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Proposal of the new concept of the Stirling engine

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Abstract
The article sets forth the new concept of structure of the Stirling engine. Specific realizations of that idea have been discussed. The modification consists in replacing the crank system with the cam mechanism. As a result, the stages of heating and cooling of working gas are longer and transitory stages are shorter. The aim is to obtain higher efficiency in relation to the already existing solutions and to simplify the engine structure. The visualisation of its structure and the principle of operation have been presented. The proper shaping of the cam mechanism allowed for the change of the significant parameters influencing its efficiency. The use of such type of engine allows for the use of heat energy lost in many technological processes and installations.

Introduction

Robert Stirling invented the first engine of such type and patented it in 1816. The name of the whole family of Stirling engines comes from his name [1]. The principle of operation of that engine consists in the increase of pressure of working gas placed in the heated zone, as a result of which, mechanical work is done connected with the relocation of the working piston. Then, the piston called displacer displaces the working gas to the cooling zone where the gas decreases its volume, and the working piston moves back. Stirling engine is a reversible machine. It means that it can process both thermal energy into mechanical energy, and work as a cooling or heating machine powered with mechanical energy. The inventiveness of the new concept of the engine consists in the use of the cam mechanism instead of the crank system in a way increasing engine efficiency and simplifying its structure.

Comparing the proposed engine with other Stirling engines

In known varieties of Stirling engines, the crank system or a system working on a similar basis, coupling the movement of the piston with the movement of the displacer, occurs the most frequently. In Stirling engines the heat exchange is most intense when the displacer is in its extreme positions. In classic Stirling engines, such a situation occurs for short moments during the cycle of engine operation [2]. The disadvantage limiting the efficiency of classic Stirling engines is a short time of intense heat exchange.

Figure 1 presents the diagram of structure of the Stirling engine. In order to extend the time of intense heat exchange, the time during which the displacer is in extreme positions should be extended. Achieving such an effect was possible thanks to the use in the proposed engine the cam mechanism instead of the crank system. Such a change creates the possibility of the better use of heat and the improvement of engine efficiency. It also allowed to simplify significantly its structure. In the simplest version, it has only one movable element. Another disadvantage of the majority of known varieties of Stirling engines is the necessity to seal many movable elements. In the proposed engine, there is only one such seal (piston seal). The simpler structure allows for: the improvement

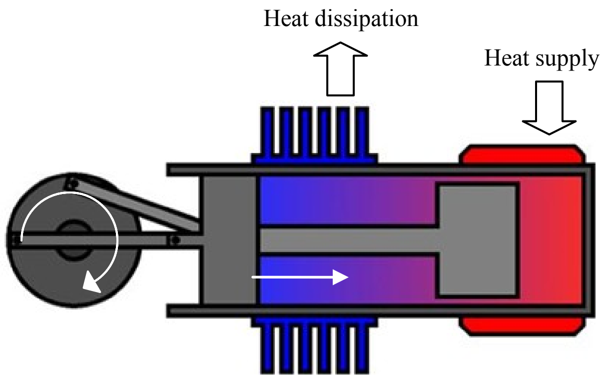

Fig. 1. Demonstration diagram of operation of the Stirling engine [3]

of operating parameters, the simplification of the production of such engines, the decrease of costs. The exact evaluation of mechanical losses and the efficiency of the invented engine, as well as the comparison of those parameters with the parameters of other varieties of Stirling engines will be possible after the creation of a mathematical model. Creating the mathematical model, and then the prototype, will be the next stage of works over the proposed engine.

Advantages and uses of Stirling engines

At present, ecology is of primary concern. Looking for savings is an equally important factor forcing to implement innovative solutions. In many industrial plants, devices and installations, heat energy is lost. An innovative solution is the use of Stirling engines for the use of heat energy. They can operate with relatively small temperature differences [4]. Small models of Stirling engines are built which use the heat of human hand for operation (Fig. 2). Hence, they can be used in places

Fig. 2. A model of the Stirling engine using the heat of human hand to operate [5]

where a steam turbine cannot be used. They can work powered with any type of heat source. The burning of any fuel can be such a source of heat. External burning can be a much better controlled process than it is in engines with internal combustion. It allows for maintaining low toxicity of combustion gases. Solid, liquid and gaseous fuels can be used. It allows for creating, on the basis of the Stirling engine, a generator that will supply mechanical or electrical energy from the combustion of any fuel. Hence, it can be a perfect generator in a situation when access to conventional fuels is hindered. Other sources of heat include fermentation processes or for instance the server room cooling system. Stirling engines are also used in isotopic power units. Such devices use the spontaneous disintegration of radioactive elements. They can operate for a very long time without significant decrease of power. In lunar missions Apollo 12–17 the isotopic power unit SNAP-27 was used. It contained 3.8 kg plutonium 238. After 10 years of operation of the power unit, the decrease of power in relation to rated power (70 W) amounted to less than 10%.

As already mentioned, different types of Stirling engines were invented quite a long time ago. They did not gain much popularity due to the poorly developed material engineering. There were no materials with good mechanical parameters and suitable thermal conductivity. That significantly decreased their efficiency. At present, the Stirling engines have a much higher efficiency (approx. 40%) and are used more and more frequently. High efficiency of those engines results from the fact that the cycle of the Stirling engine have become very similar to the Carnot cycle [6]. Solar power plants are built using Stirling engines, with the efficiency of approx. 30%. It is twice as much as in the case of photovoltaic cells. It needs to be mentioned here that the disposal of photovoltaic cells is additionally complicated, much more expensive and less environmentally friendly than it is in the case of a Stirling engine made of easily recyclable materials. Figure 3 presents an example of a solar power plant operating based on Stirling engines.

Stirling engines work well as elements of combined heat and power producing heat and electricity. They significantly improve the efficiency of such installations. Based on Stirling engines, also geothermal power plants can be built. Deflagration takes place in Stirling engines thanks to which they operate smoothly and noiselessly. Due to the specificity of work, they were used for quiet drives of submarines. Figure 4 presents HMS Gotland submarine with the drive using Stirling engines. Hence,

Fig. 3. The solar power plant using Stirling engines [8]

Fig. 4. HMS Gotland submarine with the drive using Stirling engines [9]

they can be used in places where a steam turbine cannot be used. They can work powered with any type of heat source. The burning of any type of fuel can be such a source of heat. Such external burning can be a much better controlled process than it is in engines with internal combustion. It allows for maintaining low toxicity of combustion gases. Solid, liquid and gaseous fuels can be used. It allows for creating, on the basis of the Stirling engine, a generator that will supply mechanical or electrical energy from the combustion of any fuel [7].

In all mentioned uses the proposed engine can be used. The engine can be used in high, as well as in low power systems. In high power systems the engine needs to have suitably large dimensions.

Discussion on structure and the principle of operation of the proposed engine

The cycle of operation of the proposed engine consists of two stages: heating and cooling. During the heating stage, the working gas is heated as a result of what its volume is expanded and the piston is pushed out. In the final phase of pushing out the piston, the displacer rotates by 180 degrees, and then the cooling stage occurs. Cooling of the working gas causes the decrease of its volume and the moving back of the piston. In the final phase of the moving back of the piston, the displacer rotates by 180 degrees and the heating stage occurs again. In the simplest version, the proposed engine (Fig. 5) [10] has only one movable element. That element consists of a working piston (3), a displacer (5), slider of the cam mechanism (10) and a shaft (1). Those parts are connected axially. The immovable element (4) consists of a cylinder (2), in which the working piston moves, the regenerator chamber (9), in which there the displacer is located, and the cam mechanism channel (13) made in the tube in which the slider (14) of the cam mechanism moves (10). Cam mechanism channel is shaped in such a way so that the slider moving in it moved, during bigger part of the piston movement, in a straight line. Due to the slider's movement in a straight line, the displacer does not rotate. Thanks to that, the stages of engine operation, where working gas is heated or cooled, are longer, and transitory stages are shorter. In the final stage of slider's movement

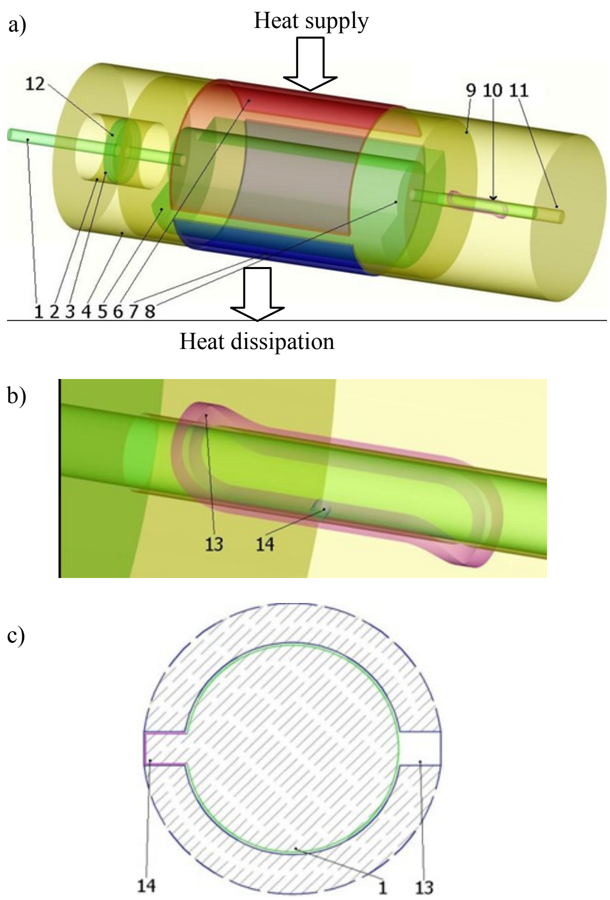

Fig. 5. a) View of the engine in the middle phase of the heating stage, b) view of the cam mechanism; the slider in the position corresponding to the middle position of the piston during the cooling stage, c) the cross section of the cam mechanism; the slider in the position corresponding to the middle position of the piston during the cooling stage

in the cam mechanism channel, the displacer rotates by 180 degrees and the engines proceeds to the next stage of operation. Figure 5 presents the view of the engine with numbered elements in the middle phase of the cooling stage. The displacer covers the cooled part of the regenerator (7), the gas inside the engine is heated and expanded causing the pulling out of the piston.

Description of elements (Fig. 5): 1 – engine shaft, 2 – cylinder, 3 – piston, 4 – engine immovable element, 5 – displacer, 6 – heated part of the regenerator, 7 – cooled part of the regenerator 8 – balancing element, 9 – regenerator chamber, 10 – cam mechanism, 11 – tube, 12 – O-ring, 13 – cam mechanism channel, 14 – slider. During the heating stage, the displacer completely covers the cooled part during the bigger part of pulling out of the piston when due to the operation of the cam mechanism the shaft is set into rotary movement and rotates by 180 degrees. This causes the rotation of the displacer and the passing to the cooling stage. Figure 6 presents the view of the engine during the movement of rotation through the shaft with the displacer. The piston is pulled out as much as possible.

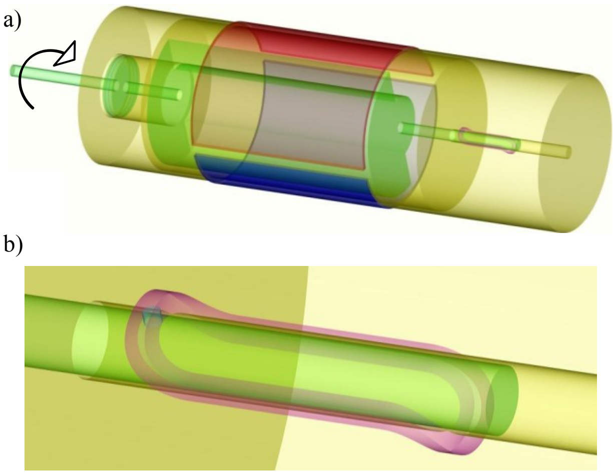

Fig. 6. a) View of the engine doing the rotary movement; the piston is pulled out as much as possible, b) view of the cam mechanism; the slider is in the location corresponding to the maximum position of the pulled out piston

After doing the rotation of the displacer by 180°, the heated part of the regeneration is completely covered, while the cooled part is uncovered, that is the cooling stage begins. It causes the decrease if gas volume inside the regenerator and the moving back of the piston. Figure 7 presents the initial phase of the cooling stage.

During the cooling stage, the displacer completely covers the heated part till the moment when due to the operation of the cam mechanism the shaft is set into rotary movement and rotates by 180

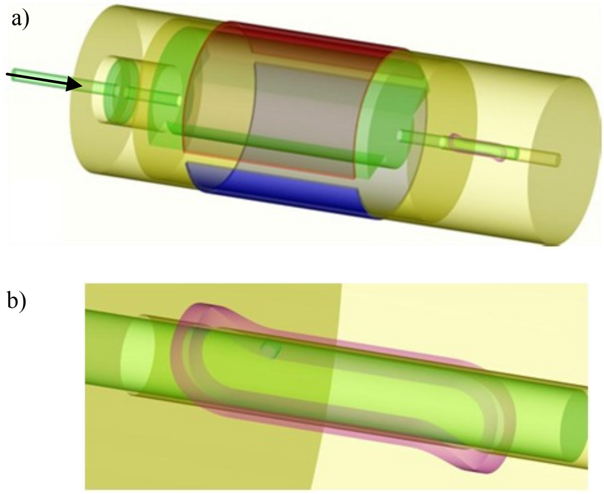

Fig. 7. a) View of the engine in the initial phase of the cooling stage, b) view of the cam mechanism; the slider is in the location corresponding to the location of the piston in the initial cooling phase

degrees. This causes the rotation of the displacer and the passing to the heating stage. Figure 8 presents the view of the engine during the movement of rotation through the shaft with the displacer. The piston is moved back as much as possible.

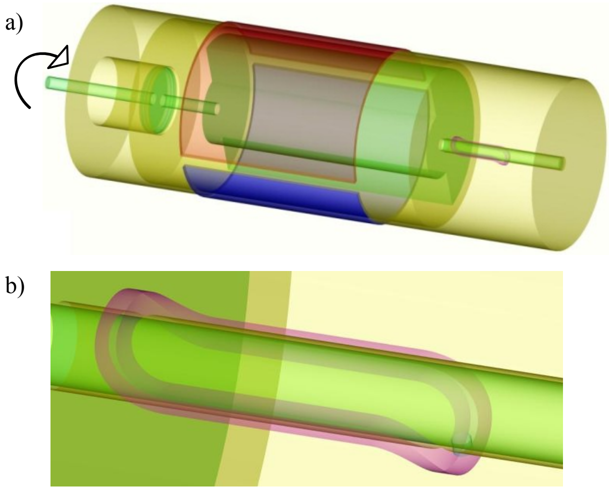

Fig. 8. a) The view of the engine during the movement of rotation through the shaft with the displacer; the piston is moved back as much as possible, b) view of the cam mechanism; the slider is in the location corresponding to the maximum position of the moved back piston

When the heating stage begins, the cycle of engine operation repeats. Figure 9 presents the view of the engine in the initial phase of the heating stage.

The heating circulation of the proposed engine is more similar to the theoretical circulation than the classic circulation of the Stirling engine. Transitions between the stages of heating and cooling of gas are fast in the final phases of piston movement. It causes fast changes of pressure. Thanks to that,

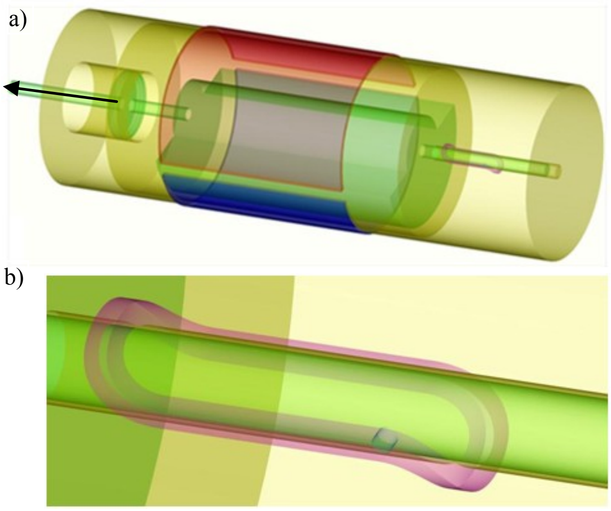

Fig. 9. a) View of the engine in the initial phase of the heating stage, b) view of the cam mechanism; the slider is in the location corresponding to the location of the piston in the initial heating phase

similarly as in the case of the theoretical circulation, it is possible to differentiate four transformations typical for the Stirling circulation.

The comparison of thermal circulation of the proposed Stirling engine and the classic Stirling engine with theoretical circulation is presented on figure 10, critical points of transformations are numbered.

- During a transformation gas is heated and its volume is increased. The view of the invented engine and the location of the cam mechanism slider during that transformation is presented on figure 5.
- During transformation 4–1 gas heating stage passes to cooling stage. The view of the invented engine and the location of the cam mechanism slider during that transformation is presented on figure 6.
- During transformation 1–2 gas is heated and its volume is decreased. The view of the invented engine and the location of the cam mechanism slider during that transformation is presented on figure 7.
- During transformation 2–3 gas cooling stage passes to heating stage. The view of the invented engine and the location of the cam mechanism slider during that transformation is presented on figure 8.

In case of big engines of such type there can be a problem of the piston rubbing the cylinder, resulting from the rotary movement of the piston, and the parasitic capacitance of the working gas resulting from the to-and-fro motion of the displacer in the regenerator. A solution to such problems can be to mount a bearing on a piston in relation to the shaft and fasten the displacer on the shaft in such a way that it can slide with the use of splines (in order to eliminate the to-and-fro motion of the displacer). In order to minimize heat losses, all elements, apart from the heated and cooled parts of the regenerator, in particular the displacer, should be thermal insulators. The heated and cooled parts of the regenerator should be, as far as possible, good thermal conductors.

Conclusions

The proposed engine differs from the majority of Stirling engines in simpler structure thanks to the replacement of the crank system with the cam mechanism. The proper shaping of the cam mechanism allowed for the improvement of the significant

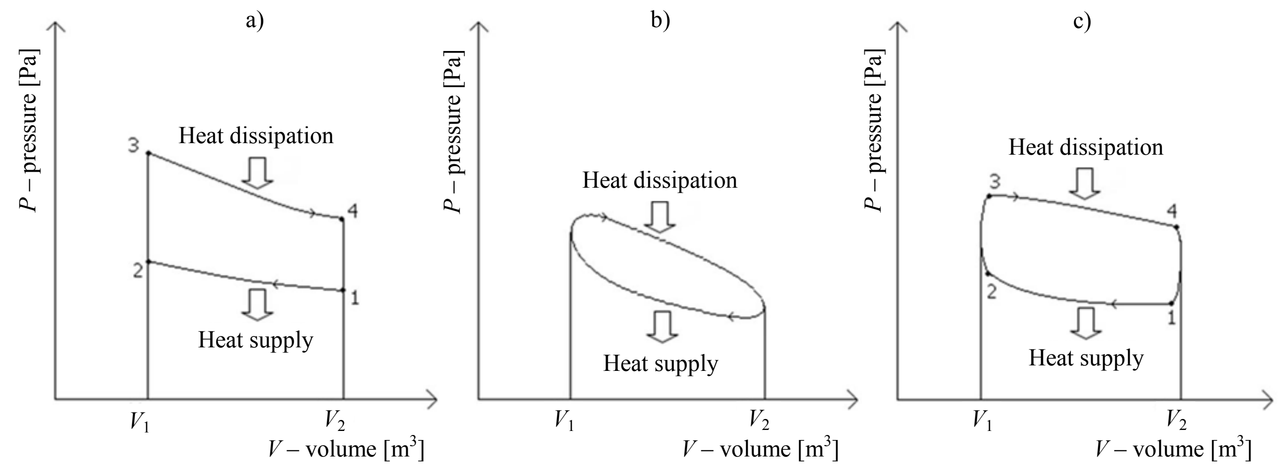

Fig. 10. a) Theoretical thermal circulation in a Stirling engine, b) actual thermal circulation in a Stirling engine, c) thermal circulation of the proposed Stirling engine

parameters influencing engine efficiency. The use of such type of engine allows for the use of heat energy lost in many technological processes and installations. Based on such an engine, generators can be built producing power from the combustion of any fuel, regardless of its physical state, or from untypical heat sources, such as for example the disintegrations of radioactive elements. They can supply energy in a situation when there are no conventional fuels. The use of Stirling engines in solar, geothermal and other power plants allows for a more efficient use of those sources of energy. Due to low production costs and simplified use in relation to other varieties of Stirling engines, this one has a big chance to be implemented.

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