Engineering solutions for an autonomous power unit's prime engines

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Abstract. Nowadays trends in a development of autonomous sources of energy, as well as positive results of a multi-year design and improvement of free-piston engines with the external feed of heat, which are working on Stirling cycle (FPSE), created prerequisites for a successful commercialization of that type of engines. Obtained characteristics of FPSE, a degree of constructive elements' elaboration and an optimization of thermodynamic cycle's parameters, will allow engines of that type in the nearest future to take steady positions on the market, especially in a segment of an autonomous power units. The presented paper is dedicated to a search of engineering options for an implementation of a primary engine for an autonomous low-power power units and a comparative analysis of main technical characteristics of FPSE with parameters of kinematic engines with an external feed of heat (EEFH).

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Introduction

Currently, the most widely spread primary engines for autonomous power units and other power equipment are diesel and gasoline piston internal combustion engines (ICE). A high degree of an elaboration in a design, low cost and high enough unit effective parameters are the reasons for that.

A search for new technical solutions for a creation of primary engines for autonomous power units resulted in an emerge of kinematic engines with external feed of heat (EEFH), working on Stirling cycle. Thermodynamic cycle and a construction of elements and systems of those engines have certain characteristics, which provide for their advantage in relation to ICE. For example, multifuel capability of EEFH allows to use thermal energy from combustible and thermal secondary energy resources, as well as solar and geothermal energy. Other important advantages of EEFH are relatively low level of harmful substances' emission with exhaust gases (EG) and low noise level.

A perspective direction of a development of kinematic EEFH is a concept of free-piston engine with an external feed of heat, working on Stirling cycle (FPSE), in which there is no rigid kinematic link between a displacer and working piston, and taking off of produced useful work can be carried out directly from working piston. While retaining all benefits of kinematic EEFH, piston-free engine has a higher effective factor of efficiency due to a reduction of mechanical losses and improved weight and dimension parameters.

The purpose of the presented paper is a search for technological options for an implementation of primary engine for autonomous power unit of low power, a comparative analysis of main technical characteristics of FPSE with parameters of traditional piston ICE and kinematic EEFH and an analysis of perspectives for use of autonomous power unit based on FPSE.

Perspective problems of energy sector and ways of their solution

Strategy of energy sector development in many countries implies an increase in a ratio of local fuels' use, such as by-products of oil & gas extraction industry, waste products of timber and woodworking industries, peat, as well as heat, produced during some manufcaturing processes. An implementation of local fuels in energy sector has the aim, in the first place, to maximize an efficient use of natural energy resources and a potential of energy sector.

A rational solution to those problems is a local replacement of obsolete power units and an increase of additional output with less expensive and more flexible, in a context of installation, autonomous power units, consuming local and renewable fuels. Autonomous power units with power output from few hundred watts to several hundred kilowatts are in an especial demand in various sectors of economy and geographical regions, which energy supply system is highly decentralized.

Engine-generator units

Today, energy supply of regions, which are located away from centralized energy energy supply systems, in general is provided by means of engine-generator units (EGU), which are using gasoline and diesel ICE. An operation of such engines is related with additional expenses for transportation of fuel to a location of a unit. A main negative effect of those EGU on environment is emission of harmful substances with EG and noise.

A dependence from delivered fuel could be reduced when by means of using associated gas as fuel for gas-piston ICE, but full-grown use of that type of fuel is difficult, since fraction composition of gas is not constant.

A problem of a dependence on delivered fuel was resolved in a case of autonomous power units based on gas-piston ICE, equipped with gas generator in order to obtain a gaseous fuel directly in a power unit by means of a gasification of various types of local fuel and renewable wastes [1]. However, for gas generators an inertance of gasification process is characteristic, which may lead to a deterioration in an acceleration of a power unit in a case of a fast transition from medium-sized loads to high, caused by an insufficient performance of gas generator. The problem can be solved by an application of gas generator produces with higher performance or fuel accumulator, produced in a form of an additional gas reservoir. However, both solutions have led to an additional increase in size and weight of a power unit, which in some operation conditions is undesirable.

Autonomous power units based on kinematic EEFH

A search for new primary engines for autonomous power units led to kinematic by EEFH, working on Stirling cycle, in which crank-type or lever-type mechanism is used, which is required to make changes in volumes of compression and expansion chambers by law, which is close to ideal law. Drive mechanism provides a transformation of a reciprocal movement of working piston in a rotational movement in an engine's output and a rigid kinematic link of displacer and working piston in order to ensure a permanent value of a specified phase angle [2].

In EEFH a feed of heat occurs as a result of a constant process of combustion of fuel in an external combustion chamber, which walls are heated to high temperature and with low pressure, which results in an achievement of a high degree of completeness of fuel combustion and low level of noise. Smooth change of a body's operation pressure during thermodynamic cycle also reduces noise level.

Low temperature in a combustion chamber of EEFH (up to 1500°C), whereas combustion temperature in gasoline ICE is over 2000 °C, provides a relatively low content of nitrogen oxides in EG, which, as it is well known, are formed at high temperatures. Initial, low amount of toxic components in EG of EEFH allows, if necessary, to use the simplified EG neutralization systems, unlike systems for a neutralization in gasoline and diesel ICE.

Variability of options for fuel selection provides multi-fuel capability of EEFH, which allows to replace expensive oil based fuels with more cheap, and significantly expand areas and regions of EEFH application.

High effective parameters of EEFH can be achieved in a case of an implementation of regenerator, which is a part of heat exchange circuit. Use of regenerator as a part of heat exchange circuit ensures an operation of EEFH without outflow of thermal energy of working gas from thermodynamic cycle, thus, ensuring closed state of the cycle. In turn, closed thermodynamic cycle of EEFH allows to significantly reduce level of noise and vibration produced by an engine, and, in a case of dynamically balanced drive mechanism's use, potential for a practical application of an engine can be significantly extended.

There are several basic configurations of kinematic EEFH (figures 1, 2, and 3), which differ in a location of working piston and displacer and a design of a drive mechanism [3]. In a drive mechanism of kinematic EEFH crank mechanism, rhombic drive and oblique washer are the most commonly used.

Crank mechanism which is used in ICE from time of its emerge, is extremely reliable and studied due to an experience gathered during its operation. Main advantages of the mechanism are its reliability, proven technology and ease of a manufacture, however, dynamic balance of an engine with that kind of drive mechanism is, practically, unachievable.

Crank drive mechanism us used in EEFH of α-configuration, which is presented in figure 1.

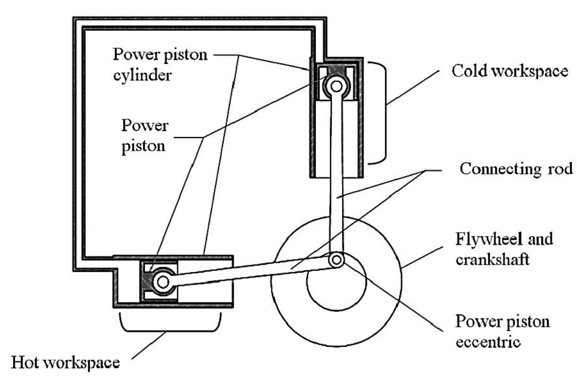

Fig. 1. EEFH α-configuration

An arrangement of the engine leads to a large dead volume, in which working gas does not move between cold and hot workspaces and is not involved in thermodynamic cycle. A high performance of pistons' seals is necessary to ensure hermeticity at high pressures of working gas.

Movement of working piston and displacer in EEFH of β-configuration is organized in a different way (figure 2), in which working piston and a displacer are moving in the same cylinder or in two separate cylinders located on the same axis. In a process of EEFH of β-configuration improvement in 1950th by "Philips" company **rhombic** drive was developed [4], which is presented in figure 2 (a).

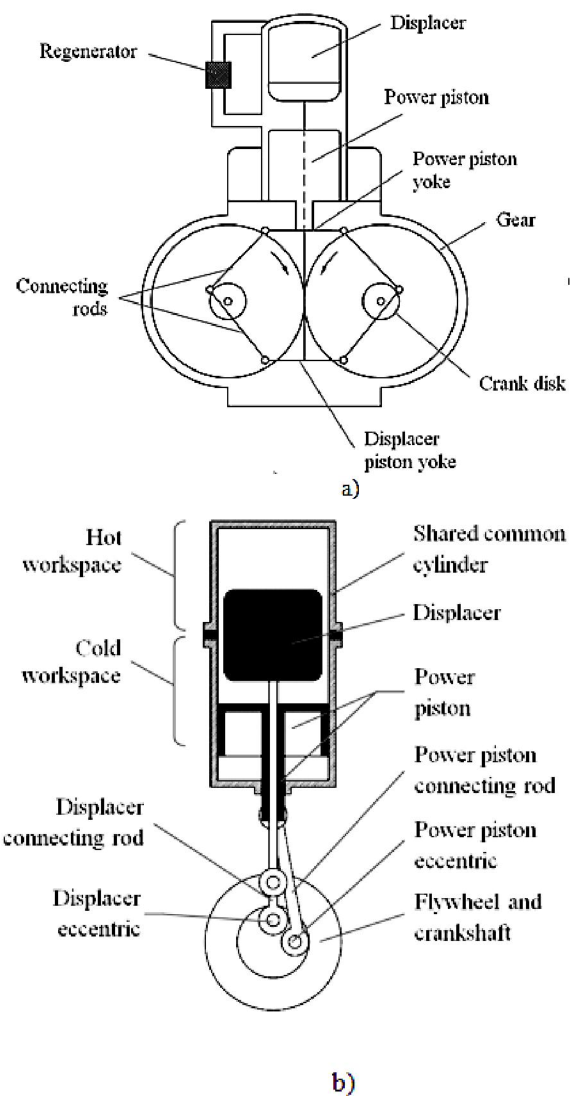

Fig. 2. EEFH of β-configuration with rhombic drive (a) and crank mechanism (b)

That drive mechanism provides dynamic balancing of a single-cylinder engine, which is its main advantage. A design of EEFH allows to compactly place elements of an engine's thermal module and to reduce dead volume. Another advantage of rhombic drive is an absence of lateral force, acting on displacer and working piston during their movement, which is extending service life of seals and some of an engine's components.

Main disadvantages are a relative complexity of a mechanism, because it consists of a large number of moving parts, and a presence of two gears, which are in an engagement, in a drive mechanism. An additional seal of a displacer's rod, which is located in a center of working piston, is increasing a ratio of overall friction losses in seals up to 35% of all mechanical losses.

EEFH of γ-configuration (figure 3) combines solutions used in engines of α- and β-configurations: two cylinders are used in a construction, similar to an engine of α-configuration and a displacer is used, which determines a similarity with β-configuration.

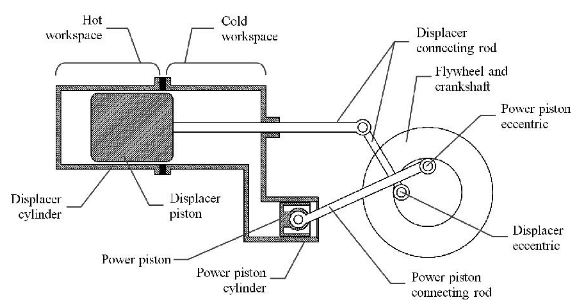

Fig. 3. EEFH γ-configuration

Disadvantages of γ-configuration are a presence of dead volume same to an engine of α-configuration and increased dimensions as comapred to β-configuration.

A problem of dimensions' reduction and an increase of mechanical coefficient of efficiency of kinematic EEFH is addressed in different ways. For example, in 4-cylinder kinematic EEFH produced by "WhisperGen" company, for a conversion of reciprocating motion into rotational motion, a patented mechanism "wobble yoke" is used [5], which uses oscillating washer principle (figure 4).

Fig. 4. Drive mechanism of "WhisperGen" engine

A drive mechanism with oscillating washer allows to isolate cylinders from a crankcase and is used mainly in engines, in which a crucial factor is compactness.

That kind of mechanism is dynamically balanced only with a certain angle of inclination of a washer. An adjustment of angle of inclination of oscillating washer allow to change an engine's piston stroke and to regulate an engine's power, but an engine will be dynamically balanced with only one specific value of angle of inclination of a washer.

All kinematic EEFH, despite measures for an improvement of a design, are facing a number of serious technical problems, which are impossible to fully resolve at the present time, even with an implementation of all contemporary engineering means. Problems include ensuring durability of bearings and sealing elements, a complexity of working chamber sealing in order maintain high pressure of working gas, and a need for a lubrication of all moving parts.

A problem, which should be marked out, is the problem of a working chamber seals, which in EEFH of that type simultaneously performs two functions: a prevention of working gas leakages from a working chamber and a prevention of motor oil's ingress from a crankcase. A leakage of a working gas is undesirable, because it reduces average pressure of a cycle, which, in turn, reduces useful engine's power. An exclusion of an engine's oil ingress in a heat exchange circuit is an extremely important task, because a presence of oil in a working gas leads to a formation of deposits on a heat exchange surface, which are reducing surface area of heat transfer and are increasing aerodynamic resistance of a regenerator. A reduction of heat exchanging circuit's efficiency leads to a reduction temperatures' difference, which, as a result, reduces an engine's efficiency [6].

High values of cycle's pressure in EEFH are kept during a complete revolution of an engine's shaft, which causes high loads in a drive mechanism, which is, in turn, forces to implement special mounting bearings with high load-bearing capacity and massive drive parts.

In order to reduce loads in a drive mechanism, and to make conditions of an operation of working piston's seals easier, a buffer chamber is used, which is located under a working piston in a separate frame or in an engine's crankcase and is filled with gas,which pressure is equal an average pressure of cycle in working chambers. A buffer chamber creates an elastic force, which allows to reduce loads on mounting bearings and a drive mechanism, as well as to provide a more favorable conditions for working piston's seals operation. In order to reduce pressure fluctuations in a buffer chamber, its volume tends to be made as large as possible, but that leads to an increase in weight and dimensions of EEFH.

Above mentioned features of kinematic EEFH restrict use of those engines in areas, in which traditional ICE are now successfully used.

Autonomous power units based on FPSE

To address above-mentioned disadvantages of kinematic EEFH, FPSE [7] was invented by William Bill in 1964, in which there is no mechanical link between working piston and a displacer. A design of domestic power unit by "Microgen" company for a production of thermal and electrical energy, which is based on FPSE, is presented in figure 5.

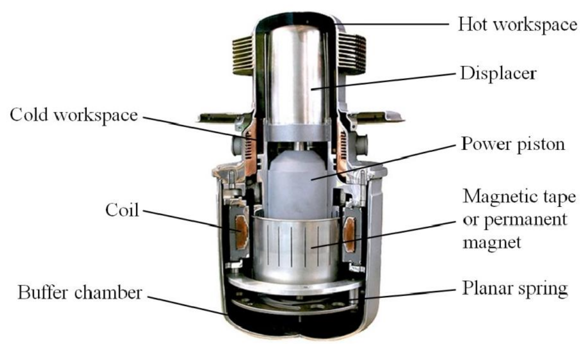

Fig. 5. "Microgen" power unit

A fully sealed construction of FPSE eliminates leakages of working gas. A lubrication system is not required for an engine's operation and a possibility of combining working piston of FPSE and translator of electric generator in one unit provides a decrease in a size of a power unit.

In a construction of a power unit on a basis of FPSE three main elements can be marked out: casing, displacer, working piston and translator of a linear generator. Displacer and working piston are placed coaxially in the same or separate cylinders and form three volumes: expansion chamber, compression chamber and buffer chamber. At that, expansion and compression chambers are connected through volume of a heater, a regenerator and a cooler.

A principle of FPSE operation is similar to EEFH operation with a drive mechanism: displacer and working piston move under pressure of working gas in working chambers, and a reverse movement is conducted under an influence of elastic force of diaphragm springs. Because of a low weight of a displacer as compared to working piston, a displacer is able to respond faster to a change in gas pressure in working chambers and to move ahead of working piston on a value of phase angle, which is a prerequisite of useful work conduction of EEFH, which are working on Stirling cycle.

While maintaining the advantages of kinematic EEFH in FPSE, a design of the major part of FPSE, due to an absence of a drive mechanism, allows you to increase the reliability and service life with a simultaneous reduction of maintenance frequency.

In order to achieve the high effective parameters of FPSE, gases with low-molecular weight are used as working gas, which ensures gas flow inside a working circuit of an engine with relatively low aerodynamic losses. Gaseous hydrogen and helium fully meet aforementioned requirements. However, those gases are able diffuse into metal and a diffusion of hydrogen into metal leads to hydrogen degradation of a material, which is manifested in a form of an embrittlement and a risk of structural failure.

Since an invention of FPSE, in United States, Europe and Japan numerous research and development works were conducted, in order to improve computational methods of an engine's components design.

An arrangement of FPSE allows, without a significant increase in size, to place a buffer chamber inside an engine, which operation reduces load on diaphragm springs, which ensures oscillatory motion of a displacer and working piston by a specified law.

A potential, which FPSE concept has, is impossible to put into practice without an implementation of modern engineering and design solutions. A development of materials science and material processing technology allowed to use mesh structure made from metal foil for regenerators manufacture [8], which simultaneously combine high porosity and low aerodynamic resistance. Regenerator can also be made from composite materials, which combine properties of several materials and posses a set of necessary characteristics, which is impossible to achieve using conventional materials [9].

An example of an improvement of FPSE design can be an adoption of a new concept with a displacer and working piston, which are combined in a single element [10].

A development of tribotechnology made it possible to obtain strong anti-friction materials with high operating temperature, which characteristics allow to apply them in friction pairs of FPSE [11]. In some designs of FPSE a rotational movement of pistons in a cylinder is provided, which allows to create a reliable layer of gas lubricant between parts' surfaces [12]. That solution is, from engineering point of view, is hard to realize in EEFH with a drive mechanism.

A wide use of linear electric generators with permanent magnets and an improvement of an electric generator's control algorithms allowed to reduce weight and size of a generator, internal electromagnetic losses etc. [13].

The most successful company, which has progressed significantly in a design and commercialization of high-tech FPSE is "Sunpower". The company, founded in 1974, over the past 30 years applied technology of FPSE in cryogenic units and linear compressors. Also, a significant amount of a development of FPSE was conducted by "Stirling Technology Company" (STC), which was recently converted in "Infinia" [14].

In spite of an external similarity, in a design of FPSE by "Sunpower" and "Infinia" companies quite different approaches were used. For example, in order to ensure contactless movement of linear generator's translator, "Sunpower" company used gas bearings, while "Infinia" for that task applied mechanical supports, made in a form of diaphragm springs.

Comparison of technical characteristics of kinematic EEFH and FPSE

An assessment of main technical characteristics of EEFH and FPSE was carried out using data from mass produced models of engines and previously published results of experimental studies of those engines. To obtain an objective picture during a comparison of technical characteristics, efficiency, specific weight and service life of engines were considered, the values are listed in table 1.

Efficiency

Effectiveness of heat input use during a conduction of useful mechanical work is estimated by value of efficiency. In a determination of efficiency of power units electricity generators's characteristics are taken into account.

Electrical efficiency of a cogeneration type power unit, created on a basis of kinematic EEFH V161 by "SOLO Kleinmotoren" company, is equal to 25.4% [15]. 4-Cylinder Engine P-40 by "United Stirling" company in MOD II modification in automobile version has efficiency of 38% with working gas pressure of 15 MPa [16].

A reduction of mechanical losses in FPSE as compared to kinematic EEFH provides a higher efficiency, which average value is 30-35%. In a case of using hydrogen as a working gas and a wide application of ceramic materials in a structure of an engine, value of efficiency can reach 46% [17].

Specific weight

That parameter characterizes ratio of power unit's weight to its nominal electrical power and is of interest from a point of view of an evaluation materials consumption of a design and its effectiveness.

Specific weight of power unit's based on kinematic EEFH, depending on a configuration of a drive mechanism and parameters of heat exchanging circuit and working gas, is from 25 to 90 kg/kW$_e$.

Automobile EEFH are known, which are used for a direct torque transfer of a vehicle's transmission. For example, 4-cylinder engines P-40 produced by"United Stirling" company in modifications MOD I and MOD II with a nominal revolution speed 4000 min^{-1} had a specific weight of 5.8 and 3.4 kg/kW, respectively.

In a framework of "SP-100 Space Reactor Program" realized in a period from 1984 to 1993 2 free-piston engines with an external heat input "Space Power demonstrator engine" (SPDE) and "Component Test Power Converter" (CTPC) were created, which were equipped linear electrical generator. SPDE engine with electrical power of 25 kW, which consisted of two balanced and opposed FPSE, possessed specific gravity of 12.7 kg/kW$_e$, and in a flight version a parameter was reduced to 7.2 kg/kW$_e$ [18]. The second-generation engine was created in single-cylinder version and had an electric power of 12.5 kW$_e$. With working temperature of a heater equal to 565 °C and frequency of oscillations of 70 Hz specific weight was 8.7 kg/kW$_e$.

"Infinia" company, which specializes in a development and production solar plants based on FPSE, in 2010 presented a specific weight value of FPSE based power unit under development not exceeding 26 kg/kW$_e$ and specific weight of mass produced unit, according to a preliminary assessment, will be reduced to 16-18 kg/kW$_e$ [19].

Service life

An increase in a service life of a power unit and reduced frequency of maintenance works allows to decrease a downtime of a power unit during time of maintenance, reduce expenses on spare parts, dispensable and operational materials, which, as a result, will reduce cost of generated electricity.

Currently, developers of kinematic EEFH and FPSE declare, that a service life that kind of engines will be from 30,000 to 100,000 hours, or more than 10-20 years. Periodic maintenance of an engine, as a rule, consists of a replacement of seals, filters and lubricants. Some companies provide from 1 to 4 inspections and maintenance works in one year. A design of certain engines with closed and sealed casings allows to operate them without maintenance works for several years.

Duration of work of engine V161produced by "SOLO Kleinmotoren" company between maintenance works is 5,000-8,000 hours. During every second maintenance work regenerator, oil, filters and some parts of a combustion chamber are replaced, and a total service life of an engine is approximately 180,000 hours. [15].

A high service life of FPSE is confirmed by results of test bench trials, which were conducted in "Glenn Research Center" research laboratory, as a result of which a duration of an operation of 16 test engines exceeded 336,000 hours. As a result of tests a technology of FPSE and test equipment, including control systems and in the collection of information were improved [20]. Characteristics of test engine No. 13 are presented in table 1.

Combined power units produced by "Infinia" company based on FPSE, which are designed for electrical and thermal energy production from the solar energy, have a service life of 20 years. At the same time, a service life of an electrical part of a power unit is more than 25 years [21].

Table 1. Comparison of technical characteristics of kinematic EEFH and FPSE

Parameter / Company	Efficiency, %	Specific weight, kg/kW$_e$	Service life, h	Type
«SOLO Kleinmotoren»	25.4	45	180,000	K
«United Stirling» P-40: MOD I MOD II	 35-40 38	 5.8* 3.4*	 – –	 K K
NASA (15 kW)	up to 46	–	50 000	FP
SP-100 Space Reactor Program: SPDE CTPC	– –	12.7 (7.2*) 8.7	60 000 60 000	FP FP
Infinia	32	26 (16-18*)	20 (25*) years	FP
«Glenn Research Center»	26.2	–	54000	FP

* – comments in the text.

Abbreviations: K – kinematic EEFH; FP – FPSE

Other features

Design and arrangement solutions, realized in FPSE, allow to use separate engines as universal modules during an arrangement of power units (figure 6) [19, 22].

Modular design of a power unit provides an ability to create a lineup of power units, which differ in total power, which is multiple of power of one module. Aside from a selection of a total power value of a power unit, a consumer can determine an operating position (horizontal or vertical), which can be provided with an appropriate changes in design of translator suspension system.

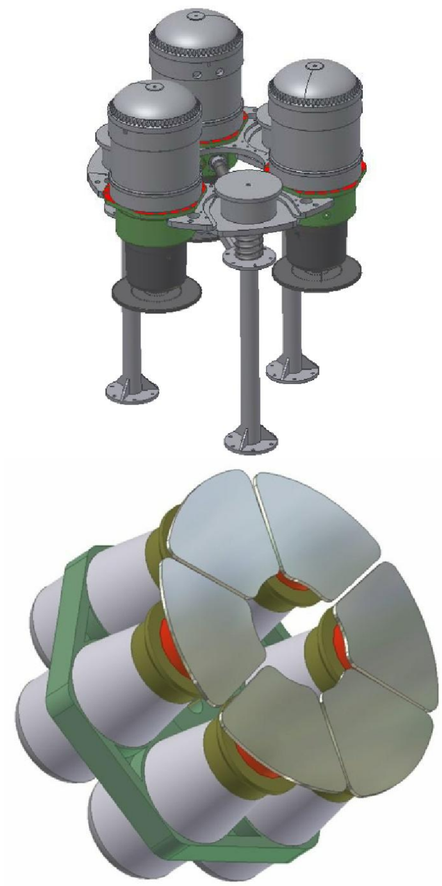

Fig. 6. Variants of an arrangement of modular FPSE

Definition of autonomous power unit concept

For a solution of above mentioned tasks of energy supply decentralization, it is reasonable to create an autonomous and multi-fuel power unit of low power. In order to ensure high parameters of energy-efficiency and consumer qualities of a power unit, its system and components must meet following requirements:

1) Use FPSE as primary engine of a power unit;

2) In order to achieve high effective parameters of an engine, it is reasonable to use helium as a working gas, since it has a small molecular weight and, when mixed with air, in contrast to hydrogen, it is not highly explosive;

3) Design of a heater and a combustion chamber must allow to use gaseous and liquid fuels;

4) An implementation of gas lubricant for a displacer and working piston;

5) Wide use of antifriction coatings of working piston and labyrinth seals with a low force of pressure on walls of piston's cylinder, which material is able to provide long-term work with no lubrication;

6) Joint implementation of flat springs in a suspension system of translator and gas filled buffer chamber;

7) Possibility to control power of FPSE must be provided;

8) Use of electrical machine based on permanent magnets, which is capable to operate in linear electric motor mode during a start of FPSE and in linear electric generator mode and control system of a power unit control a movement of translator;

8) A liquid cooling system of electric power generator must be provided, which will ensure high power and reliability of a generator;

9) System of pressure regulation in working gas, which allows, if necessary, to change amount of working gas in working chambers of an engine, as well as to compensate for any possible leaks.

A realization of presented requirements will allow to create a universal source of energy, which technical characteristics will ensure wide possibilities for an application of in areas where autonomy of energy production, high service life and low impact on environment are required.

Conclusion

In the presented paper a brief overview of engineering solution used in kinematic EEGH and in FPSE is conducted, which are designed for an implementation in an autonomous power units.

On a basis of conducted analysis main points are presented, which define the technical profile of a prospective autonomous power unit based on FPSE, which design would ensure a realization of a set of required energy, economic and environmental requirements.

As a result it should be noted that, nowadays there are no significant technological barriers for an industrial adaptation of FPSE.

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