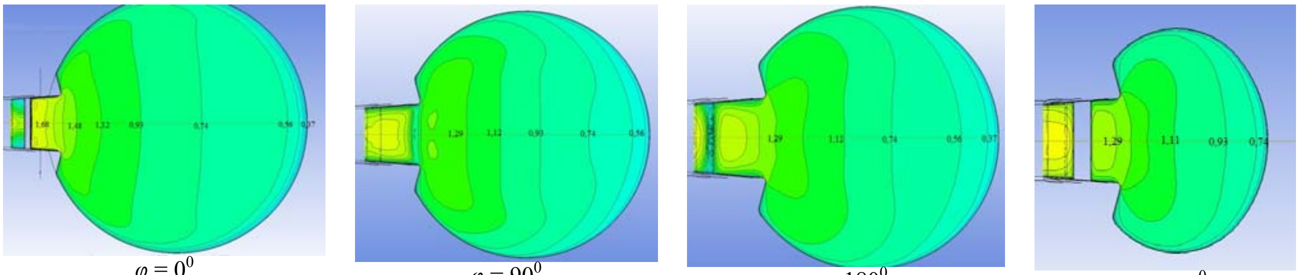
a *b*

Fig. 4 – The distribution of total pressure:
a – optimal mode; *b* – calculated mode



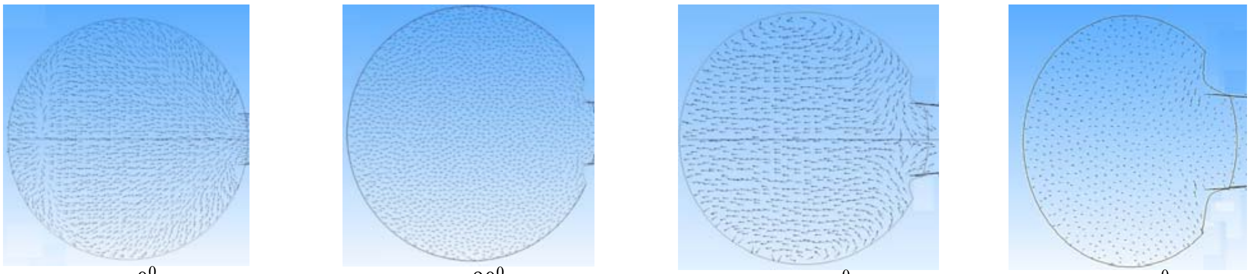
a *b*

Fig. 5 – The distribution of full velocity:
a – optimal mode; *b* – calculated mode



$\varphi = 0^0$ $\varphi = 90^0$ $\varphi = 180^0$ $\varphi = 270^0$

Fig. 6 – Isolines of velocity in the meridional cross-sections



$\varphi = 0^0$ $\varphi = 90^0$ $\varphi = 180^0$ $\varphi = 270^0$

Fig. 7 – Vector image of the meridional component of velocity

Conclusions. The analysis of the results, which were obtained by the numerical calculations of viscous fluid flow in the inlet of the radial-axial reversible hydraulic machine by special program CFD, illustrates the features of the flow and allows determining the velocity distribution, its components, pressure distribution, flow angles form by spiral casing and stator grid, providing their substantiated designing. It is shown that the stay vanes specific influence on the flow parameters in the inlet of the hydraulic machine.

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Дранковский Виктор Эдуардович – кандидат технических наук, доцент, Национальный технический университет «Харьковский политехнический институт», профессор кафедры «Гидравлические машины», г. Харьков; тел.: (057) 707-66-46, e-mail: drankovskiy@rambler.ru.

Drankovskiy Viktor Eduardovich – Candidate of Technical Sciences (Ph. D.), Docent, National Technical University "Kharkov Polytechnic Institute", Professor at the Department "Hydraulic machines", Kharkov; tel.: (057) 707-66-46, e-mail: drankovskiy@rambler.ru.

Резвая Ксения Сергеевна – аспирант, Национальный технический университет «Харьковский политехнический институт», ассистент кафедры «Гидравлические машины», г. Харьков; тел.: (057) 707-66-46, e-mail: rezvayaks@gmail.com.

Rezvaya Kseniya Sergeevna – Postgraduate Student, National Technical University "Kharkov Polytechnic Institute", Assistant at the Department "Hydraulic machines", Kharkov; tel.: (057) 707-66-46, e-mail: rezvayaks@gmail.com.

Крупа Евгений Сергеевич – кандидат технических наук, Национальный технический университет «Харьковский политехнический институт», доцент кафедры «Гидравлические машины», г. Харьков; тел.: (057) 707-66-46, e-mail: zhekr@mail.ru.

Krupa Evgeniy Sergeevich – Candidate of Technical Sciences (Ph. D.), National Technical University "Kharkov Polytechnic Institute", Docent at the Department of "Hydraulic machines", Kharkov; tel.: (057) 707-66-46, e-mail: zhekr@mail.ru.