Simulation of operational characteristics of the water-ring vacuum pumps

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Abstract. The article presents the results of calculations of characteristics for water-ring pumps. Water-ring pumps are energy-saving and high-performance equipment, often used for pumping explosive gases or when working with flammable environment. The design of water-ring vacuum pumps and compressors of many manufacturers is the same. The disadvantage of this type of compressors is their low overall efficiency. The algorithm and examples of determining the characteristics of compressor machines used in modern vacuum installations are considered. Based on the results of processing of experimental data of Erstevak ELRS models, empirical dependences and power consumption parameters are obtained. The isothermal efficiency of the liquid ring pump over the suction pressure has been normalized. Characteristics of isothermal power and efficiency are built. The dependence of the highest isothermal efficiency of the water ring pump on the performance (pumping speed) is obtained.

1. Introduction
Single-block ring water vacuum pumps of the ELRS series are used for pumping explosive gases or when working with a flammable medium. Water-ring units have a number of significant advantages. The main problem of these pumps is the low efficiency. Experimental and theoretical methods are used to increase the efficiency. Analytical dependences for characteristics are necessary to improve the design of these pumps. Therefore, it is important to create empirical models and dependencies for various applications of vacuum pumping units [1-9].

In [1] nonlinear analysis is used to describe the operation of a vertical pump. The ring heating system including heat pumps is considered in [2]. A rotating air-water ring with a bubble flow is investigated using a model of a reduced-scale turbine pump [3]. The paper [4] shows the system of reducing the catamaran roll. Vacuum pumps are used to pump water between the tanks. The solar desalination system using a liquid ring vacuum pump was experimentally investigated in [5]. The problems of creating a high vacuum using are considered in [6]. The electrical energy consumed by vacuum and liquid pumps for the operation of the membrane contactor was determined [7].

The test results at different speeds using frequency control are given in [8]. In the performance tests, a multiparameter data collection and processing system was used, and a detailed measurement method was introduced.
The article [9] considers the choice of water-ring vacuum pumps according to the parameters given in the technical data sheet to reduce energy costs. The analysis of load characteristics allows making this choice more reasonably. Characteristics of plunger pumps using empirical dependences are given in [10]. The method for assessing the energy efficiency of plunger pumps by analyzing the characteristics was developed in [10]. In this article, the named method is applied to the study of characteristics of vacuum water-ring pumps.

2. Materials and methods
The amount of liquid in the compressor machines should be sufficient to eliminate the gap between the cylindrical part of the rotor and the liquid ring in the intermediate zone.

For compressor machines operating with gas cooling, a comparison is made with conventional machines that compress the gas by isotherm. The ratio of the power at isothermal compression of the cylindrical part of the rotor and the liquid ring in the intermediate zone.

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According to the characteristic load characteristics of water-ring vacuum pumps ELRS [11], empirical dependences are obtained:

\[ N(P) = A_0 + A_1 \cdot P + A_2 \cdot P^2 + A_3 \cdot P^3. \]  
\[ Q(P) = \begin{cases} B_0 + B_1 \cdot P + B_2 \cdot P^2 + B_3 \cdot P^3, & P_0 < P < P_*; \\ Q_0 = \text{const}, & P_* < P < P_a. \end{cases} \]  

Hereinafter \( P_0 \) – limit (min) suction pressure, the pumps ELRS \( P_0 = 3.3 \) kPa. Empirical constants were found by the least squares method. In particular, for the ELRS-60 model at 420 rpm empirical constants: \( A_0 = 123.35 \) kW; \( A_1 = 1.50 \) kW/ kPa; \( A_2 = -0.030 \) kW/ kPa²; \( A_3 = 7.14 \cdot 10^{-5} \) kW/ kPa³; \( B_0 = 102.11 \) m³/min; \( B_1 = 2.24 \) m³/(min·kPa); \( B_2 = -0.067 \) m³/(min·kPa²); \( B_3 = 6.226 \cdot 10^{-4} \) m³/(min·kPa³); \( P_* = 45 \) kPa; \( Q_* = 124.7 \) m³/min.

3. Results
Using the same algorithm, using formulas (3), (4), the dependences \( Q(P) \) and \( N(P) \) for water-ring pumps of ELRS-45 and ELRS-57 models are obtained (figure 1-2). The dependence \( Q(P) \) has no maximum in figure 1. However, it should be noted that the experimental data [11] have an error of 10%, and the local maximum performance is greater than the nominal value by only a few percent.

![Figure 1. The dependence of the performance of water-ring pump ELRS-45 from the suction pressure: 1 – 472 rpm; 2 – 530 rpm; 3 – 590 rpm; 4 – 660 rpm. Experimental data points [11], lines – calculation results according to the formula (4).](image-url)
In figure 3, the isothermal power of the pump $N_1$ is calculated by the formula (2) for the test results of the water-ring vacuum pump ELRS-60 at 420 rpm. The isothermal efficiency of the vacuum water ring pump tends to zero at the lowest suction pressure and atmospheric pressure. The dependence has a flat maximum in the middle of the interval from 40 to 50 kPa. The maximum of dependences $\eta_1(P)$ and $N_1(P)$ occur at different pressures.

The values of the isothermal efficiency (points) are obtained by dividing $N_1$ by the values of $N$ from the experiments [11]. An approximating polynomial is found from the points by the least squares method. An acceptable approximation error is obtained if the polynomial is not lower than the 4th order:

$$\eta_1 = \eta_2 \cdot \left(a_0 + a_1 p + a_2 p^2 + a_3 p^3 + a_4 p^4\right).$$

The dimensionless suction pressure is denoted by $p$ in formula (5). In addition, we introduce a normalized value of efficiency:

$$p = P / P_0, \quad \bar{\eta}_1 = \eta_1 / \eta_2,$$

where $\eta_2$ is the maximum efficiency value for the given conditions.

Figure 4 shows that the isothermal efficiency of the ELRS-60 water-ring vacuum pump calculated by the formula (5) for different speeds of rotation is in good agreement with the points obtained from the test data [11]. According to the physical meaning $\eta_1 = 0$ at $P \rightarrow P_a$ and $P \rightarrow P_0$. The dashed line in figure 4 is drawn from the point of maximum efficiency. The increase of the rotation speed shifts the efficiency maximum to lesser suction pressures.
According to figure 5a, the normalized isothermal efficiency decreases with increasing pumping speed (rotational speed). The position of the maximum normalized efficiency is shifted to the right (figure 5b).

4. Conclusion
With the help of the previously developed algorithm, empirical dependences of performance and power on pressure for water-ring pumps of the ELRS model are obtained. Experimental data of the pump manufacturer were used. The data has an error of 10%. An approximating polynomial is found from the points by the least squares method. An acceptable approximation error is obtained if the polynomial is not lower than order 4.

The normalized isothermal efficiency decreases with increasing pumping speed (rotational speed). The position of the maximum normalized efficiency is shifted to the right.

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