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ANALYSIS OF METHODS OF IMPROVING ENERGY EFFICIENCY OF PUMPING STATIONS POWER UNITS OF WATER SUPPLY SYSTEMS

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Abstract. The article shows the importance of the problem of improving efficiency of energy use in technical and technological systems. One of the ways of improving energy efficiency of water supply systems is the use of new energy-efficient technologies and pumping equipment, the use of modern management systems. Modern trends in the evaluation of energy consumption for operation of pumping equipment of water supply systems were analyzed. New methods of improving energy efficiency of pumping units in water supply system, taking into account the real operating conditions, were presented.

Key words: energy efficiency, pumping unit, pressure, flow, regulation, working field, the target value, the index of efficiency.

CURRENT STATE OF THE PROBLEM

Improving of resource and energy efficiency is a prerequisite for sustainable development of the country, industry, company. Energy efficiency is the characteristics reflecting the ratio of the beneficial effect from the use of energy resources to the costs of energy resources produced in order to obtain such an effect in relation to products, technological process, legal entity, individual entrepreneur. Energy efficiency is a problem branch at the turn of engineering, economic, legal and sociological disciplines.

Increased energy efficiency occurs when the specific energy consumption per unit of useful product, service or work is reduced. Energy efficiency always rises when the beneficial effect increases and energy consumption decreases. If energy consumption increases and the beneficial effect falls, then energy efficiency is always reduced. Reducing of energy consumption – energy saving – on condition that the beneficial effect decreases more rapidly than energy consumption, can take place with a decrease in energy efficiency. It was in Germany, Sweden, Russia in the crisis year of 2009. Growth in energy consumption can be accompanied by an increase in energy efficiency, if the beneficial effect increases faster than energy consumption.

The hierarchy of indicators of energy efficiency makes it possible to estimate the use of energy resources, both at the level of the country's economy in terms of energy intensity of GDP, and at the level of the industry, at the level of production of the same type products by specific values. At the lowest level of indicators, the efficiency of energy consumption in individual technological processes, technologies and types of equipment is considered, that is in the ratio of the beneficial effect from the use of energy resources to the expenses. [1].

Upgrading of energy use efficiency and of resources in economic technical and technological systems, on the one hand, increases the reliability of energy consumption systems, on the other hand, it reduces the demand for natural resources, and also increases safety of vital activity. At any level of indicators, energy efficiency increases with the growth of useful effect and the reduction of energy consumption. However, a reduction of energy consumption in energy conservation measures can lead to a decrease in energy efficiency indicators, in a case if beneficial effect decreases more rapidly than energy consumption. Just as the increase in energy consumption may ensure the growth of energy efficiency indicators, if the useful effect grows faster than energy consumption. The most important characteristics of the technical level of the system being designed and operated, the machine, their aggregates are energetic, which represent the amount of required energy resources for providing the corresponding beneficial effect from their use. Energy consumption of products determines the cost of their life cycle for ultimate users, as well as additional expenses for other resources.

The main points of energy efficiency improving of engineering systems buildings in the European Union are reflected in Directive 2002/91 / EC which is one of the fundamental European documents [2]. The Directive notes that buildings of various purposes account for up to 40% of the total energy consumption in Europe. The document became the legislative basis for the development of the totality of measures aimed at increasing the efficiency of energy use in buildings. In addition, the document establishes the practice of conducting regular energy inspections of buildings for identifying energy conservation reserves. The implementation of this set of measures is inextricably linked to the issues of improving the economic feasibility of the pumping equipment operation served in various engineering systems.

In the structure of the cost of services for water supply and sanitation, expenditure of electricity can reach 50%, including unproductive expenses up to 20%. An important component of expenses in the structure of costs is the loss of water while it is distributed and transported to consumers which can reach at least 30% of total volume. Elevated pressures in the network create additional losses which reduce the energy efficiency of the system as a whole [3]. The point of increasing the energy efficiency of pumping equipment in water supply and sanitation systems is a priority, despite the traditional approaches in the fields of design, construction, production and operation [4].

ANALYSIS OF PUBLICATIONS AND REVIEW OF EVALUATION METHODS

The problem of increasing the energy efficiency of the technological process of water supply, which must be supplied with the required pressure in accordance with the needs of consumers, is one of the main problems for water supply and sanitation systems. In recent decades in the technical literature a significant amount of research has been dedicated to the development of new designs and technological processes for increasing energy efficiency of pumping stations power units of water supply systems. Modern Water Supply Systems (WSS) represent a complex set of technological processes, engineering structures, machinery and apparatus that contain mechanical, hydraulic, power equipment, pipelines, fittings, instrumentation and automation. This complex is destined for receiving water from natural sources, improving its quality, storing, transporting, supplying and distributing it among consumers under the required pressure in accordance with their needs.

At all stages of the life cycle of WSS, along with providing the required pressure and water supply for normal and emergency conditions, it is necessary to provide at the lowest costs for their construction and operation: the required degree of reliability, durability, economy, and the fulfillment of a number of other requirements. In WSS energy consumption of pumping equipment is one of the main components of operating costs of public utilities. Therefore, improving the energy efficiency of pumping equipment is the main reserve for reducing energy consumption costs of WSS.

Low energy efficiency of WSS during transportation and distribution of drinking water, as well as during its purification is caused by the following reasons:

- outdated methods of calculating the static parameters of the hydraulic network in accordance with existing norms of water consumption and hourly unevenness factors, as well as requirements for maximum headers in a network with high energy intensity;
- the complexity of ensuring the correspondence of the variable parameters of the WSS networks to the working fields of the characteristics of Centrifugal Pumps (CP);
- application of pumping units with low efficiency due to their wear and tear or initially constructively or technologically imperfect in the conditions of their application;
- use of energetically ineffective ways of regulating the operation modes of the systems pumping unit – network

Especially big problems in organizing the operation of water supply are caused by the operation of complex networks of large cities which are associated with the following points:

- the presence of several hydraulically interdependent zones located at different geodetic marks;
- simultaneous operation of several pumping stations with different pumping units on a branched hydraulic network which causes a redistribution of water flows when changing the operating mode of at least one of the Pumping Stations (PS);
- Peculiarities of geographical relief, connection of new consumers, as well as different floors of housing estates and houses;
- Overrun of electricity from 15% to 50% as a result of installing equipment with excess capacity to ensure the maximum possible water supply [5].

All this in WSS leads to the following negative consequences:

- overstating the costs and pressures of pumping equipment installed on PS which leads to inefficient electricity consumption, increased water losses in networks, increased risk of water hammering and deterioration of water quality;

- ineffective response of PS units and regulatory systems to changing operating conditions;
- the rise of emergency situations due to gusts of pipelines, breakage of pipeline fittings and pumping units;
- increase in the specific electricity consumption for pumping 1 m^3 of water.

The main areas for increasing the energy efficiency of WSS are:

the introduction of new energy-efficient technologies, the development of pumping equipment with the lowest possible energy consumption; its correct selection taking into account the real operating conditions; qualitative installation, commissioning and skilled operation; optimization of the system operation pump - water supply system, use of modern control systems. To make certain decisions on improving the energy efficiency of WSS, it is necessary to analyze the real energy consumption of existing pumping units.

In accordance with the definition above, energy efficiency is understood as the ratio of the useful effect from the use of energy resources to the expenses of energy resources, to obtain such an effect. An estimation of the energy efficiency of PS aggregates as a physical efficiency of a technical system using the classical approach can be represented as:

$$\eta_c = \frac{Auseful}{Acon},$$

where:

$Auseful$, $Acon$ – useful and consumed energy.

However, the use of this indicator is impractical, since useful energy is needed not only for delivering of water to the consumer but also to overcome the forces of hydraulic resistance of the water supply network. Useful in WSS is the fact of water delivery to the final destination and not the work that was spent, and, obviously, it should be reduced. To evaluate the energy efficiency of pumping units of WSS in research [6], it is suggested to consider the ratio:

$$EE = \frac{Q}{N}. \tag{1}$$

where:

Q – pumping units delivery,

N – power consumed by the motors to provide feed.

Energy efficiency of pumping units of WSS by formula (1), taking into account the dependence for the power consumed by the electric motors, has dimension $\left(\frac{m^3/s}{kW}\right)$ and is defined as:

$$EE = \frac{1000}{\rho \cdot g \cdot H} \cdot \eta_{н} \cdot \eta_{эд} \cdot \eta_{пр}, \tag{2}$$

where:

ρ – density of pumped fluid, *кг/м*^{3}; g - free fall acceleration*;* H - pump head in *m;* η_p - efficiency of pump; η_{em} - efficiency of electric motor; η_{fc} - efficiency of regulating or converting device (frequency converter, fluid coupling, etc.)

Consequently, the energy efficiency of pumping units of WSS is a function $EE = f(H, \eta p, \eta_{em}, \eta_{fc})$ and its increase may be provided in two ways: increase of coefficient of pumping unit components efficiency or reduction of pressure. If the first way is obvious, the second one requires additional analysis. The pressure which is created by the pumping units in the WSS consists of the pressure, which is necessary to perform a certain technological process for the consumer, and the head, which is necessary to overcome the hydraulic resistance forces of the pipeline network. The pressure which is necessary for performing of technological process, is regulated by specification standards, it cannot be reduced but the pressure which is necessary to overcome the hydraulic resistance of the pipeline network can be reduced by optimizing the distribution of flows in the network and eliminating unnecessary local resistance, increasing the diameter of the water conduit, etc. From relation (2) it also follows that the levels of pressures in pipe networks, which are incorporated in the requirements of specification standards substantially affect the energy efficiency of the WSS.

Increased attention to the energy efficiency of pumping equipment is due to the fact that up to 85% of total costs, taking into account the operation and gain of the pump for the period of its pump, is the cost of consumed electric power [7]. When designing, reconstructing and modernizing pumping stations, WSS pumping units are selected from the standard range with pressure for supply and delivery, taking into consideration the parameters of the maximum mode of water consumption. An important condition for the efficient use of pumping units in WSS is the coordination of their optimal operation modes with variable parameters of the hydraulic network. The best result of the pumping set selection is ensured, if the flow rate fluctuates in the network, the deviations of the pumping set parameters by the coefficient of efficiency will be within ± 10% of the maximum value. When designing CP, their performance characteristics are optimized for a narrow working range of the nominal mode which cannot be used in operation. As a result, in practice, a high level of pumps efficiency often remains unused due to incorrect coordination of the parameters of the pumping station and the hydraulic network.

Over the past decades, the policy of European countries is an example of an integrated approach to solving energy efficiency problems. A key role here was played by the adoption of a number of documents designed to create a system for stimulating the mass introduction of energy-saving technologies. For an objective assessment of the technical level of energy-related equipment indicators, products and machines, over the past decades a direction has been formed to mark its energy efficiency. The essence of the labeling is based on the analysis and testing of energy consumption in the group of energy-related products, each of which is assigned a certain energy efficiency index, fixed in the technical documentation. For the unification purposes, the energy efficiency scale for all groups of marked products is divided into several classes. The energy efficiency index is a significant parameter of any power equipment that characterizes the ratio of the power used at different operating modes to the reference power. Specification of data on electricity consumption for the majority of household electrical appliances is mandatory in the European Union since 1992.

The energy efficiency index is applied to the product in the form of special marking, and since 2005, this marking is an obligatory requirement in the EU countries and is regulated by a special Directive. Leading world manufacturers with understanding and interest reacted to the requirements of the classification of products energy efficiency. At present, index or energy efficiency class becomes a significant characteristic of the product competitiveness, as well as its quality, reliability, design. At present, modernization of energy-related equipment by the criterion of energy efficiency occupies one of the first places. The new Energy Efficiency Marking Directive 2010/30 / EC has entered into force since 2010. which covers not only household products, but extends the scope of regulation to industrial and commercial appliances and equipment, as well as to products that do not consume energy themselves, but can to have a significant direct or indirect effect on its economy. It covers not only household products, but extends the scope of regulation to industrial and commercial appliances and equipment, as well as to products that do not consume energy themselves but can have a significant direct or indirect effect on its economy. The implementation of the outlined set of measures is inextricably connected with the issues of improving the energy efficiency of the pumping equipment operated in various engineering systems. With these goals in recent years, the European standards EN16297-1-2015 `General requirements and methodology for testing and calculating the energy efficiency index (EEI)` [8] and EN16297-2-2015 `Calculation of the energy efficiency index (IEA) of self-contained circulation pumps` [9]. The criterion for assessing the efficiency of the pump within the framework of the introduced classification is the Energy Efficiency Index (EEI) which is defined as the ratio of the weighted average power consumed by the pump in various operating modes to the base power calculated for the mode with the maximum coefficient of performance.

Table 1 presents the classification scheme of energy efficiency indexes for energy-related equipment which indicates that the lower is the value of the energy efficiency index, the higher is its energy efficiency, and the higher is energy equipment class. The given index indicates the ratio of the total operation of power equipment in various modes to power consumption at maximum mode (reference).

Table 1. Correspondence of energy efficiency classes and indexes

Class	Energy Efficiency Index (EEI)
A	EEI<0.4
B	0.4≤EEI<0.6
C	0.6≤EEI<0.8
B	0.8≤EEI<1
E	1≤EEI<1.2
F	1.2≤EEI<1.4
G	1.4≤EEI

CP has been estimated to develop energy efficiency concept and currently the European standard EN16480 `Minimum required efficiency of centrifugal water pumps` is at the discussion stage [10]. This standard will define the effectiveness of pumps with up to 1000 m^3/h of six design cantilever, console – monoblock, cantilever monoblock with in-line nozzles, vertical multistage and submersible multi-stage pumps for which an energy efficiency index is introduced - minimum efficiency index. This index is a decimal number which is less than 1.0 and reflects the quantitative ratio of the products of different technical level on the market. The index of minimum efficiency allows to identify not only the actual value but also to define the necessary order of actions for achieving the targets. Achieving the performance work parameters of pumping equipment to values that would be higher by 2015 for MEI = 0.4 and for 2020 at MEI = 0.7 is one of the priorities for pumping equipment manufacturers.

The work [4] shows the examples of calculation of EEI and MPEI on the basis of techniques given in [8, 9, 10] and with the initial data of pumping equipment operating at the pumping station for pumping into the hydraulic grid of WSS, taking into account the geodetic features and in real operating conditions. It is important to admit that the suggestions on standard EN16480 determine the procedure for assessing the technical level of the CP at three points of its performance factor: when Q_{BEP} is applied at the maximum efficiency point, when QPL is applied at the partial load point, at $Q = 0.75Q_{BEP}$ and when Q_{OL} is applied to the overload point at $Q = 1.1Q_{BEP}$. These points determine the efficiency values that form the "efficiency house", below which the actual values of the pump efficiency cannot be lowered. The performed calculations of these indicators of the energy efficiency of the CP have shown their complexity regarding the need of a large volume of additional information. The actual energy efficiency index can be established, taking into account the real load profile of CP. For WSS pumping stations that work for the consumer, the load profile of the CP can be obtained as a result of statistical processing of operational parameters. Therefore, in the selection of pumping equipment in WSS, energy efficiency indexes are not applied and energy efficiency is estimated mainly by the coefficient of efficiency of pumping unit assemblies. However, the methodology for estimating the energy efficiency of PS pumping units' operation, taking into account the operating conditions, makes it possible to establish the correctness of the pump sizes choice, their drive motors, and also to determine the real reserves of energy saving.

RESULTS OF INVESTIGATIONS

The analysis of methods for increasing WSS energy efficiency has shown that the most rational ways of solving this number of problems are based on modern methods creating for monitoring the operating conditions of pumping units, methods of controlling PS operating and also the use of modern automated systems.

The process of WSS functioning is characterized by changes in the parameters of its condition in time. These changes depend on numerous internal and external factors, control on most of which is problematic [11]. The strategies for constructing mathematical models of WSS operation modes are based on the theory of random functions but the problem of using these techniques lies in the difficulty of obtaining statistical data on the operating modes that are necessary for the application of these techniques and the construction of models [12]. Because of this, scientific research is conducted on the operating modes of modern WSS with their subsequent generalization and systematization for the development of adequate mathematical models.

We shall deal with temporary changes in the parameters of WSS functioning as a random process. To construct a mathematical model of a random process, the following stages were achieved [13]:

- collection and registration of experimental data;
- the previous analysis of the properties of water consumption random process;
- analysis of a random process and formulating of its characteristics.

The correctness of using certain methods of analyzing a random process depends on a large extent on its properties. They include, first of all, stationarity, the presence of periodic components and the fact that the process goes in a normal way.

The assumption of the process stationarity is verified by analyzing the available realizations. Assuming that the chosen implementation length significantly exceeds the period of its low-frequency component and, taking into account the above definitions, to check the stationarity from the data on individual implementation, the following sequence of operations is planned:

- the realization is divided into N equal intervals;
- The estimations of mean values and variances are calculated and are arranged in ascending order of the interval number;
- the obtained sequences are tested for the presence of a trend using nonparametric criteria for which knowledge of sample distributions of estimates is not required, such as a series criterion or an inversion criterion.

With a sufficient set of realizations of a random process that is obtained as a result of measurements of its parameters, it is possible to calculate the estimations of their mean values and variances by sections of the random process. The general scheme for analyzing the preliminary analysis of a random process is shown in Fig. 1. The given scheme can be used for statistical analysis of pumping units' parameters of the operating PS. To justify the parameters that provide optimal operating conditions for pumping units, it is necessary to obtain the distribution laws of the processes under study, according to the results of a statistical analysis. Although, in order to solve the practical problem of PS operation optimizing, it is sufficient to have a mathematical model, describing the behavior of the mathematical expectation of the random value of PS feed.

If a steady state of the process is proved, the mathematical expectation has a constant value and its interval estimation can be obtained with a given degree of accuracy in any section of the process. If the original data contains extraneous trends, then there may be significant distortions in estimations of the probability distribution density, covariance and spectral characteristics. The most common way to remove a trend is to construct a polynomial of the minimal order based on the method of least squares

The initial statistical data is the results of measuring the water flow supplied by the PS for at least two months with the discreteness of time $\Delta t = 1\ h$. Sixty realizations of a continuous random variable have been obtained and each of them has twenty-four sections. It was assumed that the conducted experiment, within 24 hours, can be repeated under statistically identical conditions. That is, at this stage of the investigation, we neglected the possible influence of the seasonal trend, differences in water consumption by individual days of the week, etc.

With an outfit of realizations $Q_k(t)$; $m=\overline{1,60}$; $t=\overline{1,24}$ of the random process, estimation of the average value is obtained by averaging the cross section [17]:

$$\mu_Q(t)=\frac{1}{N}\sum_{k=1}^{N} Q_k(t); \quad t=\overline{1,24}, N=60 \tag{3}$$

Estimations $\mu_Q(t)$ are random variables and satisfy the requirements of unbiasedness and consistency. Confidence interval for the mean value $M_Q(t)$ for significance level α is given by the formula:

$$\mu_Q(t)-\frac{s_Q(t)\cdot t_{n;\alpha/2}}{\sqrt{N}} \le M_Q(t) \le \mu_Q(t)+\frac{s_Q(t)\cdot t_{n;\alpha/2}}{\sqrt{N}} \tag{4}$$

In (4) $s_Q(t)$ is unbiased estimation of root-mean-square deviation $\sigma_Q(t)$ of a random process $Q(t)$ at the moment of time t, is determined by the formula:

$$s_Q(t)=\left[\frac{1}{N-1}\sum_{i=1}^{N}\left(Q_i(t)-\mu_Q(t)\right)^2\right]^{1/2} \tag{5}$$

$t_{n;\alpha/2}$ is quantile of the t-distribution of the Student with $n=N-1$ of freedom degrees. With a sufficiently large sample, formula (4) is also valid for non-Gaussian processes.

The results of calculation by formula (4) are performed in the standard program STATISTICA and presented in the graphical form. Type of dependence $M_Q(t)$, in consequence of the mathematical expectation inconsistency, allows us to confirm the hypothesis of the nonstationarity of the random process of water consumption. If there is data on the characteristics of real water consumption, using the methods of mathematical programming, it is possible to determine the optimal modes of PS aggregates operation. The optimization task is no longer applied to a single nominal regime but to an entire range of modes that are characterized by the necessary ranges of changes in feeds and pressures, as

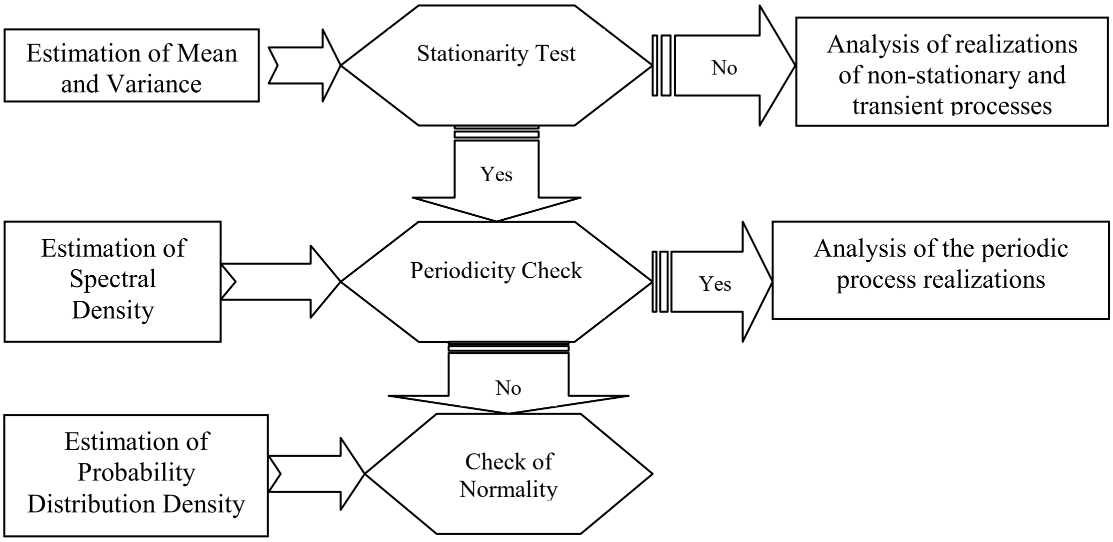

Fig. 1. General scheme of preliminary analysis of a random process

well as the permissible reduction in the energy efficiency of the pumping unit. To implement these directions on increasing pumping units' energy efficiency, the following tasks were solved.

Task 1. *The development of an optimization model for minimizing the total costs of PS for ensuring the water supply process and finding the optimal volumes and time intervals for water supply to the consumers.*

Work [13] shows the procedures of CP optimal parameters determination and time intervals of water supplying $Q(t)$ to the consumers with a reserve capacity of the volume $V_{\max}$ by the criterion of the minimum cost of water supply, with the known function of daily water consumption $Ras(t)$ and electricity tariffs $St(t)$. As the objective function of the optimization problem, condition is:

$$\rho gH \cdot \int_0^{24} Q(t) \cdot St(t) \cdot dt \to \min$$

and the constraint system is represented by a system of dependencies:

$$\begin{cases} 0 \le \int_0^t \left(Q(t) - Ras(t)\right) dt \le V_{\max} - V_{рез} \\ \int_0^{24} \left(Q(t) - Ras(t)\right) dt = 0 \\ Q(t) \ge 0 \end{cases}$$

Task 2. *Development of an optimization model for a stepwise method for regulating the parameters of PS pumping units.*

With the step-by-step method of regulation, the change in the characteristics of the PS is achieved by changing the number of working pumps. The value of the `step` of switching depends on the performance and type of characteristics of the pumps used. Step regulation is relatively simple and cheap, therefore the change in characteristics by switching the number of uncontrolled CP has found the greatest application in most incremental PS.

Optimization of the parameters of the stepwise regulation procedure is a multicriteria optimization problem. By way of criteria for the solution optimality, the following criteria may be involved:

- the minimum number of CP used;
- minimum number of changes in CP operating mode;
- minimum reserve capacity;
- the amount of water in the reserve capacity is non-negative function of time;
- the absence of excess water in the reserve capacity at the end of the characteristic time period;
- the maximum coefficient of performance of each CP.

The procedure for step - by- step regulation optimization of PS pumping units' parameters based on the proposed block diagram is organized in the form of a worksheet of the mathematical package MathCAD.

Task 3. *Increase in the energy efficiency of the frequency method for regulating the parameters of the boosting PS pumping units.*

One of the modern ways to adjust the PS power units' parameters is frequency regulation which is provided by changing the rotational speed of CP impeller. By adjusting the rotational speed of the impeller of the pump set, in some cases it is possible to reduce energy costs [15]. However, the effectiveness of CP regulated electric drive introduction depends on many factors and requires detailed research and justification. The work [16] shows an analysis of the main methods of frequency regulation of parameters and operation modes of PS pumping units of the second-rise .

The most widely used method is frequency control with the limitation of the maximum permissible pressure in the network, for the calculation of which dynamic head losses taken into account in the regime of the maximum water consumption. When the rotation frequency is reduced while maintaining the maximum permissible pressure in the network, the overpressure is inflated by the value of the dynamic pressure difference at the maximum and changed feed rate. Taking into account the fact that the maximum water consumption in the water supplying system can be only a small part of the working time, this method of regulation contains a significant potential for increasing the energy efficiency of the WSS as a whole.

The work [17] justifies the parameters of stepped frequency regulation on the basis of mathematical modeling of PS pumping units operation modes of the second generation. By way of illustration during the year the operational parameters of PS swap, in one of the city districts with an average daily flow of 2500 m^3 / day and a continuously maintained pressure of 60 m due to the installation of a frequency converter in the drive of the pumping unit.

Analysis of operational data showed seasonal unevenness, as well as a tendency to reduce water consumption. Areas in which the outstanding peaks of hourly water consumption are noted, can already be analyzed for the selected date, month or season of the year. The data array can easily be transformed for the analysis of daily, weekly and seasonal patterns of PS hourly feed. The results of statistical processing of the annual operating parameters of PS power unit show that in the feed range with the need to maintain the maximum pressure of CP 60 m only 13.7% of the total operating time was working.

Accordingly, a new step-by-step method for regulating the parameters of the system `Powertrain-water system` is suggested, on the basis of a change in the rotational speed of CP impeller by different values of maintaining the pressure at the exit from CP. These pressure ranges are determined by the pressure characteristic of the power unit, taking into account the results of statistical processing of the operating parameters during the specified observation period. For the considered PS, the variant of regulation of the rotation speed of PS impeller at three levels of pressure stabilization: the maximum - 60 m; average 55 m and minimum 50 m. At the same time, the system operates at the upper pressure level - 13.7%, on the average - 75.8%, and at the minimum level - 10.5% of the total operating time. Fig. 2 shows the hourly values of the pumping unit power consumption during the day by different control options. The upper dot curve shows the hourly values of the power consumption of the pumping unit at the rated speed of the impeller, i.e., without adjusting the rotational speed of the impeller. The average dotted curve shows the power consumption when adjusting the rotational speed of the impeller of CP with a constantly maintained pressure in the network of 60 m. The lower curve shows the hourly power consumption levels of the power units of the PS, with a three-step pressure control, with the selected values for pressure: 50-55-60 m. The graph shows that during the peak hours of water consumption, the lower and middle curves coincide. The difference in areas that are limited by these curves corresponds to the value of the daily energy savings.

In the example, with the stepwise frequency control method, the energy efficiency is increased by 9.7% with respect to the control at a constant level of the maximum pressure; and by 20.8% with respect to the uncontrolled pumping unit. For PS considered in the article, increase in energy efficiency by 9.7% provides an energy saving of 30,000 kWh per year.

It should be noted that with step-wise regulation, the pressure forces acting in the network are reduced which ensures an increase in the reliability of WSS and a reduction in water losses due to leakages. A distinctive feature of this method of regulation is that it does not require large expenditures with the frequency converters already installed in motor control systems. To change the control modes, it is enough to install controllers with additional settings of pressures in the network according to time, which are determined from the results of statistical processing of water consumption regimes.

Task 4. *Increase of energy efficiency of the parameters regulation combined method of boosting PS pumping units.*

The wide application of CP in water supply and distribution systems is due to the simplicity and manufacturability of their design, the provision of large feeds, the possibility of pumping contaminated liquids with different properties and characteristics. The main disadvantages of the CP which are caused by their hydronic principle of operation, are the low level of the created pressure, a relatively low efficiency and also non-rigidity of the pressure characteristic, resulting in a

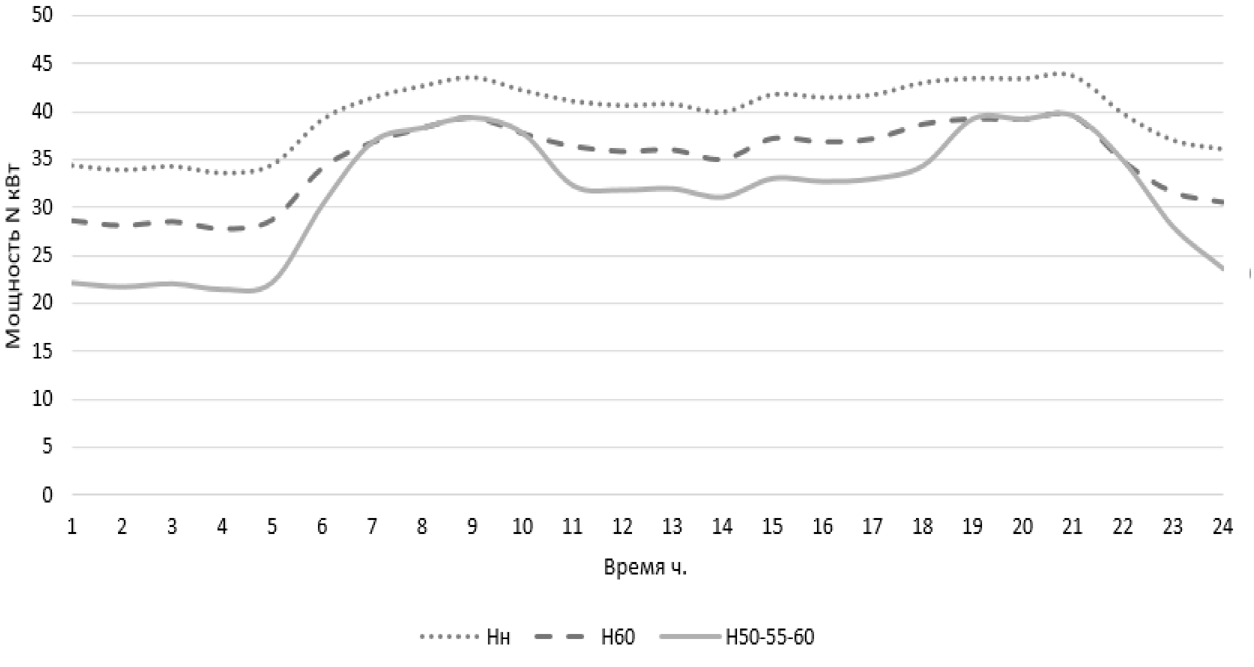

Fig. 2. Daily diagrams of the power consumption of the pumping unit at various ways of regulation

change in flow to a significant change in pressure and efficiency. Water consumption in centralized WSS is a non-stationary random process which determines the complexity in providing the required operating modes of pumping units for energy efficiency.

For the most modern method of qualitative CP parameters regulation due to the changes in the rotational speed of the impeller, it has been established that this method does not always lead to a significant reduction in energy consumption which is caused by the complexity of linking networks characteristics and their changes with the pressure and energy characteristics of pumping units. The creation and application of fundamentally new pump designs for water pumping, as well as the use of energy-efficient methods of regulation is an effective way to solve the problem of improving the efficiency of the operation of WSS. One of these constructions are volumetric bi-rotor pumps which provide a reduction in size and weight, increase in working pressure and stabilization of efficiency in a wide range of parameters [18]. A distinctive feature of the operation of bi-riot volumetric pumps, is their rigid pressure characteristic, that is, practically constant supply that does not depend on the pressure but is determined by the rotational speed of the impeller.

As a combined method of regulation, the work [19] suggests the ways of increasing the energy efficiency of pumping unit systems due to the parallel connection of the central heating system and volumetric bi-rotor pumps with variable speed. Fig. 3 shows the working field of CP field with its frequency control and the parallel connection of a bi-rotary pump with a variable speed.

From the analysis of the presented dependences, it follows that with the combined control method CP working field with an adjustable frequency of rotation

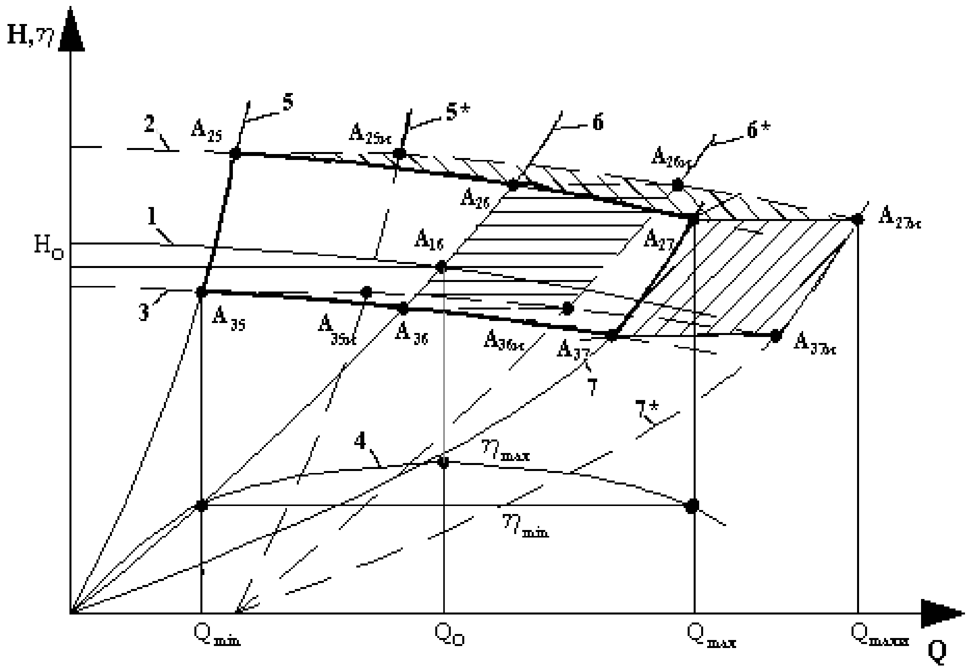

Fig. 3. Working field by the combined method of CP operating modes regulating with frequency control and parallel connection of a volumetric pump with a variable speed: 1 – CP pressure characteristic at the rated speed of rotation $n_{ЦH nom}$; 2 – CP pressure characteristic at the maximum speed $n_{CP\max}$; 3 – CP pressure characteristic at the minimum speed $n_{ЦH\min}$; 4 – CP efficiency characteristic; 5 – parabola of CP similar modes with the minimum feed $Q_{\min}$; 6 – parabola of CP similar modes for optimal feed rate Q_O ; 7 – parabola of similar CP modes at the maximum feed $Q_{\max}$; 5* – parabola of similar CP modes with the minimum feed $Q_{\min}$ and the maximum feed Q_{OH}; 6 parabola of similar CP modes with optimal feed Q_O and the maximum feed Q_{OH}; 7 – parabola of similar CP modes at the maximum feed $Q_{\max}$ and the maximum feed Q_{OH}.

▧ – increase in the working field due to the increase in pressure;

▨ – increase in working area due to increased feed rate;

▤ – Optimal working field which provides the maximum efficiency.

substantially increases both in pressure and in feed. The conditions for the formation of an optimal working field are also established, in which the maximum efficiency of the combined pumping unit is ensured by changing the speed of CP impeller in accordance with the parameters of a parabola of similar modes passing through the coordinates of the optimum operating point at the nominal speed.

CONCLUSIONS

1. The general principles of increasing the technical level of energy-related products are energy principles which represent the amount of the necessary energy resources to ensure the corresponding beneficial effect from their use. The main objectives of the implementation of the federal policy of energy conservation and energy efficiency improvement are the dynamic reduction of the integrated energy efficiency index, as well as the reduction of the technological gap in equipment and technological processes with the leading countries.
2. For housing and communal services as one of the largest consumers of energy resources in the Russian Federation, improving of energy efficiency is one of the main tasks. Water supply and sanitation systems belong to the most energy-intensive housing and communal services where the main consumers of electricity are PS power units.
3. Water consumption in centralized WSS is a non-stationary random process that, in order to justify various methods of regulation and to ensure optimal operating conditions for pumping units, requires the development of a mathematical model of a random process based on the statistical operational parameters processing.
4. The analysis of four previously suggested methods of PS power units regulation is fulfilled, and the main advantages on the possibility of adjusting the parameters are presented. It is substantiated that further improvement of these methods of regulation should be based on research of operational parameters of power units, with the purpose of revealing the laws of distribution of these parameters by time.

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