Studying a low-temperature engine with external heat supply

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Abstract. The article presents some results of studying the most optimal parameters of the displacer and the piston of a low-temperature engine with external heat supply to increase its efficiency when converting low-grade heat. The developed design of the engine does not have a displacer rod, which provides better sealing and reduces mechanical friction losses. Synchronization of the piston and the displacer movement is ensured by the permanent magnets interaction. The analysis of the results of computer simulation of the PV diagram with an increased diameter of the displacer in relation to the piston diameter plays a positive role in increasing the efficiency and power of the engine. Increasing the diameter of the displacer also leads to increasing the area of the PV diagram and its approach to the ideal thermal Stirling cycle. The simulation results show that increasing the diameter of the displacer above 17/1 does not lead to increasing the area of the PV diagram, and with a larger ratio, on the contrary, it reduces the parameters of the engine efficiency. Further increasing the diameter of the displacer is not advisable in terms of technical and economic ratios. The proposed engine with external heat supply is capable of converting heat from geothermal or industrial wastewater, as well as heated water using a solar collector.

1. Introduction

The Stirling engine (SE) has been in use for over 200 years; this type of engine belongs to the type of engines with external heat supply (EHSE). Analysis of the literature shows that scientists and engineers are still working at improving and developing various designs. There is a certain progress in the development of fairly effective designs of well-known world manufacturers of the SE, such as Philips, STM Inc., Daimier Benz, Solo, United Stirling [1, 2]. Particular success was achieved by Philips that produced compact electric generators based on an external heat supply engine operating according to the Stirling cycle with the efficiency of about 40% that is not yet achievable for a modern internal combustion engine (ICE) [1, 2]. There are certain unavoidable circumstances that did not allow piston diesel engines becoming widespread in comparison with internal combustion engines. The SE has a number of significant advantages over the ICE [1–3]. Now there have been developed free-piston and thermo-acoustic diesel engines, which have high efficiency and advantages in
comparison with internal combustion engines and piston diesel engines, for example, one can note the development of the NASA [3]. SEs or EHSEs can be used to generate electrical energy for autonomous consumers, for example, to rotate a synchronous electric alternator. Various designs and basic provisions for the development of EHSEs, as well as prospects of their use are discussed in detail in works [4–14]. There is a known method of converting thermal energy into electric current using Peltier elements [4], but they have low efficiency, especially with low-temperature heating up to 90 °C. The development of simple design and effective converters of low potential heat into electric current capable of operating in the temperature range from 80 to 90 °C is urgent. The task is to develop our own design of a thermoelectric converter based on a piston EHSE capable of converting low-potential heat into mechanical energy with a high efficiency at the working fluid heating temperature in the range from 80 to 90 °C, for subsequent generation of electrical energy.

2. Experimental study results

The development of our own design of a thermoelectric converter is based on a piston EHSE using the previously known information [1–3]. Figure 1 shows a diagram of the utility model of a EHSE with the longitudinal section indicating the main positions of the structural elements of the engine with external heat supply.

![Figure 1. A diagram of a utility model with the longitudinal section indicating the main positions of the EHSE design elements.](image)

The prototype was manufactured within the framework of the project "Micro thermal power plant of the coherent type with heat recovery" (No. AP05131751). The EHSE contains heater 1 and cooler 2; displacer 3; working cylinder 4; piston 5 equipped with O-rings 6; bracket for mounting piston 7; rod 8; flywheel hub bearing 9; crank mechanism 10 with a rod fastening washer; flywheel 11; permanent magnet 12; separating heat-insulating ring 13; flywheel hub bearing support 14; regenerator 15; compression cavity 16; expansion cavity 17. The external view of the utility model indicating some positions of the structural elements of the engine with external heat supply is shown in Figure 2. The cooler, the heater and the working cylinder are made of duralumin disks. The cooler can be conventionally designated as a "Cold heat exchanger", which operates in the temperature range from 20 to 30 °C, and the heater as a “Hot heat exchanger” operating in the temperature range from 80 to 90 °C. In the future, there can be used water heated in the solar collector that will be supplied to the "Hot heat exchanger", and cold water will be supplied to the "Cold heat exchanger". The working
cylinder has convection fins on the lateral surface, which improves heat removal and cooling the working fluid and the cylinder itself. To reduce the frictional force of the piston against the cylinder wall, it is made of graphite. The piston is fitted with fiberglass O-rings to seal the interior and ensure tightness. Ensuring tightness is important in achieving a high efficiency of the EHSE, as well as its power. The displacer is in the form of a disc and is made of extruded polystyrene foam. Transparent plastic was used to make the flywheel.

![Figure 2. The utility model physical form.](image)

All the elements of the crank mechanism are made of mild steel. The cooler and the heater are separated by a transparent plastic ring for thermal insulation. Air is used as the working medium, but experiments with helium have shown that the engine power increases up to 3 times, respectively; air is a less efficient working medium. If the temperatures of the heater and the cooler become equal, the engine will stop running. Good cooling from the cooler side is important for this engine. The higher is the temperature difference between the heater and the cooler, the higher is the engine power and efficiency. The expansion cavity is formed on the heater side, and the compression cavity is formed on the cooler side. The regenerator is made of steel wires with cells with the diameter of 1–2 mm and is designed to accumulate heat and to increase the efficiency of the engine. The working fluid circulates constantly through the regenerator, moves from the expansion cavity to the compression cavity, giving it a part of its heat. Accordingly, cooling the working fluid in the cooler is improved. The principle of operation of the EHSE and SE is described in detail in works [1, 2]. The design difference from the known engines with external heat supply is the absence of the displacer rod, which improves tightness and reduces friction losses in the seals. The design change consists in the following. In the lower part of piston 5 there is permanent magnet 12, a similar magnet is located on the upper part of displacer 3. Accordingly, when piston 5 moves downward and approaches the lower point of working cylinder 4, the permanent magnets of piston 5 and displacer 3 are attracted, while displacer 3 rises upward, moving the working fluid from the compression cavity into the expansion cavity. The working medium is moved from cooler 2 to heater 1. The working medium heats up and expands again, pushing piston 5 upward, while the displacer is in the extreme upper position at cooler 2. When piston 5 moves to the extreme upper point of cylinder 4, the force of attraction of the magnets weakens, the displacer is lowered onto the surface of heater 1, while the working fluid is displaced from the expansion cavity into the compression cavity. The cycle is repeated many times, thanks to synchronization by means of rotating flywheel 11. The movement of the working piston is shifted by 90° relative to the movement of the displacement piston. With a 0° shift, the engine does no useful
work. Flywheel 11 allows starting the engine and facilitates the passage of crank mechanism 10 through the dead zone and the piston return to the lower position. Support 14 is used to mount the flywheel hub bearing. The engine starts up as follows: when the working medium heats up to the temperature of 80 to 100 °C within 30–40 seconds, it is needed to turn flywheel 11 clockwise several revolutions, after which the engine starts working, and its flywheel 11 rotate. The rotation speed depends on the temperature difference between heater 1 and cooler 2. The absence of displacer rod 3 and its synchronization is ensured with flywheel 11 due to the attractive force of permanent magnets 12, which eliminates mechanical losses due to friction of the rod against the seal, better sealing of compression cavity 16 and expansion cavity 17; working piston 5 is made of graphite and equipped with three glass fiber O-rings 6.

Figures 3 and 4 show the results of computer simulation of the Stirling heat cycle PV diagram [2]. The change in the design of the displacer and the heater concerns their diameters, they are increased in relation to the piston diameter by the factor of 10, this makes it possible to reduce significantly the heating temperature from 80 to 90 °C, which is not achievable for classical SE designs that operate from the open flame temperature, which is four and more times higher. The PV diagram of the Stirling thermal cycle is the dependence of the pressure and volume change of the working fluid with changing the position of the piston and the displacer. The program included the geometric parameters of the utility model of the engine with external heat supply shown in Figure 2.

![Figure 3](image1.png)

**Figure 3.** The results of computer simulation of the PV diagram with the displacer diameter increased in relation to the piston diameter by the factor of 10.

![Figure 4](image2.png)

**Figure 4.** The results of computer simulation of the PV diagram with the displacer diameter increased in relation to the piston diameter by the factor of 3.

The boundary and initial conditions of modeling the movement of the working piston are shifted by 90° relative to the movement of the displacement piston, respectively, the displacer moves ahead, the
working piston follows it [1–3]. The cooler temperature is 25 °C, that of the heater is 90 °C. The minimum working fluid pressure is 99500 Pa, the maximum pressure is 122900 Pa, the developed mechanical power is about 1.8 W.

The generated power of the low-temperature DVPT directly depends on many factors, in particular, on the number of shaft revolutions, which must be stabilized and kept within 300 rpm (Figure 5), when the speed drops below the specified value, the power will decrease, which will negatively affect its efficiency. Experiments have shown that the proposed design can develop a rotation speed of up to 500 rpm, a positive point is the reduction of mechanical friction losses within 30% compared with known designs. Figure 6 shows the derived dependence of the excess of the volume of the displacer over the volume of the working piston; the recommended ratio may be 40/1.

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![Figure 5. The EHSE electrical power dependence on the shaft rotation frequency.](image-url)
3. Conclusions
Analyzing the results of computer modeling of the PV diagram with an increased diameter of the displacer in relation to the piston diameter plays a positive role in increasing the efficiency and power of the engine, as well as increasing the area of the PV diagram and bringing it closer to the ideal Stirling thermal cycle. Simulation shows that increasing the diameter of the displacer above 40/1 does not lead to a significant increase in the area of the PV diagram, and with a larger ratio, on the contrary, it reduces the parameters of the engine efficiency and a further increase in the diameter of the displacer is not advisable in terms of technical and economic reasons. With increasing the temperature of the working fluid from 90 to 150 °C, decreasing the area of the PV diagram is observed, but the pressure increases, which leads to increasing its power but decreasing its efficiency. Improving the efficiency of a low-temperature engine with external heat supply operating in the temperature range of the working fluid from 80 to 90 °C consists in optimizing its geometrical parameters but not in increasing the heater temperature.

Accordingly, a low-temperature engine with external heat input can convert low-grade heat energy in the range from 80 to 90 °C into mechanical energy, and then into electrical energy. The proposed engine with external heat supply is capable of converting heat from geothermal or industrial wastewater, as well as water heated with the use of a solar collector.

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