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DEVISING A METHOD FOR ENSURING THE RELIABILITY OF FIRE CENTRIFUGAL PUMPS WHILE REDUCING THEIR WEIGHT AND DIMENSION CHARACTERISTICS BY OPTIMIZING THEIR STRUCTURAL ELEMENTS

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An algorithm for calculating the strength and reliability of centrifugal fire pump housings has been developed, aimed at determining the optimal mass-dimension parameters of centrifugal fire pumps. To this end, a method has been devised for determining the main indicators of reliability, an optimization mathematical model has been built, and an algorithm for solving the optimization problem using the Monte Carlo method has been developed. When devising a method for determining the main reliability indicators of centrifugal fire pumps, the strength and kinematic parameters have been taken into consideration, as well as an economic indicator of reliability and the costs of ensuring reliability. These indicators make it possible to establish the optimal consumption of materials for the manufacture of structural elements of centrifugal fire pumps that ensure their strength and reliability. When building the optimization mathematical model, a pump weight minimization was used as the objective function while the applied difference criterion makes it possible to take into consideration the economic indicator in the manufacture of centrifugal fire pumps and to reduce their cost. It was established that the principal indicator that affects the weight of a pump and the cost of its manufacture is the thickness of the pump housing wall. Based on the developed optimization mathematical model, the flowcharts of the algorithms have been constructed for solving it using the Monte Carlo method. The calculation results showed that the width of the PN-40 UV pump housing can be reduced by 1.18 from the rated one. Applying the optimization mathematical model in the process of designing fire centrifugal pumps makes it possible to reduce the pump weight by 9–11 % while ensuring high reliability and reducing the cost of its production by 10 %

Keywords: fire centrifugal pump, housing, optimization mathematical model, reliability of fire pumps

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1. Introduction

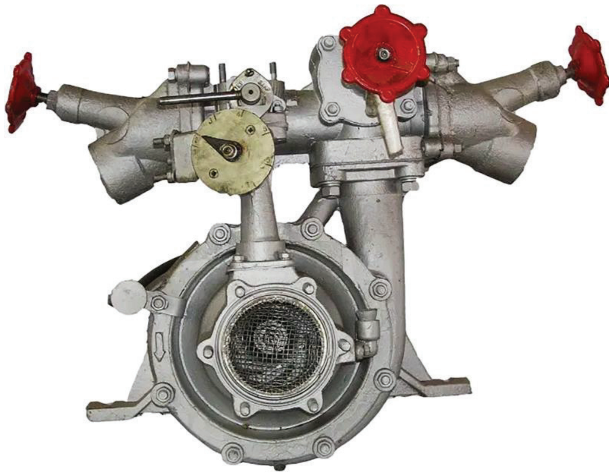
The readiness of fire and rescue units (hereinafter referred to as a fire brigade) for actions intended largely depends on the reliability of fire and rescue equipment. The main strategic task of the unit during the elimination of fire (after rescuing people) is to supply a fire extinguishing substance to its site. To ensure the supply of a fire extinguishing substance to the fire site, a centrifugal pump is used, which is mounted on a fire vehicle. One type of such centrifugal pump is shown in Fig. 1.

The pump is mounted on fire vehicles, which are used by fire brigades during firefighting; it is an important element that enables the functional capabilities of the fire brigade.

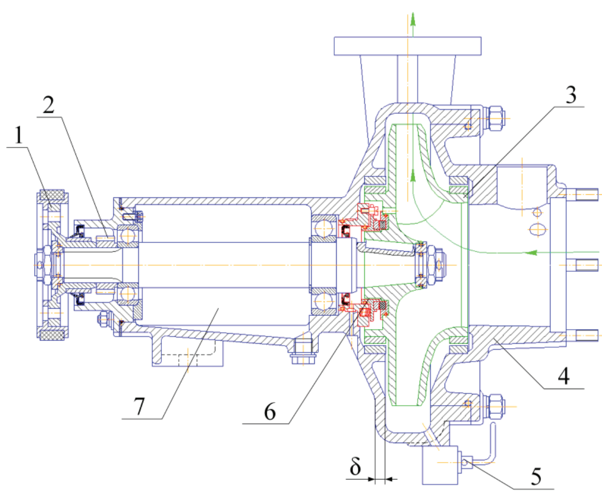
The main technical parameters of such pumps, including, for example, the PN-40 UV type (Ukraine) are as follows: performance, 40...60 l/s; head, 100...110 m; power, 62.2 kW; efficiency coefficient, 0.65; the diameter of the pump's impeller, 45 mm; rotation frequency, 2,980 min^{-1}; overall dimensions, 900×700×700 mm; weight, 65 kg; service life, 11 years.

Among the main requirements, which are set for fire pumps, are their reliability and optimal values of their structural parameters. The reliability, design parameters, and technical characteristics are set to reduce the weight of the entire pump while ensuring its reliability and technical characteristics according to the specified criteria.

Study [1] showed that the time of a failure-free operation of the centrifugal fire pump is 150 hours; its modernization makes it possible to increase this figure by almost two times. The PN-40 UV pump operates under difficult conditions as it supplies water from open artificial and natural reservoirs where the share of suspended particles exceeds the values permissible for this device. Therefore, these pumps often malfunction as a result of the reduced feed and head, vibration, and the elevated temperature of individual structural elements.



a



b

Fig. 1. Fire centrifugal pump, PN-40 UV type: *a* — centrifugal pump in assembly with a foam mixer, collector, and valves; *b* — centrifugal pump in longitudinal section (1 — pump flange; 2 — shaft; 3 — pump impeller; 4 — pump housing; 5 — drain valve; 6 — sealing unit (glass); 7 — crankcase (oil bath)

Therefore, it is a relevant task to optimize the structural elements of the parameters of the housing and other parts of the centrifugal pump. To achieve this goal, it is necessary to devise an effective method for synthesizing the basic structural elements of the pump based on discrete programming.

2. Literature review and problem statement

Substantiation of the size of structural elements of frame structures is based on the method of linear programming. These methods were initially used to determine the optimality conditions for different parts of machines in the process of making structural decisions. However, the use of a given method produces a significant error because the processes associated with the operation of centrifugal pumps are nonlinear.

The application of mathematical programming methods to solve the systems of nonlinear equations or inequalities using computer design for elastic structures exposed to loading is proposed in work [2]. The provisions developed in the cited work are still used. However, the analytical solution to a system of nonlinear equations suggested in this work is quite complex and not universal.

The use of a finite-element method for solving the systems of nonlinear equations that describe the strained-deformed state of structural elements is reported in paper [3]. However, a given method implies the use of specially developed software packages that are expensive, which, in practice, makes this method economically impractical.

To simplify the calculations, the authors of work [4] determined that the ratio of a maximum bending moment $M_{\max}$, which acts on the walls of the housing, to the torque T is a stable value, which ranges within 1.8–1.95. Then, in order to simplify the calculations, the maximum bending moment $M_{\max}$ can be determined from the following dependence:

$$M_{\max} = (1.8...1.95)T. \quad (1)$$

Based on the condition of strength at bending, a dependence was derived to determine the maximum thickness δ of the housing from the following dependence:

$$\delta = \sqrt{\frac{6M_{\max}}{L[\sigma]}}, \quad (2)$$

where [σ] is the permissible stretching stress of the housing material; $L=D+l_l$ is the length of a dangerous section of the housing wall; D is the diameter of the outer bearing ring of the pump's impeller; l_l is the length of the supporting plate to the center of the opening in the cast cover of the bearing of the pump's impeller to the base.

However, the cited work does not pay attention to selecting the optimal parameters for centrifugal pumps.

In work [5], designing the structure implies the sequential solving of problems related to the structural and parametric synthesis based on mathematical models. The main element of the structure assessed in the cited work is cylindrical gearboxes; however, the parameters of the design of toothed gears were not considered. This drawback was eliminated in study [6], which examines the optimal parameters of the structure of toothed gears. Despite this, these parameters were not considered comprehensively although the structure of centrifugal pumps includes both elements.

This approach was applied in [7]. The purpose of that work is to devise a method for synthesizing machine-building structures using the finite-element algorithms. These algorithms ensure an increase in the process of searching for the rational parameters for parts and centrifugal pumps using deterministic and stochastic models to solve the tasks of optimal design and the automation of design calculations. The cited work does not include the design of these centrifugal pumps. Designing the structure of fire pumps using the method proposed in previous work was reported in [8]; however, as noted above, a given method is complex and expensive.

The reliability of individual elements was considered in work [9]. In particular, its authors assessed the reliability of automated axial balancing for multistage centrifugal pumps. In that case, the optimization and reliability of other structural elements were not considered. Thus, the optimization of the impeller blade with the modified channels with micro-channels was considered in paper [10]; however, other elements of the pump design remained unaddressed. This drawback was eliminated in work [11], which proposed the optimization of all parameters of the centrifugal pump operation, including weight and volume; however, the authors do not take into consideration the operation of the pump exposed to dynamic loads, which does not make it possible to determine its reliability.

Optimization of the design of the centrifugal pump was considered in paper [12] taking into consideration the losses of energy during its operation; however, such a parameter as the weight of the pump was disregarded.

All this allows us to argue about the expediency of conducting a study aimed at devising an improved method for calculating the housings of centrifugal pumps. A method should be built taking into consideration the strength of the structural elements of the housings. The results of using the method should ensure strength and reliability during the operation of centrifugal pumps, including the effect of dynamic loads.

3. The aim and objectives of the study

The aim of this study is to develop an algorithm for calculating the strength and reliability of centrifugal fire pump housings, taking into consideration the economic indicator of reliability. This would make it possible to establish the minimum weight-dimension characteristics of the structural elements of centrifugal fire pumps, which could meet a condition for the strength and reliability of the pump in general.

To accomplish the aim, the following tasks have been set:

– to devise a method for determining the basic reliability indicators of centrifugal fire pumps;

– to develop an optimization mathematical model for determining the thickness of the housing wall of centrifugal fire pumps taking into consideration a condition of strength and reliability;

– to construct an algorithm for solving the optimization problem to determine the minimum thickness of the pump housing.

4. An algorithm for calculating the strength and reliability of centrifugal fire pump housings

4. 1. Devising a method for determining the basic indicators of reliability for centrifugal fire pumps

At the first stage, we determine the strength and kinematic parameters. The power P on the shaft of the pump's impeller is:

$$P = \frac{P_n}{\eta_n}, \tag{3}$$

where P_n is the pump power, kW; η_n is the efficiency coefficient of pump operation.

The angular velocity of the pump's impeller shaft is:

$$\omega_b = \frac{\pi n}{30}, \tag{4}$$

where n is the rotation frequency of the pump's impeller shaft, min^{-1}.

The rated torque on the pump's impeller shaft is:

$$T = \frac{10^3 P}{\omega_b}, \tag{5}$$

In the second stage, we determine the main structural element of the housing. The maximum bending moment $M_{\max}$, from dependence (1), and the housing wall thickness:

$$\delta = \sqrt{\frac{10^3 \cdot 6 M_{\max}}{L[\sigma]}}. \tag{6}$$

Next, we proceed to determine the factors that take into consideration the reliability of the pump. It is known that the basic factors that characterize the quality of any article include reliability indicators. Consider determining the main indicators of reliability.

1. Economic reliability indicator E of the pump housing [13] is:

$$E = K_e \cdot T_B, \tag{7}$$

where K_e is the cost of ensuring reliability, UAH/hour; T_B is the average time of a pump housing failure-free operation, h; Q_B is the technological cost of making the workpiece of a housing, arbitrary units:

$$K_e = \frac{(Q_B + Q_E)}{T_B}, \tag{8}$$

where Q_E is the total operating cost, arbitrary units; T_E is the specified period of operation, h; a T_E value is taken as the average value of the full resource T_p, namely, $T_E = T_p = (11 \cdot 365 \cdot 24) = 96.360$ h; Q_B is the technological cost of making the workpiece of a housing, UAH;

$$Q_B = (M + Z) \cdot \left(1 + \frac{H}{100}\right), \tag{9}$$

where M is the price of a material, arbitrary units; Z is the salary for executing the operations of molding, casting, knocking, cleaning, arbitrary units:

$$Z = \frac{B}{1.000} \cdot m \cdot k_m, \tag{10}$$

B is the basic salary for executing these operations per 1 t of the cast, arbitrary units ($B \approx 55$ arbitrary units); m is the weight of the unit of the workpiece volume, kg; k_m is a coefficient that depends on the grade of a material.

For gray cast iron, the coefficient $k_m = 1$; for modified – $k_m = 1.08$; for carbon steels, $k_m = 1.22$; H is the overhead of an enterprise making the housing, %;

$$M = m \cdot \left(\frac{S}{1{,}000}\right) - (m - m_g)\left(\frac{S_b}{1{,}000}\right), \tag{11}$$

where m_g is the weight of the unit of the finished part, kg; $m_g = (0.8...0.9)$ m; S, S_b is the price of 1 t of workpiece material and the waste, respectively, arbitrary units:

$$Q_E = B_j \cdot \sum Q_j, \tag{12}$$

where B_j is the cost of one inspection during the operation of the pump housing, arbitrary units ($B_j \approx 5.5$ arbitrary units). According to the schedule of planned repairs (PR), the equipment must be inspected, maintained, repaired, and, at the end of the repair, undergo an overhaul, corresponding to 18 intermediate periods; $\Sigma O_j = 18$ is the total number of inspections.

2. The cost of ensuring the reliability Q_H of the pump housing can be determined from a dependence reported in [13]:

$$Q_H = Q_P \cdot \left(\frac{T_B}{T_E}\right)^{\alpha}, \tag{13}$$

where Q_P is the cost of a prototype with the predefined values of reliability indicators (T_B, T_E), arbitrary units; α is an indicator of the extent that characterizes the level of progressiveness of production in terms of the possibilities to improve the reliability of an article; α=1.3...1.5.

4. 2. Building an optimization mathematical model for determining the size of the elements of centrifugal pump housings

The objective function of the model was defined in the first stage. The main indicator of the optimization mathematical model is the weight of the pump housing. To reduce the weight of the housing, one must reduce the thickness of its wall. The task is to determine the optimal thickness of the pump housing wall, which would ensure its required strength.

Based on these provisions, the objective function adopted is the mass m of the dangerous section of the housing, which should tend to min. Then, taking into consideration the specific weight of the housing material, the objective function is:

$$m = 7.8 \cdot 10^{-6} L\delta^2 \Rightarrow \min. \tag{14}$$

In the second stage, the optimization criterion was chosen to evaluate our results. There are criteria by Savage, Hurwitz, Bayes-Laplace, Hodge-Lemon, a minimax criterion, a difference criterion, an optimistic criterion, a product criterion, and a neutrality criterion. Because reliability is ensured on the basis of economic indicators, then, in this case, the most likely criterion is the difference criterion, that is:

$$0 \le |E - Q_H| \le \psi, \tag{15}$$

where ψ=(0.05...0.1)$|E-Q_H|$.

The next step is to build an optimization mathematical model to determine the size of the main structural elements of the centrifugal fire pump housings. The mathematical optimization model can be written in the following form:

– objective function:

$$m = 7.8 \cdot 10^{-6} L\delta^2 \Rightarrow \min; \tag{16}$$

– based on the criterion:

$$0 \le |E - Q_H| \le \psi; \tag{17}$$

– considering the constraints:

$$\left.\begin{array}{l} a_1 \le P \le b_1; \\ a_3 \le T_E \le b_3; \\ a_4 \le t \le b_4; \\ a_5 \le R(t) \le b_5; \\ a_6 \le [\sigma] \le b_6; \\ p \ge [p], \end{array}\right\}, \tag{18}$$

where P is the power of a fire centrifugal pump, kW; T_E is the specified period of operation before an overhaul, h; t is the total time for one inspection of the pump housing in accordance with PR to ensure the reliability of its operation (in practice, once a month, corresponding to 720 hours), h; $R(t)$ is the probability of a failure-free operation of the pump housing, determined from the dependence by Weibull [14], since the distribution of Weibull is two-parametric, and quite versatile, and is used in the theory of reliability to assess the reliability of complex technical systems:

$$R(t) = \exp\left[-\left(\frac{t}{T_B}\right)^b\right], \tag{19}$$

where T_B is the average duration of a failure-free operation of a pump housing, h; b is the indicator of the shape of the distribution curve (one can accept the value b=2); $[\sigma]$=150...300 MPa is the permissible value of stretching stress for the walls of a pump housing depending on the grade of cast iron, MPa.

These results were obtained by analyzing operational documentation for fire trucks operated by the State emergency service units in Lviv oblast (Ukraine).

The condition for the bending strength of a pump housing $[\sigma]$ is recorded in the following form:

$$\sigma = \frac{10^3 M_{\max}}{W_z} \le [\sigma], \quad W_z = \frac{L\delta^2}{6}, \tag{20}$$

$a_1, a_2, ..., a_6$ are the minimum values of operational and structural factors; $b_1, b_2, ..., b_6$ are maximum values of operational and structural factors; p is the probability of the examined point entering the region of permissible solutions.

4. 3. An algorithm for solving the optimization problem of determining the minimum thickness of a pump housing

A Monte Carlo method was used to solve the optimization model. To apply a given method, the generation of pseudo-random numbers μ_i in the interval 0...1 is followed by their conversion to factor values using the following dependence:

$$x_i = a_j + \mu_i \cdot (b_j - a_j), \tag{21}$$

where x_i is the value of the factor at the i-th stage of solving the problem; μ_i is the pseudo-random number at this stage; a_j, b_j are, respectively, the minimum and maximum value of the j-th constraint.

To solve the above optimization problem, a flowchart of the algorithm was developed (Fig. 2).

The flowchart of the algorithm includes all the necessary dependences to calculate and determine the required factors for pump housing.

Unit 1 must include the input data, namely the rotation frequency of the impeller shaft (blade), the cost of a cast iron pouring, the cost of waste, the cost of one inspection during the operation of the housing. Also included are the overhead of an enterprise-manufacturer, the total number of inspections during the operation of the housing, the cost of the prototype, etc. It is also necessary to specify the permissible value of the probability of the examined points entering the region of permissible solutions.

The initial data must include the following values:

– a_1, b_1 is the minimum and maximum value of pump capacity, kW;

– a_2, b_2 is the value of the coefficient that takes into consideration short-term overload;

– a_3, b_3 is the value of the specified period of operation before the overhaul, h;

– a_4, b_4 is the value of the total time, during which one inspection of the pump housing is performed in accordance with PR to ensure the reliability of its operation, h;

– a_5, b_5 is the value of the probability of a failure-free operation of the pump housing;

– a_6, b_6 is the value of permissible stretching stress for the walls of a pump housing, MPa.

Unit 2: the N_i and K_i parameters are assigned zero values.

Unit 3: the N_i parameter is assigned the serial number of the program application cycle.

Unit 4 generates pseudo-random numbers in the interval [0, 1], that is, it works as a generator of pseudo-random numbers μ_{1i}, μ_{2i}, ..., μ_{6i}.

Unit 5: determine P_i, $K_{\Pi i}$, T_{Ei}, t_i; $R(t)_i$, $[\sigma]$.

Unit 6: determine the shaft angular speed ω, the torque T_i, and the maximum bending moment $M_{\max i}$ acting on the shaft.

Unit 7: determine the length of the dangerous section of the housing wall L and the wall thickness δ_i.

In unit 8, the optimization mathematical model is solved using the pseudo-random numbers, objective function, criterion, and constraintsIn unit 9, the structural elements of the centrifugal pump housing are printed.

The basis for determining the optimal values of the structural elements of the centrifugal pump housing is the optimization criterion, which is represented in the form of cost differences (13).

In this case, an article will be composed of the optimal structural elements when this difference accepts a minimal value.

The graphical dependence of the difference indicator on the duration of centrifugal fire pump operation, as an example, is shown in Fig. 3.

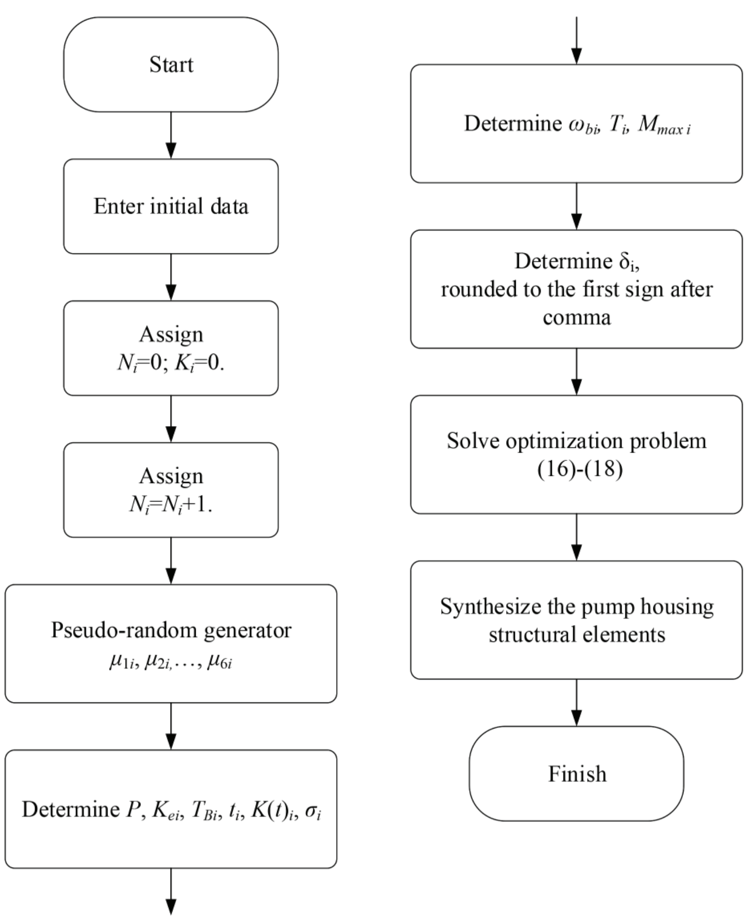


Fig. 2. Flowchart of the algorithm for synthesizing the structural elements of a pump housing

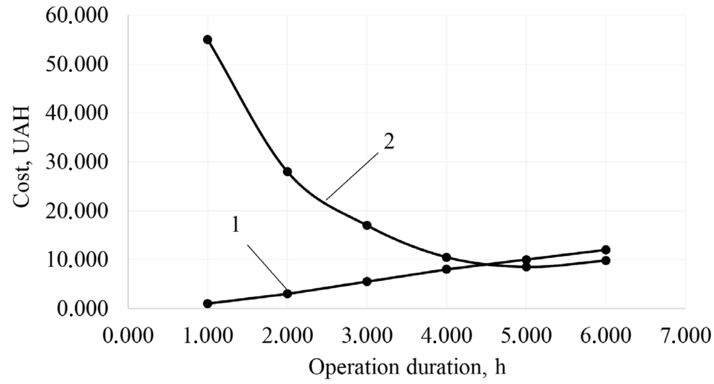


Fig. 3. Criterial dependences: 1 – Q_H; 2 – E

Based on the analysis of the graphical dependences, it can be argued that the best value of the difference criterion for choosing the optimal design of the housing is the point of intersection when the cost of ensuring the reliability Q_H is equal to the economic indicator of reliability E. This means that the reliability of the pump will be ensured at minimal cost for its manufacture. Reducing the cost of fabricating a pump can be achieved by reducing the cost of materials for the manufacture of the pump housing while ensuring its strength and reliability.

By solving the optimization problem, we have established the minimum thickness of a pump housing wall, which is 8.5 mm, which is 1.5 mm less than that in existing samples of fire centrifugal pumps. Such an unreasonable excess leads to larger material consumption for the housing, by 3.2 %. Reducing the thickness of the pump housing wall makes it possible to reduce its weight by 9...11 % while reducing the cost of production of one housing by 10 %.

5. Discussion of results of computer synthesis of the structural factors of a centrifugal pump housing

A special feature of the devised method for determining the main indicators of reliability of centrifugal fire pumps is taking into consideration, when calculating the strength and kinematic parameters, the economic reliability indicator (7) to (12) and the cost of ensuring reliability (13). These indicators make it possible to establish the optimal consumption of materials for the manufacture of structural elements of centrifugal fire pumps, ensuring their strength and reliability. Accordingly, to determine the minimum thickness of the pump housing wall, an optimization mathematical model was built using the difference criterion (15). As shown in Fig. 3, the best value of the difference criterion for choosing the optimal design of the housing is the point of intersection when the cost of ensuring the reliability Q_H is equal to the economic indicator of reliability E, that is, the value of this criterion is 0. The objective function of the optimization model is to minimize the mass of a fire pump (16). A Monte Carlo method was used to solve the optimization problem. It is this approach to solving the problem that has made it possible to establish the optimum thickness of the pump housing wall.

The development of a given method makes it possible to simplify the calculation of the optimal thickness of a pump wall, without resorting to time-consuming and costly computer simulation of the strained-deformed state of the structure, proposed in work [3]. When applying a finite-element method one should repeatedly model an object, gradually reducing the thickness of the wall of a fire pump housing, which certainly leads to significant time costs. In addition, the method applied, in contrast to existing ones, takes into consideration the cost of ensuring reliability and the economic indicator of reliability, which makes it possible to reduce the cost of manufacturing pumps.

When implementing the obtained results in further studies, it is necessary to take into consideration the restrictions that apply to fire pumps, namely ensuring the rated power of a fire centrifugal pump, the long-term operation until an overhaul, as well as preventing that the value of the stretching stress on the walls of the pump housing, depending on the grade of cast iron, reaches critical values.

A given method makes it possible to calculate centrifugal pumps. When estimating other types of pumps (piston, membrane, jet, etc.), it is necessary to change the objective function (16) and restrictions (18) in accordance with the parameters of the pump and the forces that operate on the pump housing.

6. Conclusions

1. When devising a method for determining the basic reliability indicators of centrifugal fire pumps, it is proposed to apply the condition of strength and reliability of the centrifugal fire pumps combined with the economic reliability indicator. This makes it possible, when designing and manufacturing these pumps, to take into consideration, in addition to the strength and kinematic parameters, economic costs as well, which is a prerequisite for building an optimization problem to minimize the mass of the pump by reducing the thickness of the fire pump housing.

2. We have built an optimization mathematical model whose special feature is the application of a difference criterion while the chosen objective function is the minimization of the pump weight. The use of the difference criterion makes it possible to take into consideration the economic indicator in the manufacture of centrifugal fire pumps and reduce their cost by determining the optimal thickness of the pump housing wall.

3. To solve the optimization problem, the Monte Carlo method was used, implemented by the developed algorithm. The calculation results showed that the width of the PN-40 UV pump housing can be reduced by 1.18 of the nominal one. This, in turn, makes it possible to reduce the weight of the pump by 9...11 % while reducing the costs of producing one housing by 10 %.

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