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Research of multi-flow and multi-channel flow parts of the vortex expansion machines with the external peripheral channel

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Research of multi-flow and multi-channel flow parts of the vortex expansion machines with the external peripheral channel

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Abstract. At present, work on the use of vortex expansion machines for utilization of the expander installations is being carried out to solve energy saving problems. Significant radial load on the rotor arises at high pressures in the single-flow vortex stages. This problem can be solved by switching to a multi-flow scheme. In this connection, the flow and radial loads on the rotor in single- and multi-flow flow parts of the vortex expansion machine with an external peripheral channel were studied. As the result of applying the theory of experimental planning and optimization studies in the ANSYS software complex, the geometric and gas dynamic parameters of the studied flow parts are determined from the point of view of the efficiency.

1. Problem setting and purpose of the research

Over 1,600 gas distribution stations (GDS), more than 51,000 gas-regulating points (GRP) and 80 compressor stations (CS) with gas turbine gas pumping units are operated in the branched gas transportation system of Ukraine [1]. The main gas pipelines and their outlets feed gas to the gas distribution system with the pressure of 5.5 or 7.4 MPa. At the gas distribution system, the gas pressure is reduced to 1.2 MPa or 0.3 and 0.6 MPa by means of the reducing valves. The gas from the GDS is supplied to the distribution network of inhabited localities and industrial enterprises, where the gas pressure is reduced to 0.3-0.05 MPa by means of the reducing valves. At present, as a rule, the gas pressure reduction on GDS and GRP is carried out by throttling, which is accompanied by the loss of energy.

The wide introduction of turbo-expander utilization units, especially with a capacity of up to 500 kW, is possible only based on the solutions that ensure a quick and inexpensive reconstruction of existing pressure reduction systems. The main problem here is an expansion machine, which should be simple in design, reliable in operation, and should not require complex auxiliary systems.

There are low power turbine sets based on jet-powered turbines [2-4], which are simple in construction but have a high rotor speed.

To utilize the energy of excess pressure at the reduction nodes, it is prospective to use a vortex expansion machine in turbine sets and installations in the power range up to 500 kW. Vortex expansion machines, having all the values of centripetal and axial turbines, also have a number of advantages over them: they are much easier to construct and cheaper to manufacture and maintain, relatively low-speed, which makes it possible to create the turbo-aggregates in gearless performance.

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However, vortex expansion turbo-machines have disadvantages, too. The pressure along the flow part of the vortex single-flow stage varies significantly from input to output (Figure 1). When using a single-flow circuit, it leads to the emergence of radial force, which can be significant. This problem can be solved by switching to a multi-flow scheme. A survey of the known sources showed the absence of systematic studies on the expediency of transition to a multi-flow scheme of the expansion machine. The available experimental values of the efficiency of multi-flow schemes do not exceed 30%. In this connection, a parametric model (Figure 2) of the multi-flow part of the vortex expansion machine with an external peripheral channel was created and the effect of the main geometric and gas dynamic parameters of the dual-flow scheme on its efficiency was studied [5, 6].

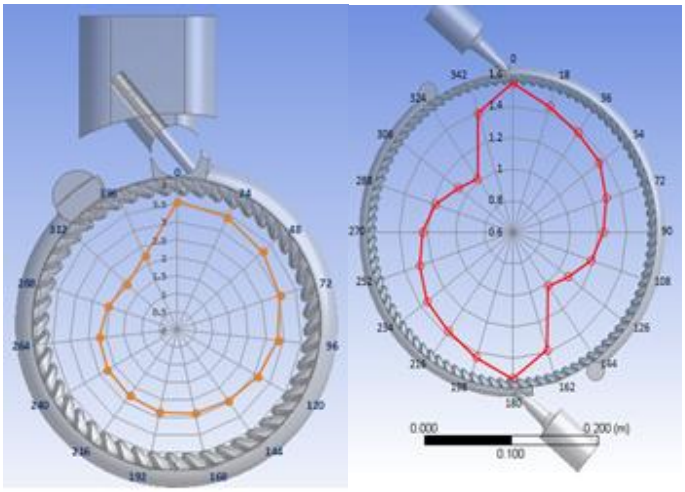

Figure 1. The pressure along the flow part of the vortex single-flow and dual-flow stage.

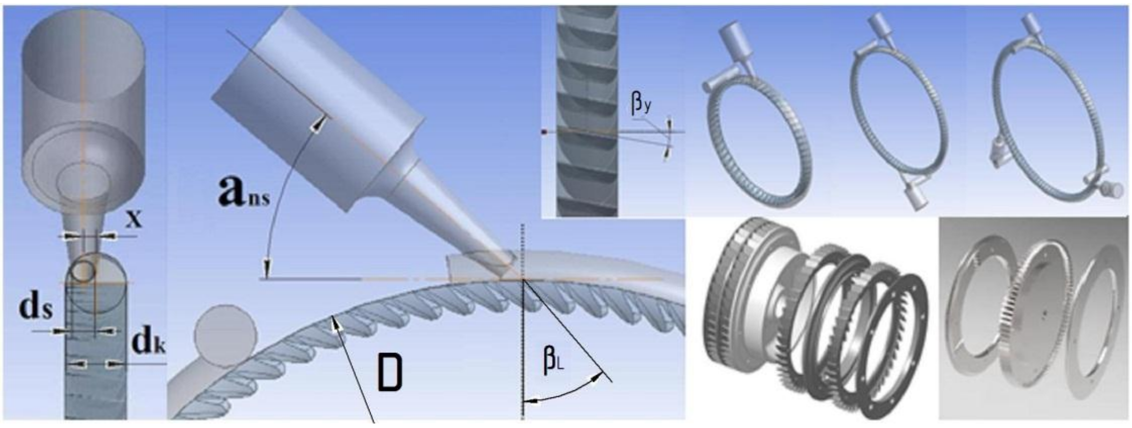

Figure 2. Parametric model of the vortex expansion machine with an external peripheral channel.

The purpose of the research is to determine the optimum geometric and gas dynamic relationships for a single-, dual- and three-flow part of the vortex expansion machine with an external peripheral channel from the point of view of the efficiency.

2. Methods of the research

The optimization task is to find such an admissible, i.e. satisfying the constraints, combination of factors that would give an extreme value to the objective function. To obtain a formal model, the regression analysis apparatus and the theory of experimental design were used [7]. As a functional connection between the geometric parameters of the flow part and the output data, a second-order polynomial was chosen:

$$y = a_0 + \sum_{i=1}^{n} a_{ii} x_i^2 + \sum_{i=1}^{n} \sum_{j\langle 1} a_{ij} x_i x_j \tag{1}$$

To reduce the number of experiments, the most influential parameters were determined and their number was reduced based on the already existing results of the vortex machines studies [8,9]. The reduction of the number of influencing parameters can also be achieved by the transition from several separate parameters to dimensionless complexes, which are formed from them. Influencing parameters were set in a certain range, where it was supposed to obtain the optimum of the objective function (efficiency).

The following most influential factors were distinguished:

- the reduced peripheral speed of the impeller on the outer diameter $\overline{U}$,
- the relative diameter of the flow part, equal to the ratio of the diameter of the meridian section of the flow part dк to the outer diameter of the impeller D, $\overline{d_{ph}} = d_k / D$ (Figure 2);
- the relative diameter of the nozzle, equal to the ratio of the diameter of the nozzle to the diameter of the meridian section of the flow part dк, $\overline{d_s} = d_s / d_k$ (Figure 2);

and the range of their variation was determined [8,9]: $\overline{U} = 0.1...0.2$; $\overline{d_{ph}} = 0.03...0.16$; $\overline{d_s} = 0.3...0.45$; $\alpha_{ns} = 25...50\,deg$.

The reduced peripheral speed $\overline{U}$ characterizes the turnover and loading of the expansion machine:

$$\overline{U} = \frac{U}{C_s} = \frac{\pi \cdot D \cdot n}{60 \cdot \sqrt{2h_s}} \tag{2}$$

where

U is the peripheral speed of the impeller at the outer diameter, m/s;

D is the outer diameter of the impeller, m; n is the rotational speed of impeller, rot/min;

Cs is the isentropic flow rate, characterizes the available specific work of the expansion machine, m/s;

h_s is the specific isentropic enthalpy drop (specific available work of the expansion machine), J / kg.

The geometric relationships and parameters of $\overline{d_{ph}}$, $\overline{d_s}$, α_{ns} influence the organization and quality (intensity) of the longitudinal vortex flow in the flow part of the machine.

To construct a quadratic model of the response function, it is necessary to vary the independent factors on at least three levels. In order to study the influence of four factors on three levels, 81 experiments are required. To reduce the number of experiments, symmetric Box-Bencken non-compositional plans are applied, which allow obtaining the values of the coefficients of a quadratic polynomial for the four factors performing only 27 experiments. In this paper, the calculation points of the computational experiment were chosen according to the Box-Bencken plan. At the points of the plan, numerical simulation of the gas flow was carried out using the ANSYS CFX software. The problem was solved on the basis of the Reynolds-averaged Navier-Stokes equations. Modeling of turbulent effects performed by means of the SST model. The total pressure and the total inlet temperature, static pressure at the outlet of the computational domain and the rotor speed were used as the input data for the calculations. The working body is viscous compressible air. According to this technique, single-, dual- and three-flow single-channel flow parts were optimized.

3. Results of the research

As a result of the studies, the optimal values of the influencing factors in the investigated ranges and the regression equations for the single-, dual- and three-flow flow part of the vortex expansion machine were obtained (Figure 2).

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Figures 3-5 show the maps of the level lines (response surfaces) for the output parameter (adiabatic efficiency) of the single-, dual- and three-flow flow parts, respectively.

On the basis of the results obtained, certain ratios of the geometric and gas dynamic parameters can be recommended, providing a relatively high level of efficiency of the vortex machine with an external peripheral channel in the range of variation Πт = 2-6 (Πт is the degree of pressure reduction in the expansion machine) for:

- the single-flow scheme: $\overline{U} = 0.12...0.18$; $\overline{d_{ph}} = 0.08...0.10$; $\overline{d_s} = 0.28...0.38$; $\alpha_{ns} = 25...50\,deg$.
- the dual-flow scheme: $\overline{U} = 0.15...0.19$; $\overline{d_{ph}} = 0.05...0.07$; $\overline{d_s} = 0.28...0.38$; $\alpha_{ns} = 25...50\,deg$.
- the three-flow scheme: $\overline{U} = 0.18...0.22$; $\overline{d_{ph}} = 0.02...0.04$; $\overline{d_s} = 0.28...0.38$; $\alpha_{ns} = 25...50\,deg$.

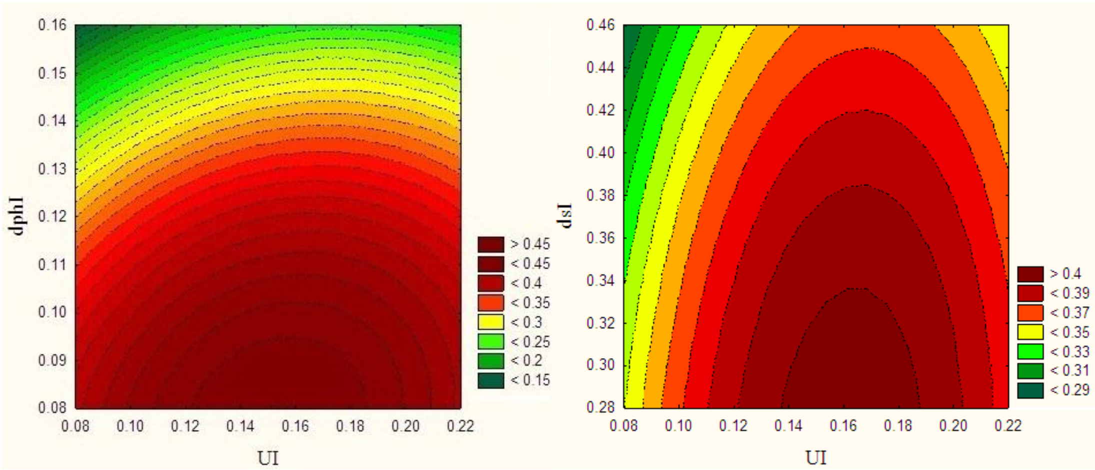

Figure 3. Maps of level lines (response surfaces) for the output parameter eff - adiabatic efficiency of the single-flow flow part.

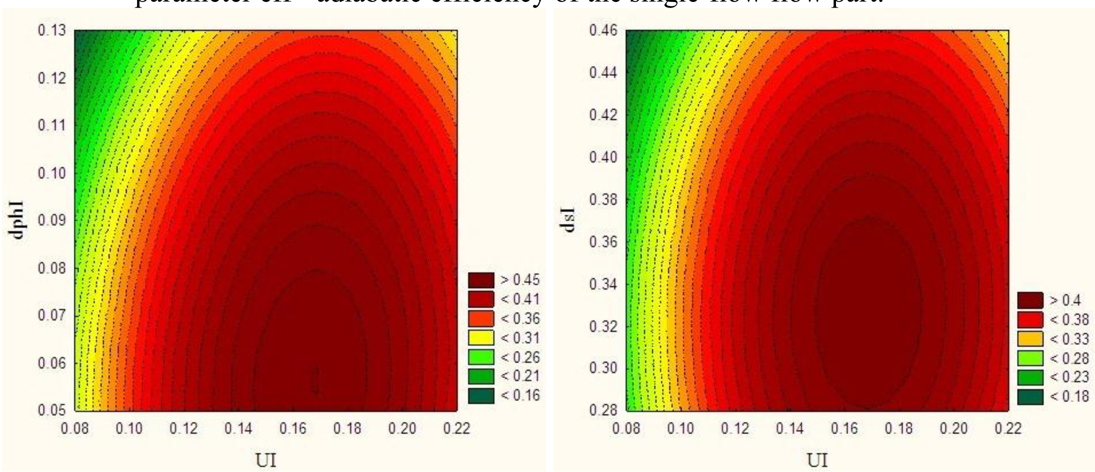

Figure 4. Maps of level lines (response surfaces) for the output parameter eff - adiabatic efficiency of the dual-flow flow part.

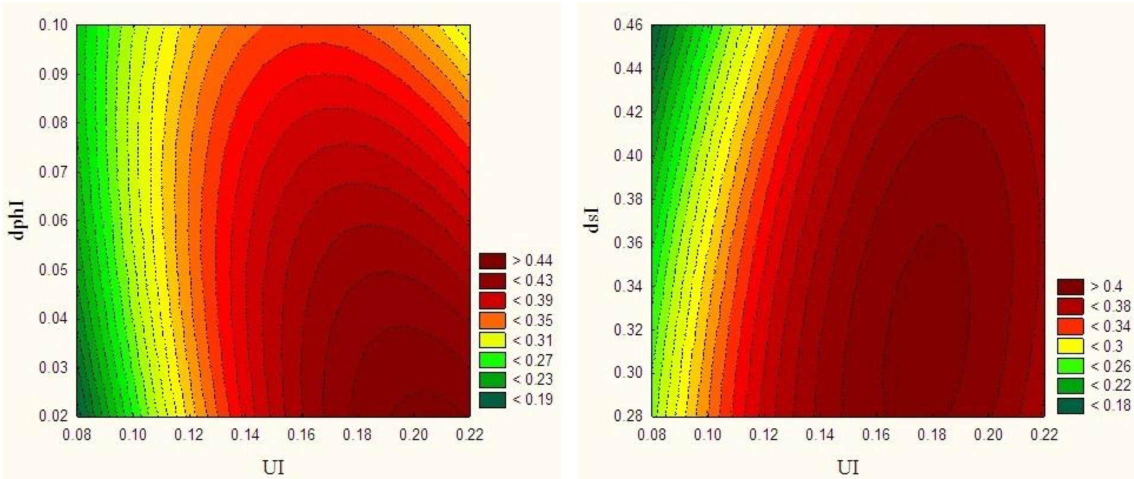

Figure 5. Maps of level lines (response surfaces) for the output parameter eff - adiabatic efficiency of the three-flow flow part.

On the basis of the obtained results, the ratios of the geometric and gas dynamic parameters generalized for the three circuits providing a relatively high level of efficiency of the vortex machine with an external peripheral channel in the range of the pressure ratio Пт = 2-6 are determined: . $\overline{U}=0.12...0.2$; $\overline{d_s}=0.28...0.38$; $\alpha_{ns}=25...50\,deg$.

On the parameter $\overline{d_{ph}}$ the optimal values for the single-flow scheme are about the value $\overline{d_{ph}}=0.09$, for the dual-flow scheme - $\overline{d_{ph}}=0.06$ the three-flow scheme - $\overline{d_{ph}}=0.03$. Parameter $\overline{d_{ph}}$ for the single-flow scheme is the ratio of the length of the circumference of the meridian section of the flow part to its length in the circumferential direction:

$$\overline{d_{ph}}=\frac{\pi \cdot d_k}{\pi \cdot D}=\frac{d_k}{D} \tag{3}$$

For the multi-flow schemes it is advisable to maintain the parameter characterizing the relative length of the flow part in the circumferential direction for one flow $\overline{L_p}$, which is determined by the formula:

$$\overline{L_p}=\frac{L_p}{l_{ph}}=\frac{\pi \cdot D}{i \cdot \pi \cdot d_k}=\frac{D}{i \cdot d_k} \tag{4}$$

where

$\overline{L_p}$ is the length of the flow part in the circumferential direction for one flow, m;

l_{ph} is the length of the circumference of the meridional section of the flow part, m;

i is the number of flows.

The optimal values of the parameter $\overline{L_p}$ for the three schemes of the flow parts of a vortex machine with the external peripheral channel are about the value of $\overline{L_p}=10$ $\left(\overline{L_p}=8...11\right)$.

As one can see from Figures 3-5, the vortex stages have a relatively wide range of parameters in the optimum region. This allows the parameters $\overline{d_{ph}}$ and $\overline{d_s}$ to be adjusted by the range of their optimum to achieve the required power without significantly reducing the efficiency, without increasing the radial dimensions of the flow part. To achieve the required turbo-unit power with optimal parameters $\overline{d_{ph}}$ and $\overline{d_s}$, using the above single-channel multi-flow schemes, one can obtain the multichannel flow part of Figure 1. Such a way one can create a parametric series of vortex turbo-units for a power range up to 500 kW.

To determine the area of optimal use of the flow parts of the vortex expansion machines with the external peripheral channel, the dependences of the maximum radial load on the rotor of the vortex single-flow stage on the initial pressure at D = 0.360 m, $d_k = 0.032 \cdot m$, $d_{ph} = 0.09$ and different pressure ratios were determined (Figure 6). To build the dependencies shown in Figure 6, we used the data on pressure distribution along the length of the flow section in the single-flow vortex expansion machines. The values of the radial load on the impeller of the expansion machine were compared with the values of permissible radial loads on the rotor of standard electric generators of different power (Figure 7).

Analyzing the dependencies of Figures 6 and 7, it can be concluded that a single-flow flow part can be used without complicating the design of the turbo-generator (for example, with the impeller located on the shaft of a standard electric generator) in a limited region at input pressure (up to 1.2 ... 1.8 MPa). At higher input pressures, it is necessary to use multi-flow schemes that unload the turbo-machine rotor from the action of radial loads.

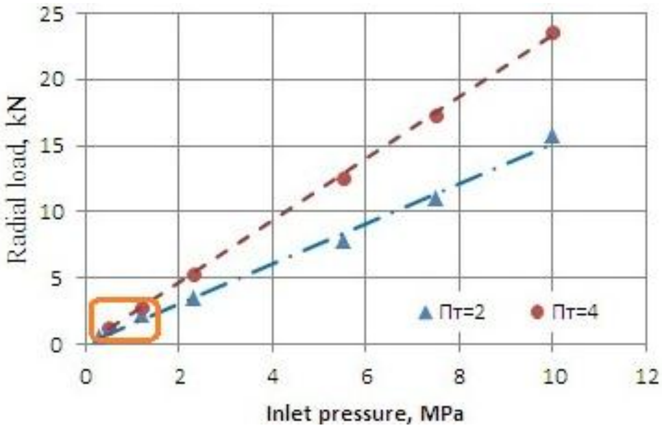

Figure 6. - Dependence of the maximum radial load on the rotor of the vortex single-flow stage on the initial pressure at (D = 0.360 m, $d_k = 0.032 \cdot m$, $d_{ph} = 0.09$).

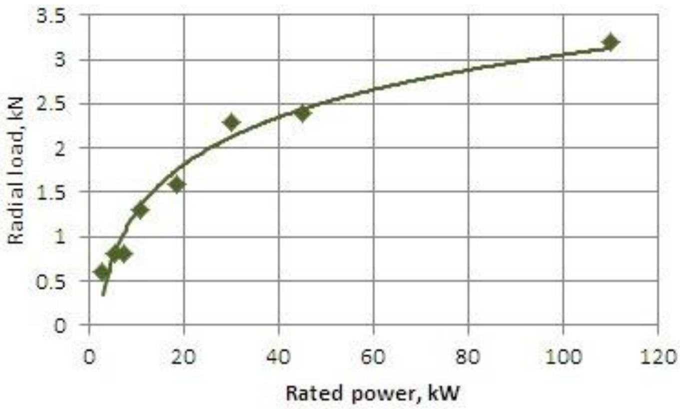

Figure 7. - Dependence of the maximum radial load on the rotor of a standard generator on its power.

4. Conclusions

A parametric model and methods for numerical study of the multi-flow vortex expansion machine in the ANSYS software complex were developed, which makes it possible to investigate the effect of geometric and gas dynamic parameters on its efficiency and characteristics. The most influential factors were identified and the ranges of their changes have been determined. Computational experiments were planned (with the application of the theory of experiment planning) and carried out, on the results of which the multi-criteria optimization was performed, which allowed to find the geometric parameters of the flow parts and their ratios providing the maximum adiabatic efficiency.

To characterize the multi-flow schemes, a dimensionless parameter $\overline{L_p}$ was added, which connects the length of the flow part in the circumferential direction for one flow with the circumference of the meridian section.

The generalized optimum values of the parameters for the three schemes of the vortex expansion machines with an external peripheral channel were obtained in the range of the ratio of pressures Пт = 2-6: $\overline{U}=0.12...0.2$; $\overline{d_s}=0.28...0.38$; $\alpha_{ns}=25...50deg$, $\overline{L_p}=8...11$

Optimal values of the efficiency of the vortex multi-flow expansion machine with an external peripheral channel were increased by more than 15% (from the level of less than 30% to the level of more than 45%).

From the point of view of radial forces, vortex single-flow stages can be used up to a gas inlet pressure of up to 1.2 ... 1.8 MPa, at higher input pressures, multi-flow schemes must be used. In comparison with the three-flow scheme, the dual-flow one has a simpler design and the optimal value of the reduced circumferential velocity $\overline{U}$ is less than in the three-flow scheme. For utilization of low-power expander units, the use of the dual-flow scheme is the most expedient, since in this scheme it is possible to balance the radial forces with a simpler and more compact design.

To achieve the required power in the entire low-power range of the turbo-unit and the maximum efficiency (with optimal design parameters of $\overline{d_{ph}}$, $\overline{d_s}$, α_{ns}) using a single-channel multithreaded scheme, a more powerful multi-channel flow part can be obtained.

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