Виготовлений вдосконалений промисловий зразок роторно-імпульсного теплогенератора (РІТ), інтегрований в теплову систему опалення промислової споруди. Роторно-імпульсні теплогенератори не займають істотних позицій на ринку опалювальної техніки через відсутність достовірних даних про ефективність використання такого обладнання в теплових системах опалення промислових споруд.

Була змінена конструкція розробленої кавітационной камери, визначені параметри каналів, розташованих між ротором і статором. Встановлено, що оптимальна ширина зазору між каналами ротора і статора при максимальному ККД 0,7 склала 8–10 мм. При інтегруванні кавітаційної камери РІТ в теплову систему була змінена конструкція теплообмінника «труба в трубі» на пластинчастий.

Проведено стендові дослідження енергоефективності роботи теплової системи. Визначено показники енергоефективності системи з удосконаленим роторно-імпульсним теплогенератором, виконаний аналіз шляхом порівняння з аналогами, приведеними в літературі. Доведено, що вдосконалення теплової системи дозволило отримати поліпшені показники енергоефективності. Стендові випробування показали, що ККД вдосконаленою теплової системи на ≈17 % вище ККД теплових систем на основі багатоступеневих РІТ.

Розроблено автоматичну систему контролю і управління тепловою системою з використанням віброчастотних датчиків для оцінки ефективності процесу кавітації. Проведені пуско-налагоджувальні роботи дозволили визначити можливість застосування розробленої автоматичної системи з відповідним програмним забезпеченням для контролю і управління роботою теплової системи.

Отримані дані порівняльного аналізу дозволяє рекомендувати розроблений роторно-імпульсний теплогенератор як гідну альтернативу використовуваним теплоагрегатам в теплових системах опалення промислових будівель і споруд

Ключові слова: роторно-імпульсний апарат, кавітаційний теплогенератор, ККД, вібраційний метод контролю, система управління

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DESIGN AND STUDY OF THE ENERGY-EFFICIENT UNIFIED APPARATUSES FOR ENERGY-TECHNOLOGICAL MANUFACTURING

V. Nikolsky
Doctor of Technical Sciences, Professor
Department of Energetic*
E-mail: vnikols1@mail.ru

O. Oliynyk
PhD, Associate Professor
Department of Computer-integrated Technologies and Metrology*

V. Ved
Senior Lecturer
Department of equipment of chemical plants*

O. Svietkina
Doctor of Technical Sciences, Associate Professor, Head of Department
Department of Chemistry
National TU Dnipro Polytechnic
Yavornytskoho ave., 19, Dnipro, Ukraine, 49600

A. Pugach
Doctor of Science in Public Administration, PhD, Associate Professor
Department of Agricultural Machinery
Dnipro State Agrarian and Economic University
Serhii Efremov str., 25, Dnipro, Ukraine, 49027

A. Shvachka
PhD, Associate Professor
Department of Computer-integrated Technologies and Metrology*
*Ukrainian State University of Chemical Technology
Gagarina ave., 8, Dnipro, Ukraine, 49005

1. Introduction

Under modern conditions, when requirements for environmental protection and energy efficiency are getting more severe, development and implementation of energy-saving systems and technologies deserve attention of researchers [1]. That is why development and research into unified energy efficient and environmentally friendly apparatuses and systems that meet modern requirements for energy efficiency and ecology for heating residential and industrial premises should be recognized as relevant.

The basis of modern tendencies in designing and constructing highly efficient energy technological systems and equipment is the block-modular principle [2]. Its essence is in the unity of the methods of apparatus-structural (AS) and regime- technological (RT) design of the process [3]. In this case, there is no distinct boundary between the methods. The RT methods are a set of techniques for intensification of heat and mass exchange processes, each of which can be used in a particular case. In practice, the use of the RT method in equipment design involves certain structural changes and using AS methods.

A promising direction in power industry today is development of unified heat generations of the new generation according to the block-modular principle of design.

2. Literature review and problem statement

The problem of choosing an efficient heating system under conditions of a wide range of proposed technologies and heat engineering equipment is weakly structured and highly relevant [4, 5].

The main part of the heating system is a heat generation source – a burner device, such as a burner, an electric generator. A flat-flame burner, developed in the Institute of the NAS of Ukraine, is a specific device, which allows organization of the open flame (opening angle is 180 °C).

The phenomenon of flame opening is organization of the Coanda effect, the nature of which is conditioned by existence of gradient of pressure across the asymmetric flow with gas jet inflow from the surfaces, limiting the operation space [6].

Along with high aerodynamic perfection, the burner design provides a wide range of sustainable work in the open flame mode in the range of 1:10. In this case, nominal gas pressure is in the range of 3–70 kN/m^2, caloricity and composition of the gas is characterized by low content of NO_x at the level of 50–70 mg/m^3 in flue gases [7].

The enumerated merits of high-flame burners made it possible to apply them not only as the AS method of formation of the RT process of heating materials in technological plants, but also for other thermal engineering devices, such as apparatuses of submersible burning (ASB).

Paper [8] describes an experience in development, research, industrial operation of the contact-modular system (CMS) for heating buildings with the use of apparatuses of submersible burning with mounting low-emission flat-flame burners.

The use of flat-flame burners in apparatuses of submersible burning fundamentally changed the AS formation of the ASB as a whole:

– a combustion chamber of the ASB is partially submerged in water, and the cut is located in water at the depth of 400–500 mm;

– combustion products come into contact with liquid phase, thus providing intensification of heat exchange process, allowing reducing dimensions of the unit;

– the heated fluid acts as a cooling medium for a combustion chamber, which has a special importance for all-metal devices.

The results of conducted state tests proved high power and ecological effectiveness of the development, efficiency of which amounted to η=0.98.

In [9], the experience of application of ASB for RT of organization of the process of radioactive effluents evaporation is described.

Under modern conditions, the tendencies of refusal to use organic fuel and transition to alternative renewable power sources are becoming increasingly common in heat supply in industrially developed countries [10, 11]. This trend is caused by:

– an increase in prices for organic fuel in energy conservation;

– minimization of pollutant emissions;

– high sanitary and environmental requirements for industrial premises [12].

The listed aspects oblige developers to find non-standard decisions when creating a new generation of energy-efficient fuel plants and energy-technological devices, which are sometimes characterized by excessive structural complexity.

In industrialized countries, heat pumps, using low-potential thermal power of the environment, are getting widely used as an alternative [13]. One of the most cost-effective sources of low-potential thermal energy for heat pumps is urban sewages, in this case, transformation coefficient of a heat pump reaches 3 and above. The main constraint in the use of heat pumps is their high cost, as well as the cost of heat exchange equipment, needed to extract the low thermal power [14]. In addition, it is necessary to take into account that techno-economic efficiency of heat pumps decreases at an increase in electricity price compared to the price of natural gas.

Research [15] focuses on the AS method of obtaining heat on the combined thermal source, consisting of a heat pump and a cogeneration unit. These energy-technological systems are characterized by high energy efficient indicators, but in this case, the system has high costs.

Heat generators, based on cavitation effects, are a new generation of thermal plants that convert mechanical and acoustic influence on liquid into warmth [16]. Paper [17] shows the indicators of energy efficiency of operation of a cavitation generator, integrated into the model of the thermal system that proves competitiveness of these devices in the market of heating equipment.

In a work that tackles the exploration of prospects for using vortex heat-generators [18], the author suggests the possibility of development of cavitation heat generators with efficiency above 80 %. However, the work has the review character and does not contain recommendations for developers of heating equipment. Paper [19] provides an overview of experiments with a cavitation chamber with various types of gas and concentration. Measurements of hot point were conducted, but effectiveness of the chamber was estimated by the observed changes in the spectra of luminescence of cavitation bubbles. In paper [20], an additional ultrasound influence is used to increase effectiveness of cavitation equipment. In this case, effectiveness of the process was evaluated by the therapeutic effect, which makes it impossible to use the results of research with respect to heating systems.

The criterial base of design features of energy efficient thermal devices, based on pulse technologies, has not been sufficiently highlighted in publications on research. This makes it impossible to apply the research results for designing actual objects.

Thus, the works, related to research and development of energy efficient heat generators, based on pulse treatment of a heat carrier with scientifically substantiated synthesis of structural elements, forming a rotor-pulse heat generator, are a promising aspect of implementation of modern energy efficient technologies.

3. The aim and objectives of the study

The aim of the research is to develop and study high-performance rotor-pulse heat generators with their subsequent integration into the system of decentralized heating of industrial buildings.

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

– to perform system analysis of the influence of the relations of design parameters of working bodies of the rotor-pulse generator on its effectiveness;

– to use AS methods for intensification by applying external energy sources and the RT method of pulse treatment of contact phases to improve the rotor-pulse heat generator (RPH);

– to produce experimental-industrial samples of the rotor-pulse heat generator with the automatic system of control of operating parameters with subsequent integration into energy-technological heating system of industrial building;

– to determine regulatory-technical parameters of sustainable operation of the heat generator and power efficiency of the system as a whole;

– to perform a comparative analysis of performance indicators of the developed heat generator with the control system with similar analogues.

4. Description of the rotor-pulse heat generator

Design elements that form the rotor-pulse generator have different energy potentials, affecting the operation of the apparatus in general.

One of the most effective methods, making it possible to synthesize a new design of the energy-efficient RPH and intensify the ongoing cavitation processes in it, is a synergetic method. The prospects of this approach is not only to create a new design of the RPH, but also in development and refining new links (synergic) between the components of the RPH. In this regard, based on the system analysis of the experimental data, various designs of the rotor of the heat generator were tested: with one and two cavitation stages, their reciprocal arrangement and geometrical parameters relative to each other were determined. The parameters of the channels, located between the rotor and the stator, were determined.

Structural diagram of the cavitation chamber of the developed heat generator is shown in Fig. 1.

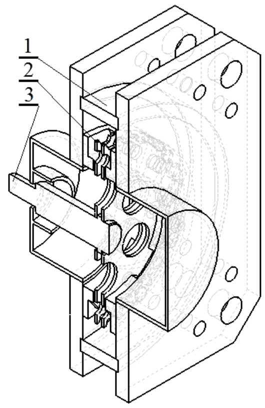

Fig. 1. Structural diagram of the cavitation chamber of the developed heat generator

The cavitation chamber 1 is a casing with impellers 2, located in it, with channels, made in the impeller's body, or holes, located on the shaft 3.

Designs of impellers are shown in Fig. 2.

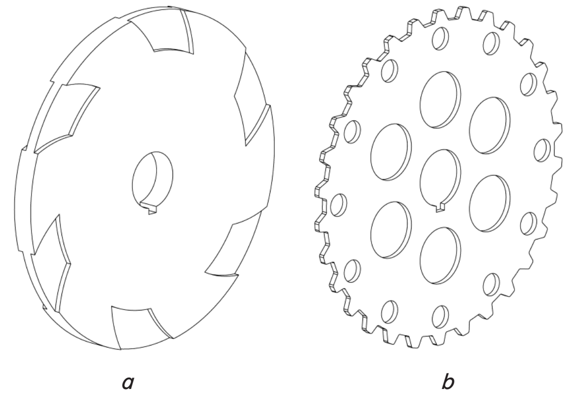

Fig. 2. Design of impellers of the cavitation chamber of the heat generator: *a* — impeller with holes; *b* — impeller with channels

During the heat generator operation, there is a periodic alignment of the rotating channels of the rotor and the stator. In the case when rotor channels are not aligned with the stator channels, pressure in the rotor cavity increases. At alignment of the rotor channels with the stator channels, the pressure decreases. In the stator channels, the overpressure pulse, accompanied by emergence of short-time pulses of decreased pressure, propagates.

The fluid, which is in the channel of the stator, tends to the exit. In this case, inertial forces cause tensile stress in the fluid, which leads to cavitation.

Impellers (cavitation stages) were sequentially located on the shaft with the gap, the magnitude of which was determined experimentally by the analysis of the data of energy efficiency of heat generator operation. The gap between the channels of the rotor and the stator was determined in the same way.

5. Thermo-technical tests of the heat generator and the thermal system

The technique of conducting thermo-technical tests of energy efficiency of the operation of the heat generator and the system in general was as follows. The influence of the design characteristics of the impellers (cavitation stages) on indicators of energy efficiency of the heat generator operation was estimated. For this purpose, impellers of different channel shape and thickness were mounted on the shaft of the heat generator's shaft. The heat generator was disconnected from the heat system and experimental heating was carried out in the autonomous mode. With a view to obtaining reliable data, each experiment was repeated 3–5 times. The error of the experiment was evaluated in accordance with the Gauss normal distribution law of Gauss [21].

The operation of the heat generator in the autonomous mode was studied by following parameters:

– the mass of heated water, *m*, kg;

– the temperature of the fluid at the beginning of heating fluid at the beginning of fluid at the beginning of heating at the beginning of heating in the cavitation heat generator, t_1, °C;

– fluid temperature on the end of heating;

– water pressure before heating, P_1, bar;

– water pressure after heating, P_2, bar;

– power, which was spent to heating N_{sp}, kW·hour;

– the time of fluid heating from t_1 to t_2, τ, min.

Based on the results of measurements of the performed series of experiments the structure of the impeller of the cavitation stage, which corresponded to the maximum indicators of the heat generator operation in terms of energy efficiency. The results of the study of energy efficiency of the heat generator with effective design of the impeller are listed in Table 1.

Table 1

Experimental data of thermal-technical tests of operation effectiveness of the cavitation heat generator in autonomous mode

t_1, °C	t_2, °C	P_1, MPa	P_2, MPa	m, kg	N_{sp}, kW·h	τ, min
19	76	1.6	3.1	70	7.3	23

The averaged values of the experimental data of the heat generator operation in the autonomous mode, processed according to the similar technique, were obtained [17] (Table 1). Efficiency of the rotor-pulse heat generator by the results of a series of experiments was η=0.64.

To improve efficiency of the heat generator and energy efficiency of its operation, the RT method of multi-stage pulse cavitation with the correspondent AK design was used. For this purpose, some impellers (cavitation stages) of effective design were sequentially mounted on the rotor shaft. The gap between the cavitation stages, as well as the gap between the rotor and the stator, were varied in the study.

Loading the rotor by the cavitation stages, we tried to prevent an increase in the set power of the electric motor (N=15 kW), as an increased power consumption of the heat generator affects energy efficiency of its operation in general.

To obtain reliable data on the potential capacity of the heat generator about the thermal load, the thermal system was simulated with 400-liter tank.

A series of 20 experiments was conducted. The results of the research into design indicators that are optimal by energy efficiency and take into account the experimentally established design characteristics are listed in Table 2.

Table 2

Experimental data of thermo-technical tests of operation effectiveness of the heat generator with the use of multi-stage pulse cavitation

t_1, °C	t_2, °C	P_1, MPa	P_2, MPa	$m_в$, kg	N_{sp}, kW·h	τ, min
18.5	60	1.7	3.3	400	25	92

Experimental values of the heat generator operation with the use of multi-stage pulse cavitation were processed applying the similar technique. Efficiency in this case was η=0.77.

Thus, application of the RT method of multi-stage pulse cavitation at the AK of the design of the rotor of the cavitation chamber made it possible to enhance efficiency of the heat generator by 17 %.

The third stage of the research involved integration of the rotor pulse generator with multi-stage cavitation chamber into the heat supply system of the industrial building (Fig. 3).

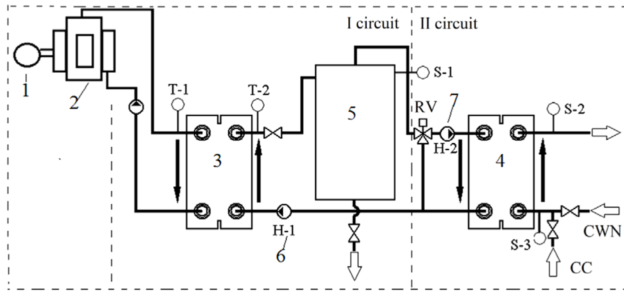

Fig. 3. Structural diagram of thermal plant for heat supply of industrial building, where 1 is the electric motor AIR-160S2, N=15 kW, n=2,930 rpm; 2 is the dual-stage cavitation heat generator; 3, 4 are the plate heat exchanger Alpha Laval AlfaQ™; 5 is the accumulation tank of primary circuit; 6, 7 are the feed pump CP3 25-6

The thermal system includes two circuits: primary and secondary. Water heating takes place in the primary circuit. The primary circuit includes: the RPH, the plate heat exchanger, the pump, the accumulation tank. The heat carrier, heated in the RPH, is fed to the plate heat exchanger, which heats the water that arrives for heating. The temperature sensor T1 records the temperature of the heat carrier at the outlet from the cavitation heat generator. Temperature sensor T2 controls the temperature of the heat carrier after the plate heat exchanger. Temperature sensor S3, located at the inlet of water of the secondary circuit, controls the temperature of the heat carrier, fed for heating to the system. This may be water from a city water supply network (CWN) or from the circulation circuit (CC).

The value of the temperature, measured by sensor S3, is compared with indicators of sensor S1, mounted at the upper part of the accumulation tank of the primary circuit. If renewable energy is used, values of sensor S1 are higher than values of sensor S3 and the system operates in normal mode.

Temperature sensor S2 at the outlet of CWN water from the secondary circuit measures the temperature value and adjusts the position of the regulating valve RV in such a way that the temperature of the CWN system could be constantly maintained and correspond to the specified value.

If the power, produced in the accumulation tank, cannot be used in the network (readings of S1 are smaller that readings of S3, the valve RV is closed, pump N2 is switched off), the primary circuit (thermal power is accumulated) with the heat generator operates in the system. In this case, heating of CWN water is provided from the reserve source of energy (for example, the cavitation vortex apparatus).

Efficiency of operation of the heating system was assessed by the following indicators:

– temperature of heat carrier at the inlet to the heat exchanger t_1, °C;

– temperature of heat carrier at the outlet from the heat exchanger t_2, °C;

– water temperature at the outlet from the cavitator t_3, °C;

– weight of the heated heat carrier, m, kg;

– electric power, consumed for heating, N_{sp}, kW·h;

– consumption of heated medium, G, m^3/h;

– time of heating to assigned temperature, τ, min.

7 experimental heating sessions were carried out till the fixed established indicators (Table 3). The temperature of the heat carrier was recorded using temperature sensors, the layout of which is shown in Fig. 2.

Table 3

Experimental data of energy efficiency of thermal operation of the system with integrated rotor-pulse heat generator with multi-stage cavitation chamber

t_1, °C	t_2, °C	t_3, °C	m, kg	N_{sp}, kW·h	G, m^3/h	τ, min
17.4	59	60	400	23	1.2	75

Efficiency, determined by the indicators (Table 3) in accordance with the procedure [17], amounted to η=0.84.

An increase in efficiency of operation of the thermal system up to η=0.84 vs. η=0.77, recorded during the operation of the heat generator with a 400-liter capacity, which modeled the thermal system, is explained by operation of automation means at the industrial site.

The operation of the thermal system with the integrated rotor-pulse heat generator with the multi-stage cavitation chamber at the industrial site was compared with the operation of the thermal system with the electric heat generator of the "Titan" brand with installed power of N=15 kW, which corresponds to the installed power of the electric motor of the improved RIH. With this aim, the thermal system (Fig. 2) was reconstructed: instead of RIH, the heat generator "Titan" was mounted, the plate heat exchanger was removed, i. e. the electric heat generator directly heated the heat carrier.

According to the described technique, similar studies of effectiveness of the thermal operation of the system with the application of an electric heat generator were carried out.

In the study, we recorded:

– temperature of feeding the heat carrier to the electric heat generator t_1, °C;

– temperature of the heat carrier at the outlet from the electric heat generator t_2, °C;

– weight of heated heat carrier, m, kg;

– electric power, consumed for heating, N_{sp}, kW·h;

– consumption of the heat carrier, G, m^3/h;

– heating time, τ, min.

The results of the experiment are shown in Table 4.

Table 4

Experimental data of effectiveness of operation of the thermal system with the electric generator boiler "Titan"

t_1, °C	t_2, °C	m, kg	N_{sp}, kW·h	G, m^3/h	τ, min
18.2	58.9	400	19	1.6	65

Efficiency of operation of the thermal system with the electric heat generator amounted to η=0.98 %.

Indicators of operation of the heat generator (RPH) with two cavitation stages of and the thermal system with the integrated RPH for heating of an industrial building were obtained experimentally. These indicators were compared with indicators of energy efficiency of the thermal system, based on the rotor-pulse apparatus RIA [22] are listed in Table 5.

Analysis of indicators of energy efficiency makes it possible to argue that the thermal system with the integrated rotor-pulse heat generator with the multi-stage cavitation chamber exceeds the corresponding analogues by energy efficiency.

Table 5

Comparative analysis of indicators of energy efficiency of operation of the thermal system with RIA and thermal systems with RIT

Name of parameter	Dimensionality	Designation	Value of parameters		
			RPT with modified thermal system	RPT with industrial thermal system	Multi-stage RPA by the data [19]
Weight of heated heat carrier	kg	m	400	400	250/340
Temperature of heating a heat carrier	°C	t	60	59	50/45
Time of heating up to assigned temperature	min	τ	92	75	25/150
Consumed power	kW·h	N_{sp},	25	23	33/30
Efficiency of thermal work of the system	–	η	0.77	0.84	0.547/0.706

6. Automatic system of RPT monitoring and control

Any system of decentralized heating is a dynamic system, characterized by a large number of disturbances. For economical operation mode of the thermal system with the improved RPT, it is necessary to foresee an automatic system of monitoring and control.

In paper [17], it was proposed to use the vibration of the apparatus for assessment of its operation effectiveness. The cavitator was considered to be an auto-vibrating link, characterized by significant pressure pulsations and consumption of phases. Cavitation caverns in this case acted as the vibrations generator in the connected vibration system hydro line-bubble.

The developed structural diagram (Fig. 4) implements the proposed method of control of effectiveness of the cavitation process by measuring vibrations of the apparatus [17] in combination with the control of key parameters of the process.

It is proposed to equip the developed thermal system with the control unit or with the microcontroller (MC). The main function of the unit is to ensure the possibility of some customizations, such as control of the maximum temperature in the plate heat exchanger, eliminates scale formation or determining average operation efficiency of the thermal system [23].

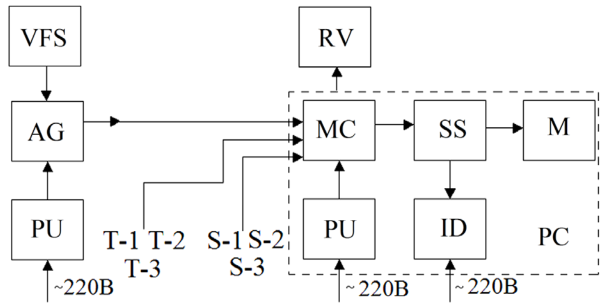

Fig. 4. Structural diagram of the automatic system of monitoring and control of operation of RPT, where VFS is the vibration-frequency sensor; AG is the auto generator; PU is the power unit; MC is the microcontroller; SS is the specialized software, M is memory; ID is the information display device; T1, T3, T3, S1, S2, S3 are the temperature sensors; RV is the regulating valve

Conducted launch and adjustment works made it possible to identify the possibility of applying a PC, equipped with ADC, MC and appropriate software to measure frequency of the signal of resonance and temperature converters.

To measure the frequency of the signal of the vibration-frequency sensor and correction of additional errors of resonance and temperature converters, the specialized software was developed. The software, developed in the Lab-VIEW environment, is a frequency converter, based on the analog-to-digital converter and a personal computer. Signals filtering is performed programmatically using a programming environment Python [24]. In the future, we plan to use a PC with installed specialized software of creation of control and monitoring of RPH operation in the automated system.

7. Discussion of results of studying the heat generator and a thermal system

Analysis of the data of conducted studies shows that the thermal system with the integrated rotor-pulse heat generator with the multi-stage cavitation chamber exceeds its analogues by energy efficiency. Efficiency of the developed system, recorded in the studies, is by 17 % higher than efficiency of the thermal system based on multi-stage RPA (0.84 and 0.706, respectively). It should be noted that the thermal system with the integrated rotor-pulse heat generator with the multi-stage cavitation chamber RPH is inferior to the thermal system with the electric heat generator (0.84 and 0.98, respectively) by energy efficiency. The thermal system with the electric heat generator "Titan" provides heating of the heat carrier without a heat exchanger, which decreases thermal losses on average by 5–7 % (depending on the design of the heat exchanger) and accordingly increases the efficiency of the system. The heat exchanger is needed in the thermal system with RPH because its mounting eliminates the gap of continuity of the heat carrier flow in the system.

The deterrent factor of a wide application of the electric thermal generators in the thermal systems is the need to use water that is chemically purified from salts of water hardness (in order to prevent "scale") and high energy costs. The latter can be compensated using the night tariff and existence of the accumulator tank. In this case, the established power of the electric heat generator must be greater than the established power of the battery and proportional to the ratio of time of accumulation tank discharge to the charging time (≈by three times).

The main advantage of the cavitation heat generator over thermal electric heaters is the absence of scale and deposits on the walls of the apparatus and the possibility to operate on different types of aggressive and flammable fluids. Efficiency of cavitation heat generators when using the night tariff reaches 95 %. Thus, "losses" of electric energy in the electric motor are entirely used for heating the heat carrier.

The prospect of subsequent studies is related to the search of possibilities of increasing efficiency of the thermal system with the rotor-pulse heat generator due to the change in design characteristics of the elements of the cavitation heat generator. The second relevant direction of research works can be the problem of minimization of structural characteristics of the cavitation heat generator, with the aim of widening the scope of application of thermal systems.

8. Conclusions

1. The structure of the experimental-industrial rotor-pulse heat generator with two stages of cavitation was developed and manufactured. The geometrical characteristics, parameters of the rotor and the stator, their reciprocal arrangement were determined, as well as parameters and geometry of the channels, located between the rotor and the stator. It was found that the optimal width of the gap between the rotor and stator channels at maximum efficiency of η=0.7 amounted to 8–10 mm.

2. Bench and industrial tests of the RPH with a dual-stage cavitation system, developed and integrated into the thermal system of heating of industrial buildings, were conducted. It was established that efficiency of the improved thermal system based on RPH is by 17 % higher than the efficiency of the thermal system, based on multi-stage RPA (0.84 and 0.706, respectively).

3. The automated system of control and monitoring with the use of vibration-frequency sensors for assessment of the effectiveness of the cavitation process was developed. Conducted commissioning works made it possible to identify the possibility of applying the developed automatic system with appropriate software for monitoring and control of operation of the thermal system.

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