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Development of the four-stage thermoacoustic engine operating in the low-temperature range of self-starting and on Stirling cycle

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Abstract

The purpose of this study is to improvement a four-stage thermoacoustic motor with a rectangular cross-section for operation in the low-temperature range of self-starting, operating on the Stirling thermal cycle, with the effect of a standing sound wave. In carrying out the research tasks, mathematical modeling methods were used to calculate technological parameters, and a prototype thermoacoustic engine with self-starting in the low-temperature range with four stages was created. Research results. It was determined that the obtained sample differs significantly from its analogues, indicating that the operating nature of the developed thermoacoustic engine differs from existing traditional ones. The hot heat exchanger is capable of operating in the range from 60 to 100 degrees Celsius. A cold heat exchanger, on the other hand, operates in the range of 30 to 50 degrees Celsius heat exchanger. On the other hand, it was determined that the engine power reaches a value of 115 Watts at 100 degrees Celsius, and the frequency varies from 50.4 to 62.3 Hz. The disadvantage is the low generation capacity, as a result of which this system can only be used as a cogeneration plant. The results can be used to create cogeneration energy sources for autonomous consumers.

Keywords: Cogeneration plants, Energy supply, Mechanics, Self-starting, Thermoacoustic engines.

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1. Introduction

The environmental problem of the environment is relevant in the modern world and requires a comprehensive solution in each sector. One of the main directions is the efficient energy supply to remote consumers, for whom the laying of communications is fraught with significant difficulties. It is also necessary to search for and develop new types of alternative sources that have higher technical and economic indicators in comparison with wind turbines and solar modules. Renewable sources cannot yet ensure balanced operation of an autonomous energy system without the use of storage devices. Kazakhstan, with its large territory and low population density, is characterized by the problem of energy supply to remote rural consumers. For a rural resident, the cost of electricity is 2 or 3 times higher than for a city resident. The cost of energy transportation and losses are borne by consumers. There is a problem associated with higher electricity tariffs for rural residents. The high cost of energy increases the cost of agricultural products, which ultimately reduces the demand and competitiveness of domestic producers.

Currently, about 500 small rural settlements and settlements do not have access to the electric grid. An important problem is that there is no direct access to energy resources, as there are intermediaries who multiply the cost of electricity, since each of the private entrepreneurs must make a profit based on the resale of energy. The current state of rural electrical networks is far from ideal, as most of the electrical equipment and lines installed during the former USSR are in operation. In many rural areas of Kazakhstan, rural electrical networks are close to 100% worn out, and their condition is maintained through constant repairs. Over the past 5 years, the modernization of rural 10–35 kV networks has begun, but this process is proceeding rather slowly. The wear and tear is high enough not only for power transmission lines, but also for transformer substations and distribution points. Energy losses during transportation are paid for by consumers, since the length of the lines is quite significant and amounts to hundreds of kilometers, which also increases the cost of energy. Lack of affordable energy carriers. Vast and practically uninhabited steppe regions located at a considerable distance from each other and large cities form a fairly extensive problem for the development of centralized power supply to remote small settlements associated with livestock farming. It is also possible to identify a number of problems in the development of central electricity supply for rural settlements, whose residents are engaged in growing vegetables and fruits, since energy is required for the operation of the irrigation system of fields.

There is a certain urgency for switching to a decentralized power supply system for small consumers, which may be more profitable and more reliable, but if you use electric generators powered by gasoline or diesel fuel, the cost of energy will be ten times higher for a rural resident than for a city resident. It is necessary to look for ways to solve the problem and respond to the emerging challenge of how to reduce the cost of energy for rural consumers. Fuel transportation is a rather expensive part of electricity production in remote rural areas, while dependence on the conditions of the fuel supplier is formed. It is possible to switch to autonomous renewable sources, but the cost of energy will be three times higher than from a coal-fired power plant, due to the initial values. Also, these sources do not have a balance and their performance is highly dependent on weather conditions.

Considering the above, this article considers the development of a cogeneration energy source capable of running on almost any type of fuel. The proposed source of the method is to use the energy obtained from the burning of agricultural waste or to use the energy of heated water using a solar collector. It is also possible to use the energy of geothermal sources. A thermoacoustic engine with an external heat supply (EEHS) is proposed, which can operate at a heater temperature of less than 100 °C, which will allow converting solar energy or other thermal energy obtained from the combustion of any type of fuel. Accordingly, it is possible to use available fuels or agricultural waste, converting the heat from their combustion into electrical and thermal energy.

TAE operates on the Stirling thermal cycle and has been known for over 200 years. For such a long period of its existence, various variants have been developed, which have some design differences and technical characteristics. For more detailed information about the design, the principle of operation and the scope of application, it is considered in sufficient detail in the scientific literature [1, 2]. There are examples of successful practical reciprocating Stirling engines as a source of mechanical energy for driving low-power electric generators from Philips, Solo, WhisperGen, EcoGenViessmann, etc. A Philips Stirling Engine with a fairly high efficiency of about 40% turned out to be quite effective, which was powered by solar energy and had a parabolic reflector for concentrating rays on the heater. The high conversion rate is still higher than the efficiency of mass-produced silicon solar cells.

When studying the materials of the source [2], one of the important conclusions can be drawn that, first of all, for its effective operation, a significant difference in the temperature of the heater and cooler is required, as well as the creation of relatively high pressure in the internal cavity of the engine and the use of Helium and Hydrogen as a working medium. An important element of the SE is the regenerator, which was proposed by R. Stirling himself, it allows to increase the overall efficiency. There are some problems with piston pumps, for example, in order to achieve high efficiency and the ability to compete with an internal combustion engine (ICE), it is necessary to maintain high pressure inside the working cylinder, which complicates the design and increases the load on seals that operate in dry friction mode. Since the mechanical part of the classic SE contains rotating parts and moving pistons, this reduces its overall reliability. The intensification of heat exchange on the hot side of the cycle requires a complex heater design and the use of a regenerator. The cooling system should be more efficient than that of an internal combustion engine, so its radiator can be up to 3 times larger. The SE cycle is not ideal and its significant difference from the Carnot cycle is that its efficiency is at the level of a conventional atmospheric diesel.

Taking into account the global experience in the development of thermal motors, the developers began to look for other design options and switched to a more promising thermoacoustic motor design, which does not have moving pistons and rotating parts, which allows solving a number of serious problems in increasing the efficiency of this heat engine and reducing its metal consumption per unit of power.

One of the options for the development of EEHS is a thermoacoustic engine (TAE), which can use a standing or traveling acoustic wave in its work. This type of EEHS converts thermal energy into acoustic energy, its thermodynamic cycle is quite close to the Stirling cycle, and according to the principle of action it can be attributed to the well-known type "Alpha". TAE can be used as a low-power cogeneration energy source for power supply to autonomous consumers. Unlike the classic SE, the TAE has an important advantage due to the absence of friction parts, namely pistons and seals, respectively, there are no friction losses, and it also has higher reliability and service life. All the advantages of TAE are considered in sufficient detail in the literature [3].

As a classic piston pump operates according to the Stirling thermodynamic cycle, accordingly, it needs a difference between the temperature of the heater and the cooler, the greater this difference, the higher its efficiency. The thermoacoustic effect was first discovered in 1877 by Lord Rayleigh and described in the scientific work "Theory of Sound", in which the basic principles of thermoacoustics are formulated. To create vibrations of an acoustic wave, it is necessary to bring heat to it when the gas is compressed, and to remove it when it is discharged. Rott [4] made a significant contribution to the development of thermoacoustics. He developed a number of theoretical foundations of TAE and a linear theory for the interaction of an acoustic wave with an environment where there is a temperature difference. His theoretical foundations were used later by other researchers [4].

In Ceperley [5] first published an article in which the results of studies of a TAE with a traveling acoustic wave propagating through a regenerator were presented Ceperley [5] proposed a TAE with a ring resonator, which became the basis for subsequent designs that were developed later.

Later, Yazaki, et al. [6], in the late 90s of the last century, developed his own TAE design [6]. However, its efficiency was very low due to the low acoustic resistance inside the regenerator, but the proposed TAE design had significant energy losses due to high acoustic speeds, as well as resistance to movement of the working fluid inside the resonator and the stage.

A little earlier, Swift [7] investigated a TAE with a reversible cycle of motion of the working fluid in the resonator and proposed a TAE design with a standing acoustic wave with a resonator diameter of 13 cm and a maximum power of 600 W at a pressure of 13 bar [7]. Swift also developed TAEs and refrigerators based on them, for more information, see his short course [8].

There are many more recent publications in which the authors refer to the early works of Swift [8] and Novotný and Vít [9]. In collaboration with S. Backhaus, Swift developed a TAE with a standing acoustic wave, which made it possible to achieve a higher thermal efficiency — 30% of the Stirling cycle, which corresponds to 41% Carnot efficiency. It was also possible to reduce acoustic losses, but the design turned out to be more complex than that of [6, 10].

In Yu, et al. [11] developed a single-stage thermoacoustic traveling wave electric power generator using a linear alternator to use low-potential thermal energy (Figure 1).

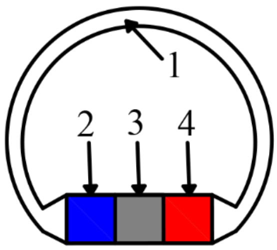

Figure 1.
Single-stage TAE.

In Tijani and Spoelstra [12] improved the design of the TAE and achieved 49% Carnot efficiency. In article Kruse, et al. [13] presented numerical studies of a single-stage TAE with an annular resonator capable of converting low-potential heat, for example from wastewater or geothermal waters. Later, in article Kruse, et al. [14] experimentally validated a looped-tube thermoacoustic engine with a stub for tuning acoustic conditions.

A lot of attention is paid to the issue of heat loss utilization, since this area is very relevant, for example, solar collectors and TAEs can be used to generate electric energy instead of solar modules, which is very promising [15, 16].

The most effective TAE for low-potential energy operation is a design with several stages, which makes it possible to shorten the length of the resonator. At the same time, the increased cross-section of the stage in relation to the resonator can significantly reduce energy losses (Figure 2).

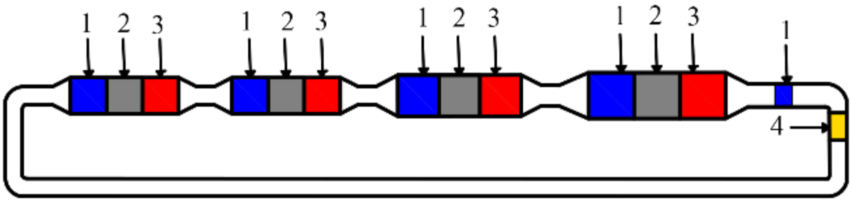

Figure 2.
Conventional schemes of four–stage TAEs with a traveling wave sequential with different diameters.

de Blok [17] proposed a multi-stage design of the TAE (Figures 3 and 4), which allows operation at a heater temperature below 100 °C. In 2010, the Dutch company Aster Thermoacoustics introduced a four-stage TAE [18]. Its difference from existing designs is the significantly larger diameter of the stage compared to the diameter of the resonator. This improvement allowed Aster Thermoacoustics to increase efficiency by reducing the gas flow rate. The idea of using 4 stages instead of one made it possible to reduce the length of the resonator. The most important achievement was a reduction in the minimum temperature difference between the heater and the cooler, necessary to start the engine when using low-potential energy. The use of 4 stages allows reducing the self-start temperature to about 80 °C.

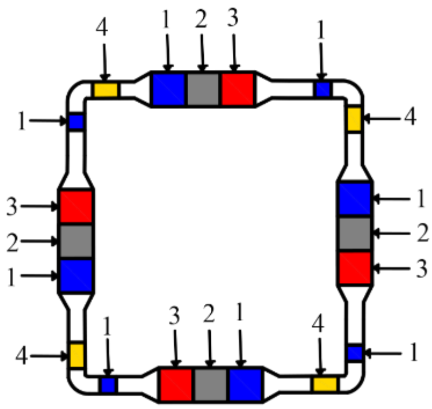

Figure 3.
Conventional schemes of four–stage TAEs with a traveling wave uniform according to the square scheme.

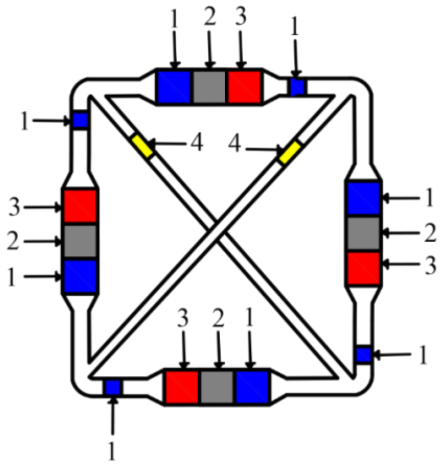

Figure 4.
Conventional schemes of four–stage TAEs with a traveling cross scheme.

Currently, there are several multi-stage TAE layouts in the world [17]. It can also be noted that an increase in pressure inside the pump leads to an increase in its acoustic power, as the friction losses of the body from the stage wall and the regenerator decrease. Thermal losses of thermal energy to the environment of the TAE are independent of pressure. TAE can operate at or above atmospheric pressure; of course, its efficiency depends on the pressure, as well as the temperature difference between the heater and cooler. de Blok [17] used bidirectional turbines to convert acoustic power into electricity, which is a more efficient system for converting gas flow movement into electrical energy. Unlike linear generators, bidirectional turbines have practically no power limitation, have a simpler design and lower production cost.

The development stages and prospects of TAE are discussed in detail in Sarsikeyev, et al. [19]. A linear generator is impractical due to the increased cost with a slight increase in efficiency. One option is to use a bidirectional turbine that rotates a synchronous generator, which is more efficient at a power of more than 1 kW compared to a linear one [20].

The main problem is the lack of alternative energy sources capable of comprehensively producing electrical and thermal energy. Renewable sources are not able to ensure balanced operation of an autonomous energy supply system during the day, as there is a certain dependence on weather conditions, and the cost of electric energy remains quite high. At the moment, rural residents need their own decentralized energy supply systems capable of running on local fuels. The use of gasoline generators in remote small towns in Kazakhstan, as well as livestock breeding camps, creates many problems, as fuel transportation and maintenance are required.

One solution is to use thermoacoustics, namely its type of TAE, which uses the temperature difference between a heater and a cooler to create sound waves, which can then be converted into electrical energy. An autonomous power plant based on TAE can solve the problem of small-scale autonomous energy in rural areas and the development of decentralized power supply systems.

2. Materials and Methods

The aim of the work is to develop a four-stage TAE with a rectangular cross-section of steps for operation in the low-temperature range of a self-starter operating on the Stirling thermal cycle, with the effect of a standing sound wave, to increase the efficiency of energy supply to remote rural areas for consumption. The object of the study is a four-stage thermoacoustic engine system with self-start in the low-temperature range.

In this article, the idea of creating an initial laboratory sample of TAE and conducting experimental studies to develop its own design is formed. There is a prospect of further use of TAE in decentralized energy supply systems. It has a number of advantages, for example, consumer independence from rising electricity tariffs, and productivity does not strongly depend on fuel quality. It should also be noted that TAE is a cogeneration source; therefore, it produces not only electrical energy, but also thermal energy. This useful function of the TAE can be used in autonomous heating or hot water supply systems. Thermal energy is taken from the cooling circuit: the better the coolant is cooled, the higher its efficiency.
As a result, this goal was divided into several tasks:

- Calculation of the design of the four-stage Stirling engine circuit;
- Design development of a four-stage Stirling engine circuit;
- System research and comparison of the results with the existing solution.

The object of the study is a four-stage thermoacoustic engine. This study investigated the possibilities of building a microprocessor relay protection device based on open-source protocols and the possibility of using IIoT technology in relay protection.

In order to perform the first task, an annular tubular resonator, heat exchangers and regenerators were used. The DeltaEC program was used to calculate the TAE [4]. The calculation was carried out on the basis of known laws of thermodynamics, acoustics, chemistry, and mechanics. The article uses telemetric information from third-party authors [1, 2] and proprietary mathematical models and expressions used to calculate the TAE parameters, which were previously published in sources [19, 20]. The article used known calculations similar to the Schmidt method, which was used to determine the parameters of the TAE. Based on this method, a computer program was developed that allows performing a theoretical calculation of the parameters of an engine with external heat supply operating according to the thermodynamic Stirling cycle using the capabilities of Excel spreadsheets.

In order to accomplish the second task, the basic principles of statistics, probability theory, mechanics, and thermodynamics were applied. In order to determine the similarity of the obtained results with the known ones, the Student's t-test method was used.

3. Results

3.1. Design Development of a Four-Stage Thermoacoustic Engine Circuit

The design of the four-stage engine was developed in 2010, using a block that modified this engine into four stages. He made a change in the diameters of the heat exchanger and the regenerator. It has a difference with the equalization with the diameter of the resonator and reduces the speed of gas movement in the regenerator area. Accordingly, this change improves the engine's performance in terms of weight and size, as well as reducing the temperature difference for the required start.

The four-stage engine consists of four stages having hot and cold heat exchangers. Heat was supplied to the hot heat exchanger from the heating source and transferred to the working fluid. Air was used as the working fluid, and automotive antifreeze was used for the liquid circulating in the heating and cooling system. As is known, a cold heat exchanger is used for cooling, which is necessary to remove heat from the working fluid. This heat exchanger can be connected to a heating or hot water supply circuit, the more heat is taken from the cooling circuit, the higher the efficiency. In the proposed design, the regenerator is located between hot and cold heat exchangers as proposed [16, 17], only the porosity of the regenerator is chosen differently. The rectangular design of the stage with two diffusers distributes the working fluid in the heat exchangers more efficiently and creates less resistance to the gas flow. As with the proposed design of the D Block [16, 17], the stages are interconnected using a resonator. The entire design of the TAE is sealed Fig. 5.

The four-stage TAE shown in Figure 5 operates according to the well-known Stirling thermal cycle with a rectangular cross-section of heat exchangers. A measurement scheme has been developed for the study of TAE. A personal computer 1 with software connected via a cord 2 to a microprocessor unit 3 for measuring pressure and temperature parameters with four thermocouples is used as a device for displaying information.

Unit 2 was used to control the temperature of the heater, and a microprocessor unit 4 with four thermocouples was used to control the temperature of the cooler. One of the main elements of the TAE is a thermoacoustic stage 5 and an annular tubular resonator 6. The thermoacoustic stage 5 contains a hot heat exchanger 7 and a cold heat exchanger 8, between them is a regenerator 9. The heated air in the heat exchangers 7 is heated to a temperature of 100 °C or more, expands and passes through the regenerator 9, where it cools down and gives off part of its heat to the regenerator.

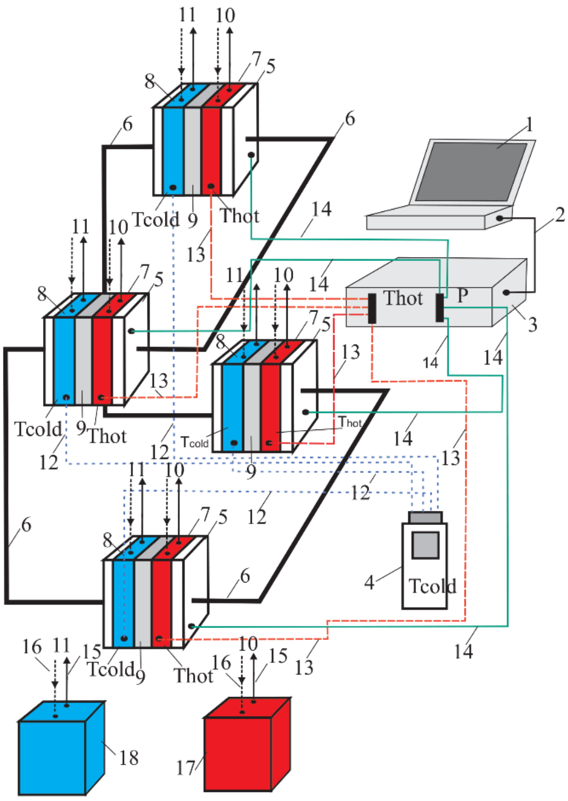

Figure 5.
The developed design of the four-stage TAE.

An expansion cycle of the working fluid takes place in the heater. Next, the air enters the cooler 7 and cools down there to a temperature of 30-50 °C, a compression cycle of the working fluid occurs. The heating system supplies heat to the stage through a pipeline 10, and the cooling system removes heat from the stage through a pipeline 11. The cooler of each stage had its own thermocouple, which was connected to the microprocessor unit 4 using connecting cables 12. The heater of each stage had its own thermocouple, which was connected to the microprocessor unit 3 using connecting cables 13, 14. In this case, the water is discharged using pipes 15, and enters through pipes 16. In order to maintain stable operation, water is heated using a boiler 17 and cooled using a cooler 18. In the experiment, a liquid heater with an adjustable power of 500, 1000, 1500 watts was used. An Arduino-based microcontroller and a 4-channel digital thermometer HT-9815 (Xintest, China) with an accuracy of 0.1% were used for temperature control.

Figure 6 shows the thermoacoustic engine stage in the section, showing the difference from the prototype described in the source [16, 17]. As you can see, the regenerator is located between two heat exchangers. Liquid is supplied to the heat exchangers for heating and cooling. Each heat exchanger is connected to the water supply system by means of two hoses with threaded fittings at both ends.

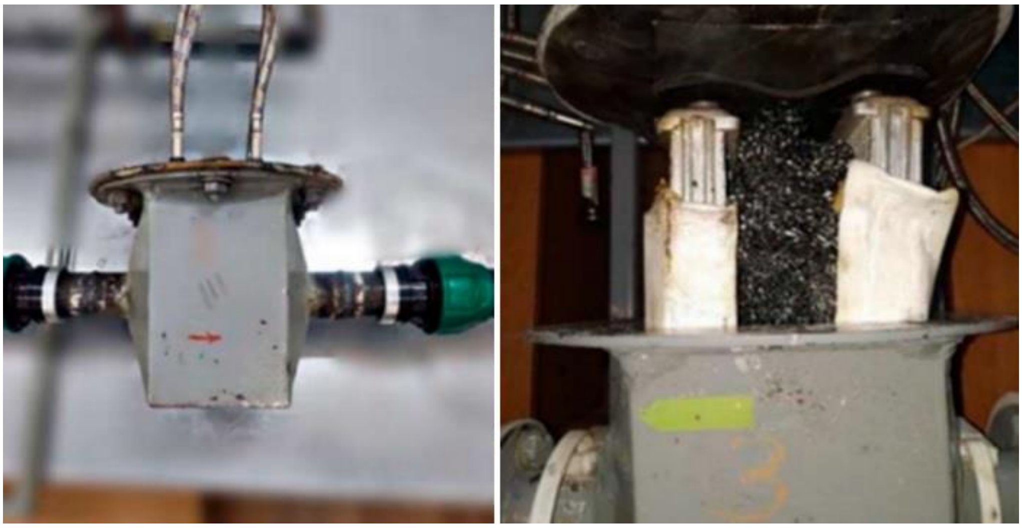

Figure 6.
Thermoacoustic engine stage.

Unlike other structures and, in particular, from the one considered in the source [16, 17], the resonators are made of plastic pipes, not steel ones. This made it possible to insulate the steps from each other without using thermal insulation pads. Thermal isolation of the hot part of the stage from the cold is very important in terms of the efficiency of the TAE, since the working fluid is not heated by parasitic heat in the resonator, which is heated from the hot part of the stage. The use of gaskets and flanges reduces the reliability of the TAE, as it increases the risk of leakage of the TAE circuit. The use of plastic resonators significantly reduces the cost of TAE. The proposed design of the TAE operates at a pressure from 1 to 10 Atm, the higher the pressure of the working fluid, the higher the power of the TAE.

A four-stage TAE with a rectangular cross-section of steps will allow it to operate in the low-temperature self-start range from 60 to 100 °C. The proposed rectangular design of the stage with two diffusers, in contrast to the already classic cylindrical design of the De Block stage, has a number of advantages. First of all, the dead volumes of the step are reduced. Secondly, it is easier to mount rectangular heat exchangers inside the stage, and the distance between the heat exchanger and the end of the resonator is reduced, which reduces the loss of acoustic energy.

3.2. Design Development of a Four-Stage Thermoacoustic Engine Circuit

Atmospheric pressure air was used as the working fluid in the engine. The total length of the resonator is 4100 mm, the length of the stage is 360 mm, there are 4 of them, respectively, the total length is 1440 mm. Finally, the length of the entire contour of the TAE was 5540 mm, which corresponds to the oscillation frequency of the sound wave of about 61 Hz. The resonator is made of a plastic tube with a diameter of 50 mm with a wall thickness of 3 mm with an area of 1962 mm. The cross-sectional area of the resonator is 4 times smaller than the steps. All connections are detachable for the convenience of adjusting the TAE and changing the frequency of the acoustic wave.

In order to conduct experiments, a specially designed four-stage TAE with a looped resonator was designed. The photo of the TAE is shown in Figure 7. It consists of four steps, which are completely identical in design. Each stage has one hot heat exchanger and one cold one, between which there is a regenerator. All stages are sealed and interconnected by a tubular resonator. The heating and cooling of all four stages was the same.

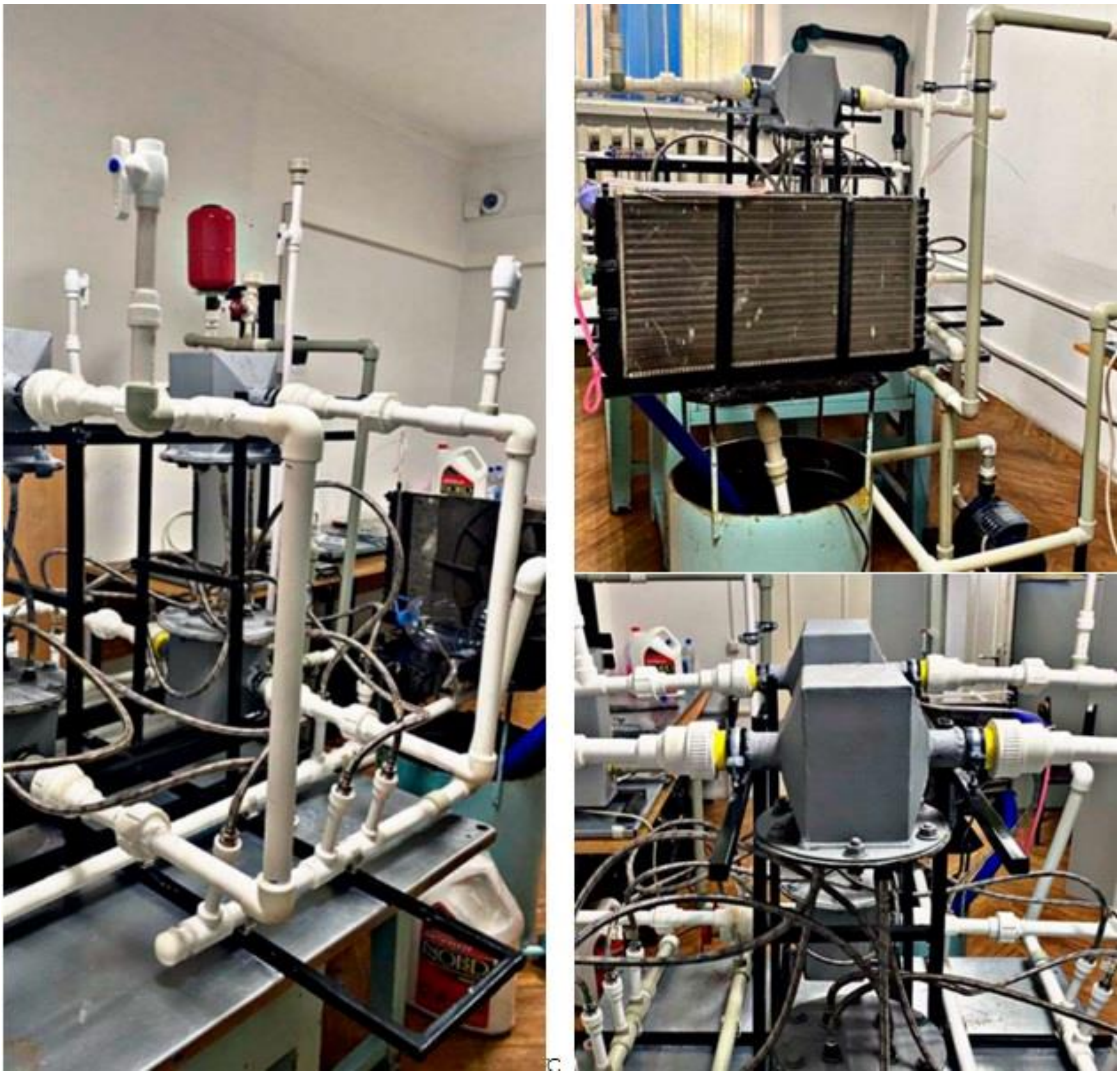

Figure 7.
Experimental engine.

The conditions of the experiment were: constant indoor air temperature, parameters of the TAE stages and resonators, pressure of the working fluid, porosity of the regenerator and heat exchangers. The main technical parameters of TAE are presented in Table 1. An important parameter affecting the effectiveness of TAE is the porosity of the regenerator and heat exchangers, calculations were performed using formulas taken from sources [1, 2], as well as according to calculations by de Block [16, 17].

Table 1.
The main technical parameters of the TAE.

Element	Width, mm	Length, mm	Area, mm^2	Porosity	Hydraulic radius, mm	The distance between the plates
Hot heat exchanger	175	182	31 850	0,5	-	0,5
Cold heat exchanger	175	182	31 850	0,5	-	0,5
Regenerator	175	190	33 250	0,766	0,164	-

The parameters of the depth of thermal penetration of the acoustic wave into the resonator material were determined.

Considering the methods and experiments of scientists of the world and the processing of statistical data of the Student's t-test, it allows an objective assessment of how changes in the design of a thermoacoustic device affect its effectiveness. This helps to draw scientifically sound conclusions about which design changes improve the operation of the device, and allows you to optimize it for further use in real-world operating conditions.

3.3. Investigating The System and Comparing the Results with the Existing Solution

The results of the experiments showed that the TAE has boundary conditions for reaching the temperature at which self-starting is carried out. In the experiment, the upper temperature value of about 100 °C was reached, the lower limit of the operating temperature was about 80 °C. The heating system provided heating of the TAE to 100 °C in 25 minutes, after which it reached its maximum operating temperature. Further, the temperature was maintained at a temperature of up to 100 °C. The average temperature of the heat balance was 90 °C. The liquid heating system operated in automatic mode with temperature control, and when the temperature reached 100 °C, the liquid heating stopped. When the liquid cooled by more than 1 °C, the heating resumed. The change in temperature over time is shown in Figure 8.

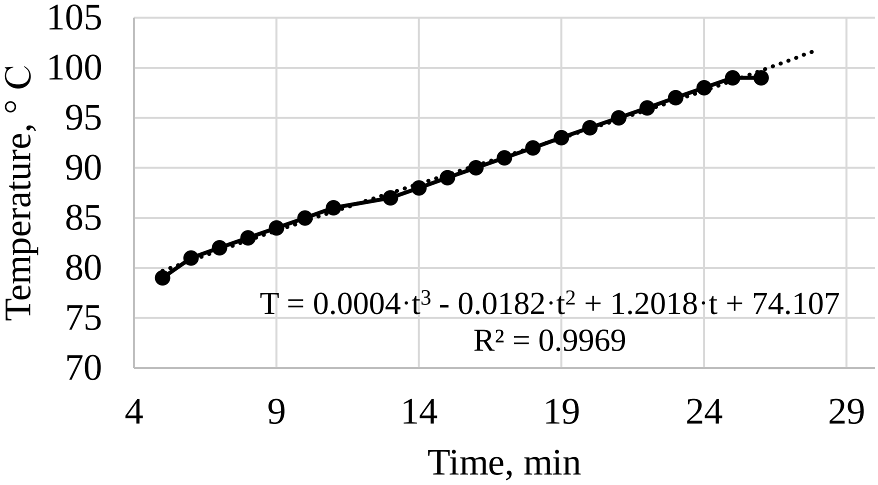

Figure 8.
The temperature of the hot heat exchanger as it approaches the thermal balance.

Automotive antifreeze with a boiling point of 125 °C was used as the coolant circulating in the heating and cooling circuit. The power of the heating system was 1,500 watts. The temperature of the liquid in the cooling system did not rise above 40 °C cold heat exchangers, the initial temperature of the liquid in the cooling system was 23 °C.

As is known, the oscillation frequency of an acoustic wave depends on the length of the resonator. Earlier in the article [3], a method for calculating the oscillation frequency of a single-stage TAE was presented. This technique was used to calculate the oscillation frequency of a four-stage TAE, since the acoustic wavelength depends on the length of the resonator and the steps. Since the studied TAE had 4 stages, the length of the resonator decreased by the total length of all stages. Dividing the speed of sound in a gas by the wavelength, provided that the total length of the resonator is 4100 mm, and the length of the entire TAE contour is 5540 mm, it is possible to determine the frequency of vibrations of the acoustic wave inside the resonator. The changes in pressure during oscillations of the acoustic wave in the resonator are shown in Figure 9.

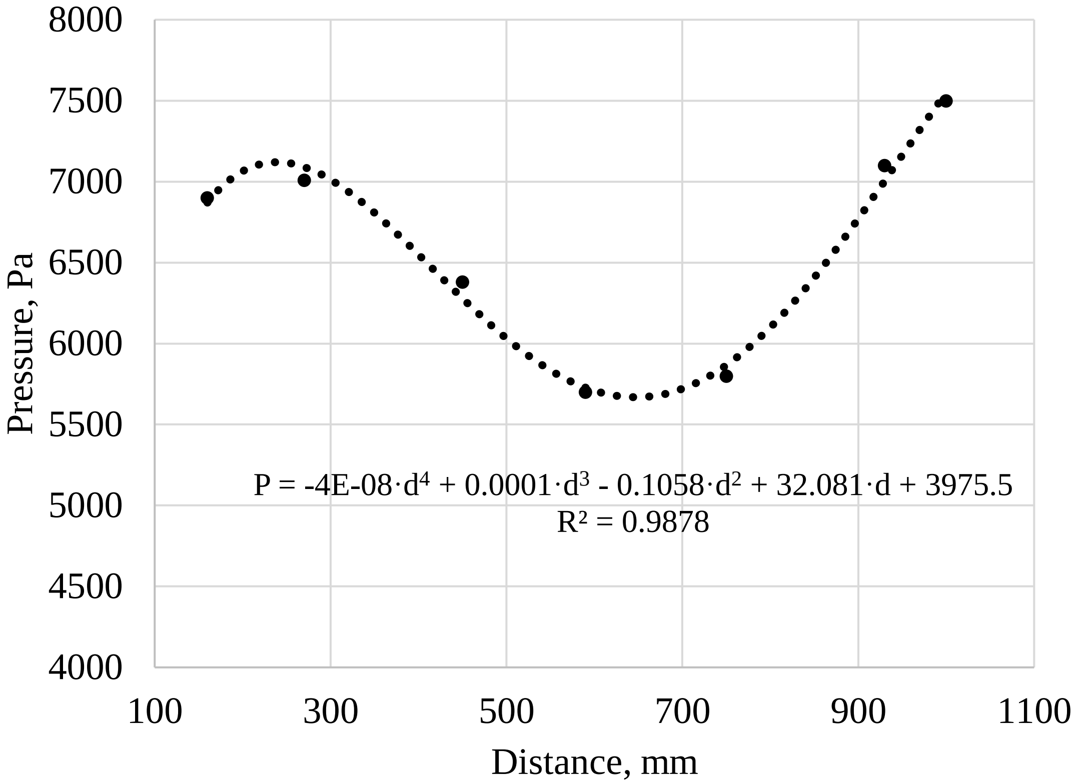

Figure 9.
Graph of pressure changes during acoustic wave oscillations in the resonator.

At a temperature of 20 °C, the oscillation frequency was 61 Hz. The dependence of the increase in the frequency of acoustic wave oscillations with an increase in the temperature of the working fluid has been established (Figure 10). The oscillation frequency decreased with increasing contour length. If it is necessary to reach frequencies of 50 Hz, which is necessary for the normal operation of a linear electric generator, then the length of the resonator should be at least 6.9 m.

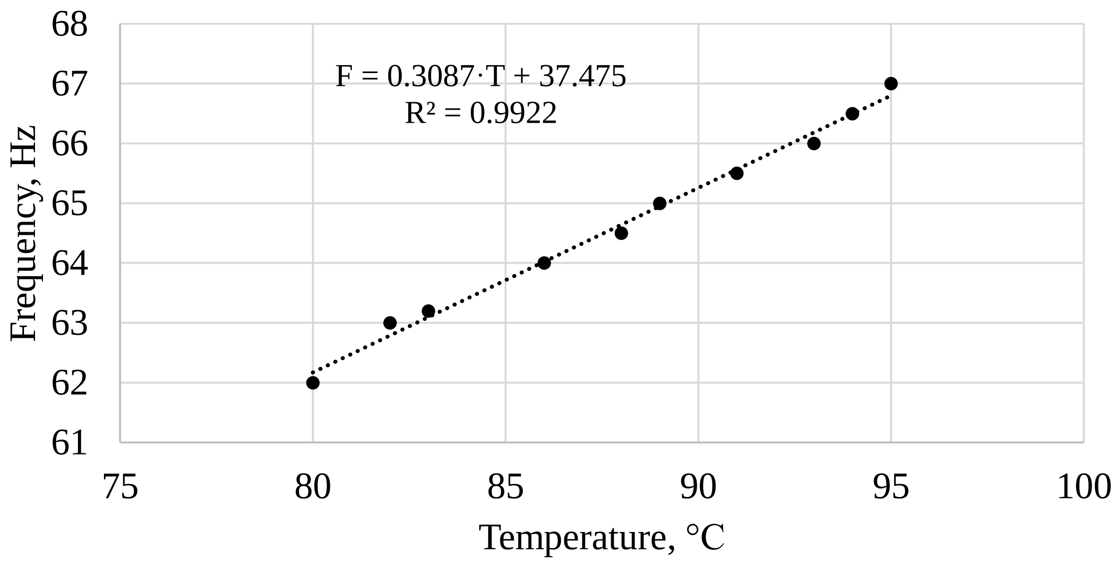

Figure 10.
The dependence of the increase in the frequency of acoustic wave oscillations with an increase in the temperature of the working fluid.

Figure 11 shows a graph illustrating the change in TAE power depending on the temperature of the working fluid. The graph shows that as the heating temperature increases, there is an increase in power.

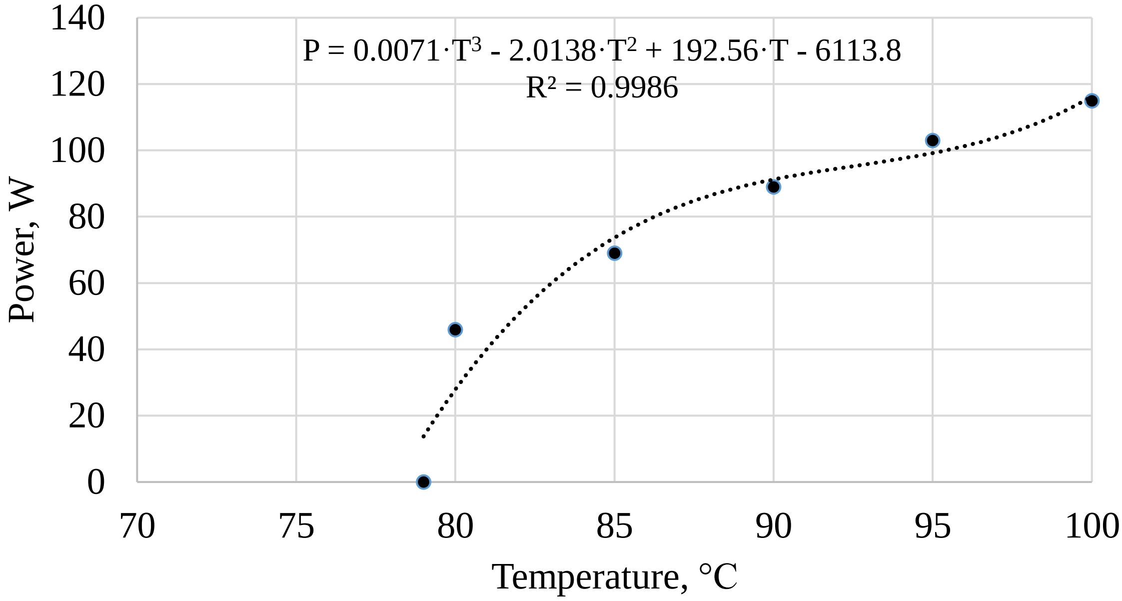

Figure 11.
Graph of changes in the power of the TAE depending on the temperature of the working fluid.

Figure 12 shows the dependence of efficiency on the power of the thermoacoustic system. Maximum efficiency is achieved at maximum power.

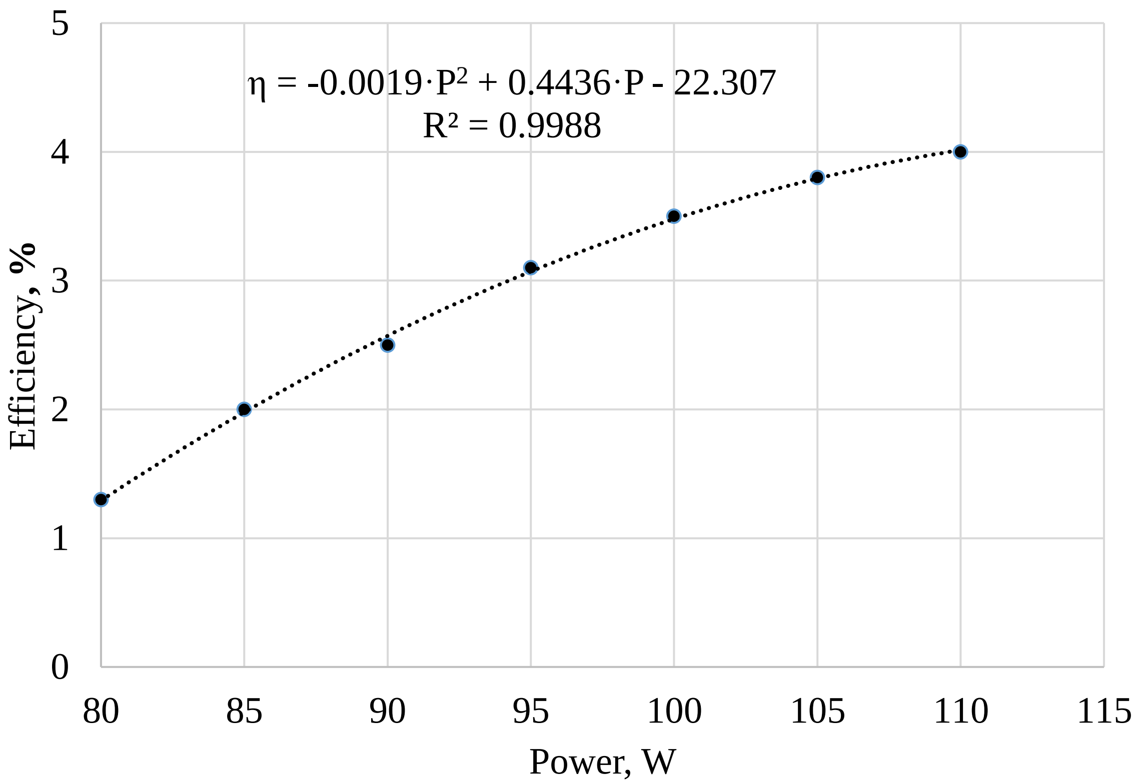

Figure 12.
The dependence of efficiency growth on the growth of TAE power.

With the initial power value equal to zero, the temperature did not reach the initial self-start value, with the temperature rising above 80 °C. The maximum power of the TAE was reached at a maximum temperature of 100 °C. After the temperature rise stopped, the increase in TAE power stopped.

4. Discussion

Experimental results have shown that the proposed design with a rectangular stage cross-section has a cross-section 16 times larger than the resonator, compared with traditional schemes [7, 17], is the most acceptable for further improvement and development. Since it allows you to reduce the temperature of the self-start of the TAE and ensure its stable operation at a temperature of 90-100 °C, which is quite achievable when using a solar collector. Accordingly, it is possible to create a cogeneration source capable of comprehensively producing electrical and thermal energy from a liquid heated to 90-100 °C (water or antifreeze). During the development, it was decided that each stage would have an acoustic load (an electric generator with a turbine). If we make a common acoustic load (an electric generator with a turbine) on all stages, as shown earlier in Figure 2, then additional research is needed to find the optimal diameter for each stage, so then we will have to make the stages different in diameter, which is not very convenient for design unification in industrial production. Accordingly, additional research needs to be conducted to find the optimal diameter ratios. An attempt to make two additional resonators running crosswise, as shown in Figure 4, is more suitable for a linear generator than for a bidirectional turbine, since their cross section should be smaller than that of the main resonator. At the same time, the additional resonators are sufficiently extended, which will cause additional acoustic losses. If we use a structure with additional resonators and a bidirectional turbine as an acoustic load, it will be impossible to self-start the engine. The lack of self-start for TAE is a major obstacle to its industrial use. When using linear generators (alternators), this problem does not arise, since they almost hermetically seal the connecting pipes. Therefore, the future design will have 4 load points, respectively, four independent bidirectional turbines will be used. Moreover, there will be only 4 steps, as this is the most rational number of steps. With 4 steps, the maximum efficiency is achieved with 4 steps. Taking into account the economic costs and weight dimensions for generating one unit of electrical power. The experiments carried out with an increase in the number of steps did not give a significant increase in the power and efficiency of the TAE. Hypotheses 5, 8, and 15 were tested. As the number of steps increases, the self-start temperature and the operating temperature of the TAE decrease, but the additional 5th or 8th stage did not significantly increase efficiency. It can be noted that the TAE with four stages is easier to fold to reduce its size, the resonators can be made spiral. Four- and five-stage designs have the maximum design efficiency, but the temperature difference required for self-start decreases with an increase in the number of stages of more than 4. If it is necessary to reduce the self-start temperature when using low-potential heat, then it makes sense to increase the number of stages more than 4. The optimal ratio of the cross-sectional areas of the heat exchanger and the resonator is five to one. The studied TAE had a heat exchanger cross-section exceeding the resonator cross-section by 4 times; in the future, it is planned to double this cross-section.

To solve the third problem, the dependence of the design on the overall dimensions of the TAE was taken into account: with smaller resonator diameters, the cross-sectional area of the heat exchanger can exceed it by 5-30 times. The smaller the TAE, the smaller this ratio is, since with a decrease in the diameter of the resonator, hydraulic losses in it increase and a resonator with a larger diameter relative to the stage becomes more efficient. It also affects the distance at which the acoustic load (linear generator, turbine) is located, since the further the load is from the hot heat exchanger, the greater the acoustic losses in the resonator, but the closer the load is to the hot heat exchanger, the higher the risk of damage by the flow of heated gas to the turbine or linear generator. In the proposed TAE, this danger is reduced, since its operating temperature did not exceed 100 °C, so the plastic parts of the turbine and linear generator are able to maintain their strength. In the future, the operating temperature will be reduced to 79 °C, which will create more acceptable conditions for the operation of plastic parts of the turbo generator made using 3D printing. A four-stage TAE with a rectangular cross-section of steps will allow operating in the low-temperature range of self-starting from 79 to 100 °C., which allows you to convert low-potential heat from wastewater, geothermal wells, or you can use heated water in a solar collector with a temperature from 80 to 90 °C. The use of a solar collector is very important for the southern regions of Kazakhstan, since there are almost always more than 300 sunny days a year, taking into account the hot summer, when the air temperature is above 0C, it is possible to use TAE efficiently enough for energy supply to autonomous rural consumers. The proposed rectangular design of the stage with two diffusers, in contrast to the already classic cylindrical design of the De Block stage, has a number of advantages. First of all, the dead volumes of the step are reduced. Secondly, it is easier to mount rectangular heat exchangers inside the stage, and the distance between the heat exchanger and the end of the resonator is reduced, which reduces the loss of acoustic energy. After refinement of the design and an increase in the cross-section of the heat exchanger in a ratio of 20 to 1 relative to the resonator cross-section, as well as an increase in the number of stages from 4 to 8, an increase in power and a decrease in the self-starting temperature of the TAE are expected to be from 60 °C or less. The results were compared using the Student's method and showed a strong difference from the sample

5. Conclusions

The structurally proposed TAE system allows it to operate in the low-temperature range. Moreover, there are four levels of efficiency and stability. A laboratory stand was assembled to test the developed TAE, which had 4 rectangular cross-section steps.

As part of the study, it was determined that the sample obtained through experiments allowed us to determine the main parameters of the TAE. Moreover, graphs of the dependence of the main parameters were constructed, which is a very important point in the development of a TAE designed for power supply to rural consumers and operation as a cogeneration energy source in a decentralized system and to work on improving the design in the future.

Dias Kaiyrly and Arystanbek Ansapov assembled and configured the setup and conducted the experiments. Zhanar Akmaganbetova planned the experiments and processed the measurement results, creating tables and illustrations. Sarsikeyev, et al. [19] designed the structure, created the drawings, and summarized the research results.

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