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THERMAL POWER PLANT BASED ON A FREE PISTON ENGINE AND A RECIPROCATING GENERATOR

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The article discusses an autonomous power supply system based on a Stirling engine and a reciprocating generator. There are analyzed the conditions of its operation, the choice of an external combustion engine and a linear synchronous generator. In the course of solving the problem of supplying autonomous consumers with thermal and electric energy remote from the city infrastructure, a power plant with the capacity of up to 100 VA was developed and manufactured. Its experimental study, as well as the analysis of the patent-information array, made it possible to determine the boundaries of using this technical object. The reciprocating generator is driven by a free-piston engine with an external heat supply. For carrying out field experiments, a prototype laboratory model of a free-piston engine with an external heat supply with a linear alternator has been developed. Its main difference from the known types of Stirling engines is the absence of a massive flywheel with a crankshaft and a crank mechanism, which makes it possible to achieve greater tightness and significantly increases the power on output shaft while limiting the outer dimensions. Air is used as the working medium with addition of a small percentage of water, which makes it possible to develop pressure up to 10 MPa. The technical calculation of the generator design has been given, the force required to develop the needed power during the movable element reciprocating movement has been determined. Solutions have been adopted to suppress acoustic noise causing discomfort to consumers. This can in particular be done by placing vibration dampers and designing a generator with a high efficiency. The design of the moving element should minimize mechanical stress on the windings or magnets. The proposed generator can be competitive and can successfully replace traditional low-power sources of electricity with diesel or gasoline engines.

Keywords: : micro power plant, Stirling engine, reciprocating generator, alternative source.

Introduction

At present, in the Republic of Kazakhstan, there exists an extremely acute problem associated with the effective power supply of small business focused on the production of agricultural products and residents of small settlements. The fact is that even in hard-to-reach areas there are abundant power lines with voltages of 10 and 35 kV that were inherited from the USSR. At the same time, the possibility of building step-down substations is often simply not considered, due to their low profitability, although in these areas electricity tariffs can be 2-3 times higher than the national average. A way out of this situation can be the development of decentralized energy sources of low power, which will allow producing electrical and thermal energy on site, without transport losses and in the required amount. It is known that the most widespread in this technical segment are power plants, in which diesel engines and internal combustion engines (ICE) are used as driving mechanisms. Diesel electric generators are more economical in terms of fuel consumption. They consume 280-350 g of fuel per kWh of generated energy depending on operating conditions.

Knowing this feature, manufacturers deliberately raise the price of diesel units in comparison with generating systems that run on gas or petrol. But there are two problems here:

- supplying gasoline, diesel fuel (and even more so gas) to districts remote from cities is often very expensive undertaking. Delivery of any of the listed types of fuel is always associated with significant transport costs, which makes it 2.5-3 times more expensive for a resident of a remote village than for an urban consumer, as statistics show, for farms of distant pasture cattle breeding the tariff can be even higher;
- for autonomously living consumers, in addition to electricity, heat energy is also needed, which is used to heat the premises. From this point of view, a diesel engine is less efficient, as it warms up more slowly than a gasoline engine.

As studies have shown, the solution to this problem can be the use of autonomous generation systems based on a Stirling engine (SE) and a multi-pole generator with combined excitation [1]. They are favorably distinguished by their ability to operate on various types of fuel including gas, coal, fuel oil and biological resources; high efficiency reaching 41-43 % (excluding power losses on sliding contacts) [2]; a low noise level and high environmental parameters that are superior to diesel engines, according to a number of literary sources [3, 4]; the simplicity of the generator design, which affects its low cost; high frequency of the output voltage, which is known to be proportional to power; the ability to operate the generating system in a wide range of rotational speeds of the Stirling engine output shaft, an extremely low level of use of semiconductor elements in the system, which makes it available to the mass consumer. With an excess of local fuel (sawdust, straw, meat/fish/poultry farms waste, etc.), as well as a sufficient efficiency of decentralized sources, they can be used not only by residents of remote areas but also by consumers connected to centralized electricity and heat supply systems [5, 6]. At the same time, the efficiency of a system with a power from 1 to 100 kW (taking into account the effect of heating the premises) can reach 80 %.

The Stirling engine (SE) has long been known and described in detail both in theoretical and practical aspects [4, 7]. The SE design has undergone various improvements and modernizations; one of the options of this engine can be a free piston engine. A mathematical model describing the principle of its operation is presented in [8]. Methods of studying the SE used in this work are taken from [9]. There are a number of works dealing with studying free piston diesel engines as a rather promising type of these heat engines; there is a mathematical description of the power plant based on them, and the results of laboratory studies are presented in [10-12]. Based on the material studied [9-12], the free piston SE was adopted for developing due to a number of advantages over other types of SEs, first of all, due to its high tightness and the ability to reach pressure of 20 MPa without the technical difficulties inherent in other SE designs. The higher the working fluid pressure, the higher the power of the SE and its efficiency. That is why the purpose of studies in the proposed work is a generation system built on the basis of a free piston engine with an external heat supply that was invented by Professor Beale. In the 50-s of the last century in the United States, the Sunpower Company manufactured an industrial design [4]. This design is the most successful of the entire SE family. The NASA engineers developed several options for use in spacecrafts. Its resource is about 100,000 hours of continuous operation. There is a well-known version of the free piston type SE developed by the NASA engineers; the details of their operation principle can be found in works [13-16].

Works [17-19] provide a mathematical description of thermodynamic, electromechanical and thermal processes occurring in the considered free piston EHSE. To carry out field studies, a laboratory model of a cogeneration-type power plant was developed on the basis of a free piston EHSE.

Scientists studied the effect of the variable purge time technology implemented in a generator with a free piston engine [10-13]. In the case where a free piston generator has different compression ratios, cycling and frequency, variable purge time technology has improved purge quality and productivity. The presented numerical model of a generator with a free piston engine was developed in the Simulink and BOOST software. Changing the characteristics of generators with a free piston engine under various unsteady conditions was also discussed. A free piston SE works on the same principle as other SE designs with a drive mechanism [10-11]. Under the action of gas pressure in the working cavities the pistons move, and the movement in the opposite direction occurs due to the elastic forces of the mechanical spring. There is no rigid kinematic connection between the pistons. The displacer, in comparison with the working piston, has a lower mass. As a consequence, it advances the working piston by a certain phase angle. This condition is necessary to obtain useful work in engines operating on the Stirling cycle [10-11].

1.Materials and methods

To carry out field experiments, a prototype laboratory model of a free-piston engine with an external heat supply (EHSE) with a linear alternator on a permanent magnet has been developed. An experimental laboratory power plant with a free piston SE is shown in Figure 1. Its main difference from the known types of SEs is the absence of a massive flywheel with a crankshaft and a crank mechanism. In addition, the design makes it possible to achieve greater tightness, which significantly increases the power on the output shaft while limiting the outer dimensions [4,7]. Air is used as a working fluid with addition of a small percentage of water, which makes it possible to develop pressure up to 10 MPa. The EHSE design is shown in Figure 2, a description of the principle of operation and the physical laws of its operation can be found in works [4, 6, 7].

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a) b)

Fig.1. Experimental laboratory setup with the power of 100 W: a) – linear generator; b) – cooling system.

When developing the EHSE design, theoretical information presented in works [4, 6, 7] was used and the recommendations of the free piston EHSE researchers [10, 11] were taken into account. In the lower part of the body, the working fluid located in the inner part of the EHSE is heated with a gas burner. Displacer 4 is made of an aluminum alloy and is hollow, since it must have a lower mass compared to permanent magnet 6. When heated, the working fluid expands and pushes the displacer upwards. The undercarriage contains an elastic membrane that rises upwards together with permanent magnet 6. The displacer and the permanent magnet are interconnected through the undercarriage elements. The magnet moves from the bottom to the top. Its movement inside the coil of an electric generator induces EMF in it.

Then the working fluid is cooled in cooler 2, after which it is compressed and the piston is lowered down under the impact of the magnet weight and the force of the pre-compressed spring. Cooler 2 is a reservoir through which coolant circulates. Then the working fluid is heated again at the bottom. The developed EHSE operates according to the Stirling thermal cycle [4, 6 ,7] and belongs to the free piston type [10, 11]. The difference from the known designs consists in the fact that the working piston is moved outside the housing and replaced by the permanent magnet. This simplifies the design and makes it easier to adjust the EHSE, and reduces its cost. The proposed EHSE has a disadvantage of a lower efficiency compared to analogs [10, 11], but its advantage is the lower cost and simplicity of design.

The reason for this is the unique thermo-physical characteristics of water vapor [20]. As follows from the tabular data obtained by Professor M.P. Vukalovich, at the saturated steam temperature T = 330 **°C, its** pressure reaches 12.8 MPa (128 atm.). In contrast to the well-known foreign samples of free piston SEs, the transition was made from helium to the mixture of air with saturated water vapor that is obtained upon heating. The volume of injected distilled water added is 3-5 cm^3 per one liter of the SE working volume. This will make it possible to achieve the following calculated parameters of the dry saturated steam: at T = 150 °C pressure P = 0.5 MPa, at T = 200 °C pressure P = 1.5 MPa, at T = 300 °C pressure P = 8.5 MPa, at T = 330 °C pressure P = 12.8 MPa. The design of a laboratory sample of a free piston SE is intended for maximum initial pressure of 2.5 MPa; for operation at higher pressures, serious changes in the design are required. Heating is carried out from below with a 1 kW gas burner. Outside the cylinder is a water-cooled jacket. The design parameters of the set are as follows: electrical power of alternating current up to 100 VA and thermal power up to 300 W.

The pressure inside the cylinder depends on the power of the burner flame and the temperature of the heater, as well as on the temperature of the working fluid. During the experiment, the pressure was varied from 0.5 to 2.5 MPa. The working pressure was selected to be 1.5 MPa. At the maximum pressure above 2.5 MPa, there is a risk of destruction of the EHSE cylinder. The temperature was measured with two instruments using a laser temperature meter Fluke 51 (Fluke, USA) to identify the hottest areas of the cylinder. Continuous control of the heating temperature was performed using a 4-channel digital thermometer HT-9815 (Xintest, China). The pressure was measured using a pressure gauge with the measurement limit of 10 MPa.

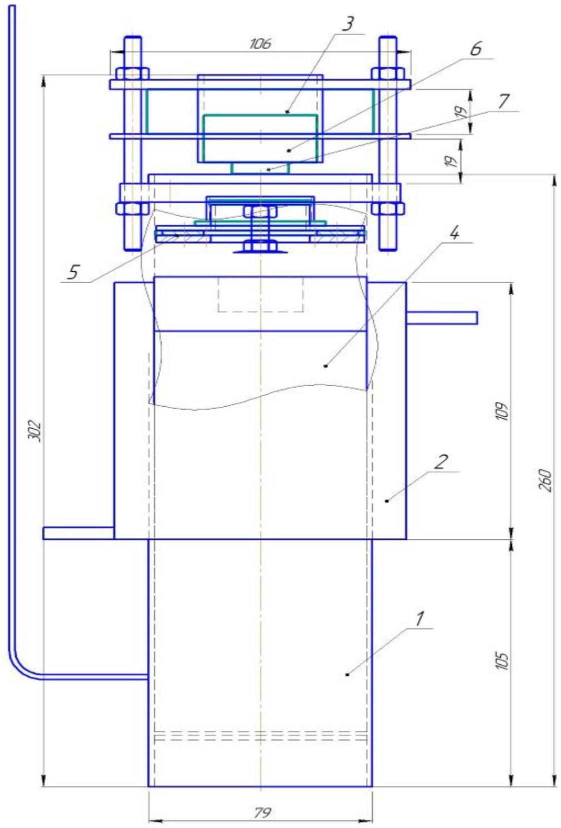

Fig.2. The EHSE arrangement:
1 - housing, 2 - cooler, 3 - electric generator, 4 - displacer, 5 - undercarriage, 6 - permanent magnet of electric generator, 7 - permanent magnet for communication with undercarriage, 8 - M6 bolt with return spring, 9 - M6 nut, 10, 11 - washer

In the course of studies [6-9], an extremely interesting feature of Stirling engines was revealed. It turned out that at the power that is lower than 2 kW, the conversion of thermal energy into mechanical energy occurs with a high efficiency if the movable element performs reciprocating movement (most of the known structures are oriented to rotation). That is why the purpose of research in the proposed work is a generation system built on the basis of a free-piston engine with an external heat supply invented by Professor Beale. In the 50-s of the last century in the United States, the Sunpower Company manufactured industrial prototypes. Their design turned out to be so successful among the entire Stirling family that the NASA engineers developed several options for using them on spacecraft. Their resource is about 100,000 hours of continuous operation. There is a well-known version of the SE of a free piston type developed by the NASA engineers; the details of their operation principle can be found in source [2].

A free piston Stirling engine works on the same principle as a Stirling engine with a drive train. Under the action of gas pressure in the working cavities, the pistons move, and the movement in the opposite direction occurs due to the elastic forces of the mechanical spring. There is no rigid kinematic connection between the pistons. The displacer, in comparison with the working piston, has a lower mass. As a consequence, it advances the working piston by a certain phase angle. This condition is necessary to obtain useful work in engines operating on the Stirling cycle. For carrying out field experiments, a prototype laboratory model of a free-piston engine with an external heat supply (EHSE) with a linear alternator has been developed. Its main difference from the known types of SE is the absence of a massive flywheel with a crankshaft and a crank mechanism. In addition, the design allows for greater tightness, which significantly increases the output shaft power while limiting the outer dimensions. Air is used as the working medium with addition of a small percentage of water, which makes it possible to develop pressure up to 10 MPa. A diagram of the cogeneration thermal power plant (TPP) with a linear generator with reciprocating motion is shown in Figure 3.

The proposed TPP is capable of operating in the cogeneration mode and producing electric and thermal energy in a complex manner. The main parameters of a free piston engine with external heat supply are shown in Table 1 below. The main parameters of a free piston engine with an external heat supply are shown in Table 1. The reason for this is the unique thermo-physical characteristics of water vapor [17].

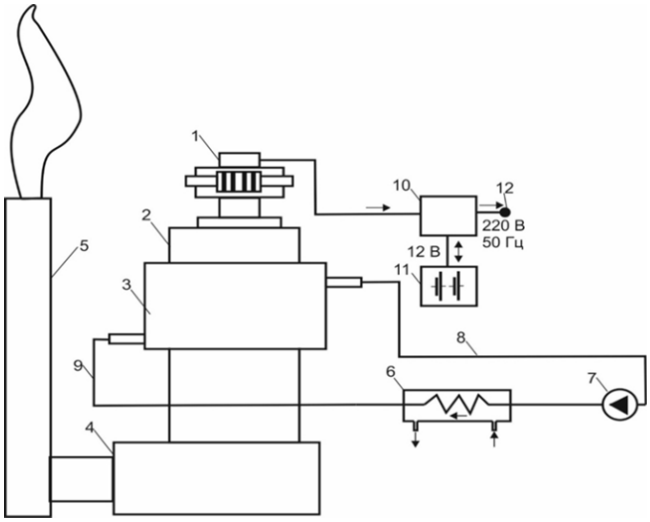

Fig.3. Diagram of the cogeneration power plant with a linear generator of a reciprocating type: 1 - linear generator; 2 - free piston EHSE; 3 - liquid cooling system; 4 - heating source (furnaces with a firebox); 5 - chimney; 6 - heat exchanger of the cooling system; 7 - circulation pump; 8 - supply pipeline; 9 - return pipeline; 10 - electrical control and conversion unit; 11 - drive; 12 - device for connecting an external electrical load

Table 1. The main parameters of a free piston engine with EHSE

No.	Parameter	Value
1.	Pressure at the temperature 150^0C, MPa	0.5
2.	Pressure at the temperature 200^0C, MPa	1.5
3.	Pressure at the temperature 300^0C, MPa	8.5
4.	Liquid temperature at the outlet of the cooling system, ^{0}C	50-80
5.	Liquid temperature at the inlet to the cooling system, ^{0}C	25-30
6.	Pump capacity, l/min	4
7	Maximum overall efficiency, no more, %.	80
8	Maximum electrical power of the generator, W.	До 100

Experiments have been carried out to construct a PV diagram of a closed Carnot heat cycle and to consider the dependence of pressure and volume on different positions of the pistons. The results are shown in Figure 4. The studies carried out allow finding the optimal parameters of the structural parts of the heat engine, to establish precise geometric dimensions of the piston and the displacer, as well as the magnitude of their stroke with the optimal value of the phase shift. If the phase shift changes from 90^0 to 0^0, then the EHSE stops working. In this case, the displacer must be at least three times lighter than the working piston, and its stroke is many times greater; this statement was noted earlier [4, 10, 11]. The obtained characteristics of the EHSE have low efficiency indicators compared to the ideal Carnot cycle, the area of which is shaded. Accordingly, there is needed the EHSE specimen refinement in order to reduce heat losses and to increase its efficiency.

To calculate the efficiency, there was used the following formula:

$$\text{Efficiency} = A/Q\ 100\%,$$

where A is the useful work (power), W; Q is the power spent for performing the work, W.

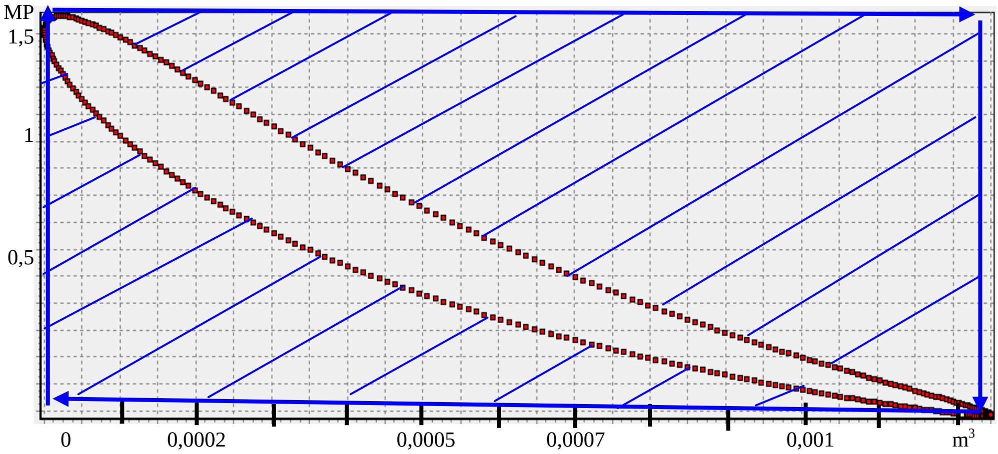

Fig.4. Free piston engine main parameters dependences when operating with the heater temperature of 2000C and the cooler temperature of 300C.

With the burner power of 1000 W, the maximum power developed by the electric generator reached 100 W, the efficiency did not respectively exceed 10%. In this case, the measurement errors made 11% due to the significant scattering of the data and the difficulty of stabilizing the heating and cooling modes. Unstable operation of the electric generator was observed, which caused the output power to fluctuate from 80 to 100 W. The EHSE power depends on the operation of the cooling system: the higher the temperature between the heater and the cooler, the higher the efficiency. According to the theoretical information [4, 10,11], the EHSE thermal power should be 300 W. The overall efficiency can reach 40-50% [4, 10, 11]. The resulting heat energy can be used for heating and hot water supply.

2. Deriving the equations and technical solutions accepted

To select the generator design, it is necessary to determine the force required to develop the needed power, with the reciprocating movement of the movable element by 4.21 mm. At the start and end points, the stem speed is zero. Neglecting the higher harmonics, the dependence of the speed on time t can be represented as follows:

$$v(t) = v_{\max}\sin(\frac{2\pi t}{T}). \tag{1}$$

Accordingly, within half the period T with frequency that is close to 50 Hz, the stem is to run:

$$L = \int_0^{T/2} v_{\max}\sin(\frac{2\pi t}{T})dt = \frac{Tv_{\max}}{2\pi}\int_0^{\pi}\sin\alpha d\alpha = \frac{v_{\max}T}{\pi} = 4.21 \text{ mm.}$$

From here it follows that the maximum speed $v_{\max} = \frac{L\pi}{T} = 661.3$ mm/s.

Mechanical power converted into electrical power is determined by the known formula:

$$N = \vec{F}\cdot\vec{v} = P = mE_1 I_1\cos\psi\,, \tag{2}$$

where $\vec{F}$ is the vector of one component of the vibro-acoustic force of the Stirling engine at the time moment considered that is involved in the process of electro-mechanical energy conversion; P is active power; m is the number of phases; E_1 is the EMF first harmonic in the phase; I_1 is current in the phase; ψ is the difference of phases between current and EMF.

Neglecting the higher harmonics, the force component involved in the electro-mechanical conversion of energy can be represented as follows:

$$F(t) = F_{\max}\sin(\frac{2\pi t}{T} - \varphi).$$

Then, the net power, or the average power for the period will be equal to:

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$$P = \frac{1}{T}\int_0^T F(t)\cdot v(t)dt = \frac{F_{\max}v_{\max}}{2}\cos\varphi ,$$

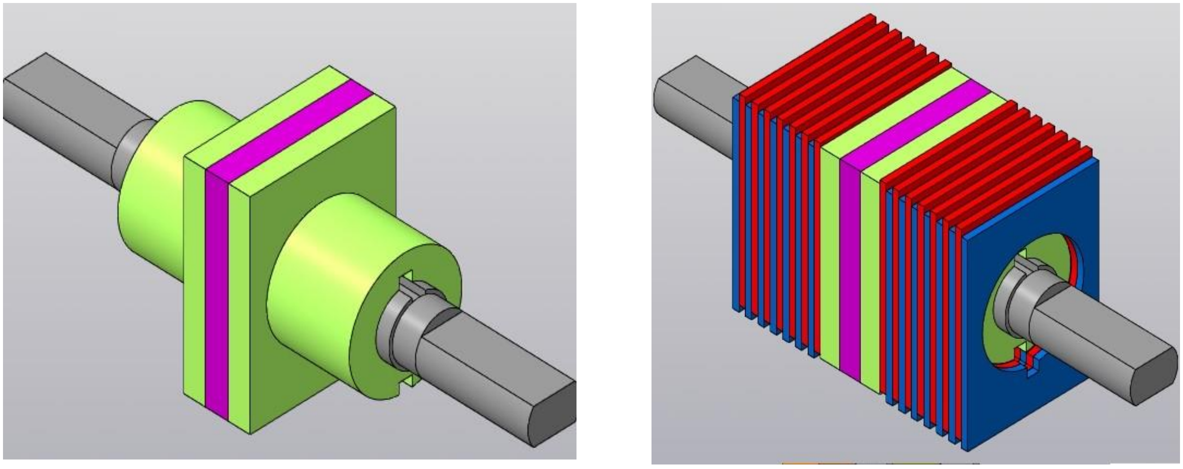
at the maximum output power $\varphi = 0$ and $F_{\max} = \frac{2P}{v_{\max}} = 302.4$ H.

The obtained value of the force at the relatively small value of W, speaks of serious difficulties arising in designing power plants of this type. Firstly, it is necessary to pay increased attention to suppression of acoustic noise that creates discomfort for consumers. This can be done, in particular, by placing vibration dampers and designing a generator with a high efficiency. Secondly, the design of the moving element should minimize mechanical stress on the windings or magnets. The results of calculating the full power of the generator at an active load are summarized in Table 2.

Table 2. The results of calculating the full power of the generator at an active load

I_1, A	1	2	3	3.5	4.0	4.5	5
$I_1 x_\phi$	3.58	7.16	10.74	12.53	14.32	16.11	17.90
$\sqrt{E_{xx}^2 - (I_1 x_\phi)^2}$	34.82	34.26	33.31	32.68	31.94	31.07	30.08
$I_1 r_\phi$	1.52	3.04	4.56	5.32	6.08	6.84	7.6
U_1, B	33.3	31.32	28.75	27.36	25.86	24.13	22.48
S1, BA	33.3	62.44	86.25	95.76	103.44	109.0	112.4

The analysis of the information array made it possible to propose a linear generator for the TPP under consideration shown in Figures 5, 6. Its rotor (the movable element) contains a shaft (Fig. 5a); a square permanent magnet with an inner hole that is magnetized along the horizontal axis; two bushings made of 45 steel along the edges of the magnet fitted on the shaft and having a rectangular outer profile; rectangular sheets (Figure 5b) made of electrical steel 2013 with the thickness of 0.5 mm.

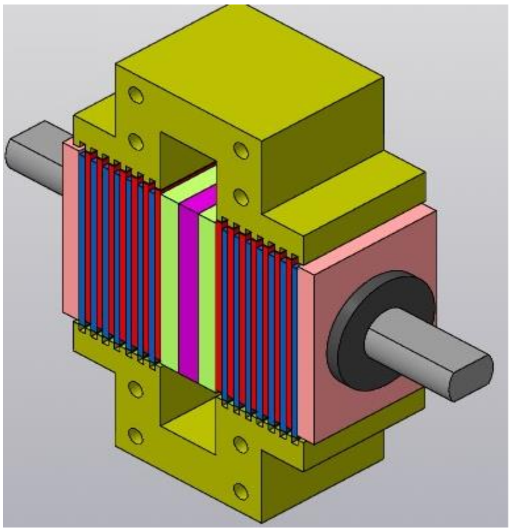


a) b)

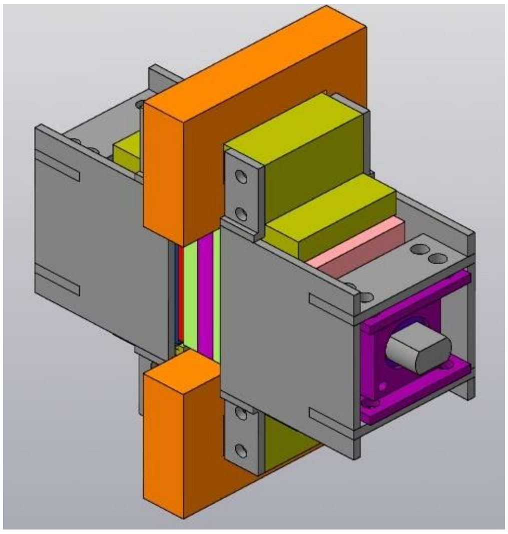
Fig.5. Moving elements of the linear generator: a) shaft with bushings and a permanent magnet; b) toothed rotor.

The ends of the shaft have a circular cross-section with a sawn-off outer part bounded by two parallel surfaces passing through two identical chords. This is needed to avoid rotation of the movable element in the bearing units. The bushings sit on the shaft along the key. The sheets are made with the offset relative to the central hole, either down or up. By alternating different types of sheets, four of each type, during blending teeth are obtained on the outer working surface, the distance between the axe s of which is 4.21 mm with the filling factor of the package with steel 0.95. The non-working part of the packages is made without teeth, the section in this part is designed to redistribute the variable flow from the upper part of the rotor to the lower part and vice versa. Along the edges, the packages are pulled together by pressure washers and nuts, which are tightened along the thread made on a non-magnetic shaft (X19H10T).

The generator works as follows. In the initial position, the axes of the teeth of the upper stator package (Fig. 6a) coincide with the axes of the teeth of the rotor located on its outer upper part. In the lower stator package, the axes of the teeth coincide with the axes passing through the slots of the rotor in its outer lower part. Thus, the flux developed by the magnet, passing through the left sleeve, enters the rotor package and, then along the path with the least reluctance moves to the upper part of the rotor package and enters the upper stator package. Penetrating the coil, the magnetic lines of force pass into the right side of the stator package, enter the rotor package and close at the south pole of the magnet. It should be noted that in the initial position, the flux passing through the lower stator package is small, since it follows the path with high reluctance.



a)



b)

Fig.6. Linear generator: a) rotor with the stator packages; b) generator assembled.

Electromagnetic and strength calculations of the generator have been performed using the ANSIS software application. The main parameters of the power plant are shown in Table 3. Below, Figure 7 shows experimental values of the total power and output voltage of the generator depending on the current strength. In the numerical experiments, the load is active.

Table 3. The main parameters of the power plant

Parameter	Value
Net power, W	100
Nominal voltage on the battery, V	24
Maximum linear speed, mm/s	661.3
Minimum linear speed, mm/s	420.7
Maximum force on S1, N	302.4
Maximum current, no more, A	4.2
Number of phases	1
Number of stator teeth per pole	8
Electrical losses in the stator winding, W	74
Inductive resistance of the winding, Ohm	3.58
Losses in stator steel, no more, W	3.6
Permanent magnet type Ne-Fe-B	45 SH

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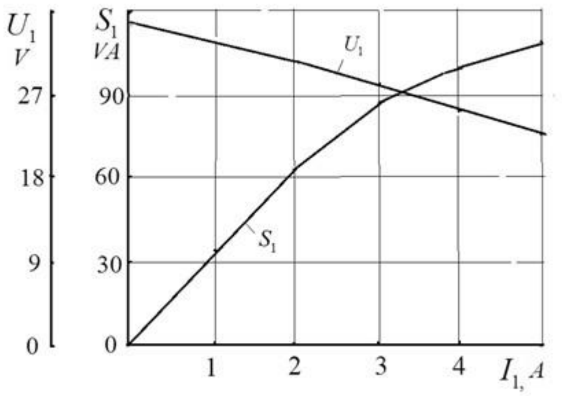

Fig.7. Output voltage and full generator power dependence on load current

Conclusions

1. This paper shows the principal possibility of designing a power plant based on a reciprocating Stirling engine and a linear generator.

2. Ne-Fe-B 45SH is capable of delivering the full power of 110 VA. With its scaling and proportional increasing the cylinder volume of a free piston EHSE, the power of 1-2 kVA can be achieved, but further increasing the power is not advisable, due to the high increasing of the electric generator cost.

3. The analysis of the power plant technical parameters shows that this technical facility is competitive and can successfully replace traditional low-power sources of electricity with diesel or gasoline engines. Comparison of the developed thermal power plant and the electricity generation system based on a generator with a rotating rotor [1] characteristics suggests that at the power that is lower than 2.0 - 2.5 kVA, the conversion of thermal energy into mechanical energy of reciprocating motion is more profitable from the economic point of view. If an autonomous consumer requires power of 3.0-12 kVA, then there is no alternative to the use of a Stirling engine and a generator with combined excitation of the rotating type.

4. A thermal power plant based on a free piston engine and a reciprocating generator is capable of producing simultaneously electrical and thermal energy, which allows it being used to supply power to remote consumers in rural areas, while this unit is capable of operating with almost any type of fuel and agricultural waste.

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