Analysis of properties of a laboratory model of a Gamma Stirling engine

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The main subject of the article is the analysis of the characteristics of a Stirling engine. The article presents a general principle of operation of the engine, its basic types and properties. The paper contains a description of the construction of a laboratory model of the engine and the results of the experimental studies. The basic criterion which guided the designing and building the engine was to maximize the energy density, efficiency, while minimizing the cost of materials – to this end the engine has been designed and constructed so as to allow replacement of particular components. The conducted experimental studies have shown that the best parameters of the engine has a cylinder made of iron, a steel flywheel and a steel radiator. The brake efficiency of the engine for this configuration was 16%.

Key words: Stirling engine, efficiency, mechanical power.

Introduction

Due to rising energy prices there is a need to seek and develop technologies enabling to improve energy balance at the final consumer, so-called prosumer. Unfortunately, the high prices of diffused generation systems of low power (both wind and solar) and the lack of simple and effective solutions for the electronic coupling systems, inhibit the development of such solutions on a large scale.

As in many situations heat is a waste (not in any way used) in the search for low-cost ways to save energy, we are looking more and more frequently towards the solutions, in which heat is converted into a useful form of energy — electricity. The answer to this type of demand may be a Stirling engine, which use wasted heat with low technical parameters to produce electricity.

Stirling engines are a type of heat engine in which the temperature difference is used to convert heat energy into mechanical energy. The history of these engines goes back to the early nineteenth century. It was not until the mid-thirties of the twentieth century, when the interest in this construction has increased, when Philips was looking for a silent source of power for generators to supply radios in the field conditions [9]. And it is this property of the Stirling engine that has been used in their application to the propulsion of submarines. Because of the possibility of using any source of heat and acoustic properties, this kind of energy converter may find application particularly there where large amounts of wasted heat are found, for example: heating buildings by the stoves. In addition, the use of such solutions perfectly becomes the part of measures designed to improve the energy efficiency of buildings as expressed in the directive [1], where the Stirling engine has been included as one of the solutions of systems of high efficiency cogeneration.

Stirling engine — the principle of action, properties

Thermal circuit with a considerable degree of simplification, consisting of a number of thermodynamic transformations is called a theoretical circuit, the example of which is the Carnot cycle (Fig. 1).

The implementation of this course is impossible — because the engine would have to have a perfect parameters. Still, this model can help in the initial stages of design, or a simplified description of the operation of the engines already existing.

During subsequent cycles of thermal cycle, the thermodynamic factor, which is an ideal gas, is subjected to changes, in which heat exchange is conducted between the gas and the environment:

- Cycle 1. Isothermal compression at temperature T_K even temperature heat source, usually a factor that gives off heat to the cooler.
- Cycle 2. Adiabatic compression is the gas heating to achieve a temperature T_H equal to the temperature of the upper heat source.

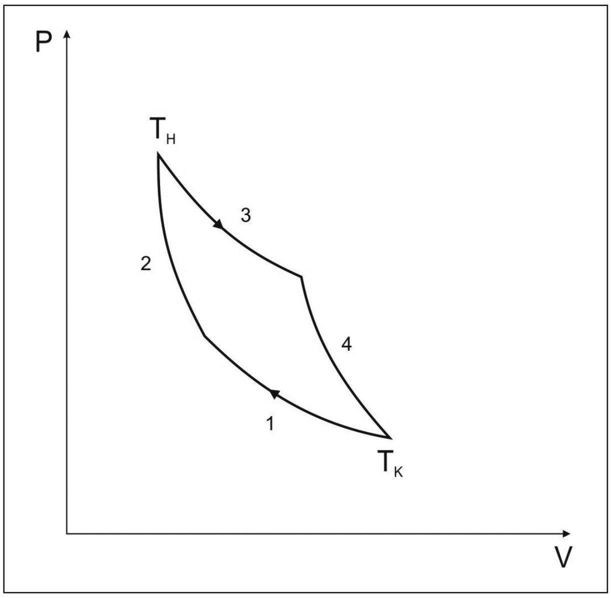

Fig. 1. Carnot thermodynamic cycle Symbols: P — [Pa], V [m³].

- Cycle 3. Isothermal expansion at T_H temperature causing reversion of gas volume to its initial value V1.
- Cycle 4. Adiabatic expansion — the working factor is expanded without changing the heat until to achieve the cooler temperature T_K.

Stirling engine belongs to a group of external combustion engines, which means that the fuel is burned outside the engine. Exhaust fumes or other medium are supplied to drive the system. In this particular type of engine, there is no need to burn the mixture, but only to ensure proper temperature needed to start up. It can be electric heating, the application of object or a material with higher temperature, as well as the light flux of sufficient intensity.

The engine circuit may occur as a closed system, which allows for the same mass of working gas participated in all cycles without exchanging it with the outside, so with the gas from the outside of the engine compartment. The system allowing to better understand the Stirling engine working is a piston engine with a single cylinder, in which a constant mass of gas is alternately compressed and expanded, under the influence of linear progressive — return movement of the piston (Fig. 2). The intense cooling of the cylinder during compression is necessary to the proper working which assure isothermal transformation. Stopping the piston at top dead point and at the same time providing heat allows to perform isochoric transformation 2–3. Isothermal expansion is another transformation by intense heating of the cylinder 3–4. The cycle closes when the piston reaches bottom dead point during the isochoric transformation 4–1. Accomplishment of such an engine from a practical point of view is currently unrealizable, because it would require the application of a special drive mechanisms that allow the interrupted movement of the piston [2].

Taking into account all the factors based on Figure 2, the Stirling engine should be characterized by [2]:

— continuous movement of the piston;

— the full exchange of the mass of gas from an area of the low temperature of the piston to the high temperature as well as vice versa, without changing its volume (closed system);

— the best carried out the heat regeneration process.

Isochoric heat regeneration can be achieved by using a material with a porous structure and high heat capacity [2]. Appropriately shaped material placed between cold and hot space is called the regenerator. The regenerator can be located inside the cylinder (and even the piston) as well as outside [2]. The use of this element reduces the losses associated with the exchange of heat energy and thus increases the efficiency of the whole system [2]. Moving the working gas between the compression and expansion space is realized in a single action engines with two pistons moving in cycles.

In addition, this solution assures compression in time when the whole mass of gas is in the cold space of the cylinder and expansion, when the whole mass is in the hot space. Realization of such an action can be achieved by using an appropriate phase shift between movements of two pistons.

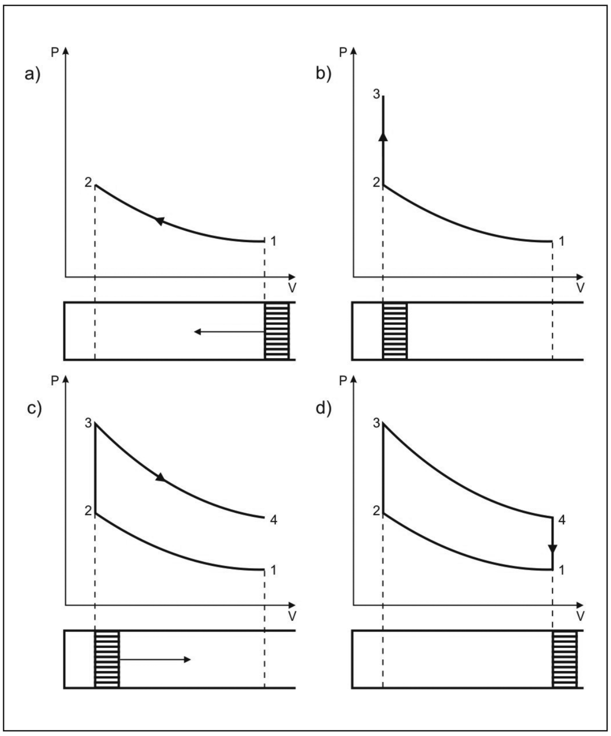

Fig. 2. The movement of the single piston during closed cycle [2] Legend: P — pressure, V — volume.

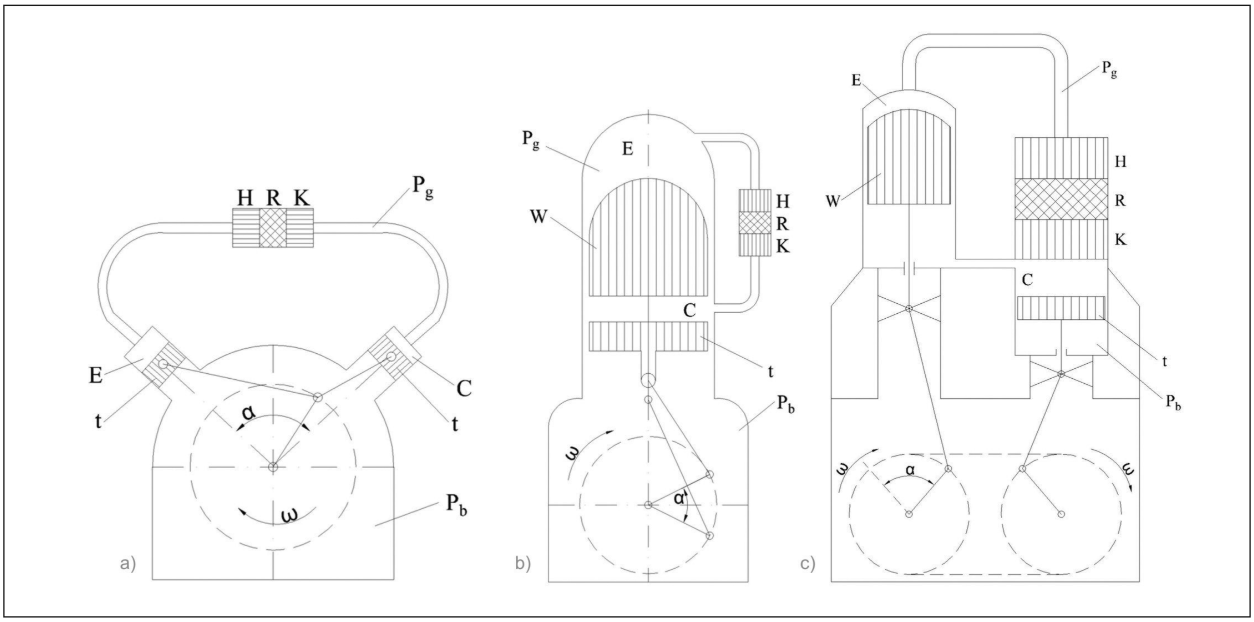

Fig. 3. The Stirling engine construction solutions: a) — type α, b) – type β, c) – type γ. Symbols: w — support, t — piston; P_g — gas pressure, P_b — pressure in the buffer, C — compression space, E — expansion space, H — heater, R — regenerator, K — cooler, α — phase angle; ω — angular velocity, t — piston, W — displacer. [2].

Types of Stirling engines

Stirling engines lived to see many different design solutions, which is evident in (Fig. 3). Here are three common types of engines which can be found in the literature [2].

a) Alpha type engine

The engine has two cylinders, inside of which two pistons work on one side loaded with variable working gas pressure *pg*, and on the other side with a constant gas pressure *pb* prevailing in the so called buffer. There is a required phase shift α of pistons oscillating around 85°–120°. It is important that when composing this type of engine components and kinematic working mechanism and the engine block must be positioned so that the working piston in the hot space outruned the movement of the piston, which works in the cold space by an angle α. Spaces of cylinders over the pistons are connected together by means of the heater *H*, regenerator *R* and cooler *K*.

b) Beta (classical) type engine

The engine has a cylinder in which two pistons move coaxially with the required phase shift by an angle α. The upper piston moves in the engine workspace pumping the gas twice during the cycle between compression and expansion space by a set of heat exchangers. Owing to this the engine is loaded only by the difference of pressures resulting from the gas flow through heat exchangers and created as the result of resistance. The set of these exchangers is connected to the compression and expansion space and buffer is located under the piston *t*. the movement of the lower piston, which is delayed by an angle α phase, implements compression and expansion of the working medium, pumped properly in the compression space *C* (cold part) and expansion space *E* (hot part).

c) Gamma (classical) type engine

The Gamma engine is the simplest and easiest type of Stirling engine to do at home [10]. This type of configuration with double-acting piston arrangement has theoretically the highest possible mechanical efficiency and also shows good self-pressurization [3]. The kinematic engine with a normal 90° phase angle is a gamma configuration engine [4]. Just as in the Beta system, the Gamma system has two cylinders (sometimes there is one large and one small), in which one is built-in by the channels connecting the set of exchangers. Cylinders must not be parallel, depending on the construction solutions they can be to each other in an oblique or perpendicular surface. Setting into motion this type of engine can happen with low heat, as compared with conventional Beta and Alpha solutions. The sufficient source of heat to run the machine can be a cup of hot water.

Project and construction of a Labolatory Model

During the construction of laboratory model engine, one was guided by the criterion of minimizing material costs and maximizing the efficiency of conversion of heat energy into mechanical. Therefore, the model of the Stirling engine was designed and constructed in such a way as

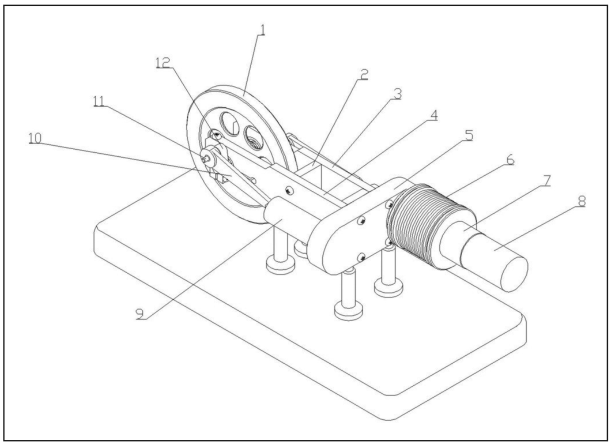

Fig. 4 Laboratory Model of Gamma type Stirling engine: 1 — flywheel, 2 — stiffening bar, 3 and 4 — supports, 5 — faceplate, 6 — cooler, 7 — regenerator, 8 — heater, 9 — working cylinder, 10 — rod, 11 — crank of the working piston, 12 — crankshaft.

that there is a possibility to replace of particular components [5]. In the conducted researches, it was decided to choose the gamma engine (Fig. 4), because this construction combines simplicity and efficiency, and it is characterized by easy replacement of components [5]. This engine consists of fewer elements that are easier and cheaper to perform than in the case of Beta type engine where working arrangement of the pistons is complicated and in the Alpha type engine, where the crankcase is a difficult feature to perform. The elements of the engine were made with an accuracy of 0.01 mm, as they must work together with minimal friction resistance, which has a significant impact on power and engine efficiency.

As mentioned thereof, in order to find the most efficient solution (in terms of maximizing the energy density, efficiency, and minimize the cost of materials), the Stirling engine model is made in such a way as to allow the replacement of its components: the flywheel, the radiator, the heater. The conducted researches included the setting of power and engine efficiency in each configuration (material and dimensional) [6]. At each stage of the research, there was used a different configuration of replaceable parts, such as for iron and steel cylinder, the dimensions of which are following: diameter 34 mm, length 140 mm, there were carried out the studies replacing particular parts: the steel flywheel 640 g with the moment of inertia I = $1352 \cdot 10^{-6}$ kg·m^2 and the aluminum flywheel 295 g with I = $6231 \cdot 10^{-7}$ kg·m^2, the diameter of the flywheels is 130 mm, aluminum radiator (A) with an outside diameter 60 mm, steel cooler (B) with an outside diameter 60 mm, aluminum radiator (C) with an outside diameter 76 mm, steel cooler (D) with outside diameter 76 mm.

Cylinder with length of 76 mm and diameter of 20 mm and working piston with length of 25 mm and diameter of 20 mm were not replaced. The tested laboratory model is characterized by additional parameters such as: the working piston stroke $314 \cdot 10^{-6}$ m^3 and displacer $730{,}25 \cdot 10^{-6}$ m^3, the size of the dead volume $42943 \cdot 10^{-9}$ m^3 and volume of displacement cylinder $69232 \cdot 10^{-9}$ m^3.

A gas burner was used as the heat source (Fig. 5). Taking into account the heat of combustion of propane-butane, H = $34{,}39 \cdot 10^6$ J/kg [11], the mass of burned gas Δm = 0,071 kg was designed the energy provided by the burner in one engine cycle W_H. Where e_m stands for the effective heat transmitted.

Fig. 5. View of laboratory gas burner.

According to the above, the efficiency of the burner, which is 30%, was designed what describes the formula (1). (Fig. 5) below presents the laboratory model of the Gamma Stirling engine type.

$$\eta = \frac{e_{ht}}{W_H} \cdot 100\% \quad (1)$$

The results of experimental researches

The subject of the research was a Stirling engine with replaceable elements. Their main objective was to determine the best configuration of particular parts so as to achieve the best parameters of the engine. One of the necessary elements to carry out the research was to survey: the number of revs per minute by means of tachometer and strength using a dynamometer, the application of which does not cause deceleration of the flywheel, but its slowdown.

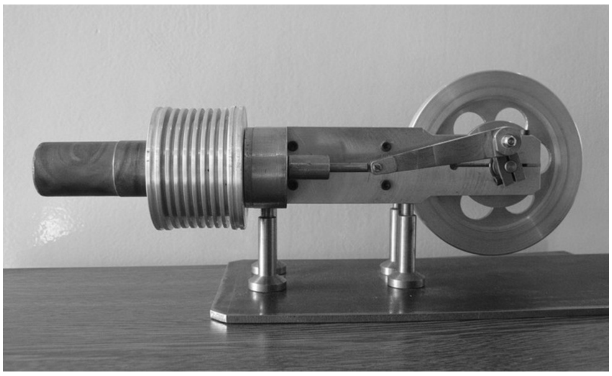

Fig. 6. Laboratory Model of Gamma Stirling engine type.

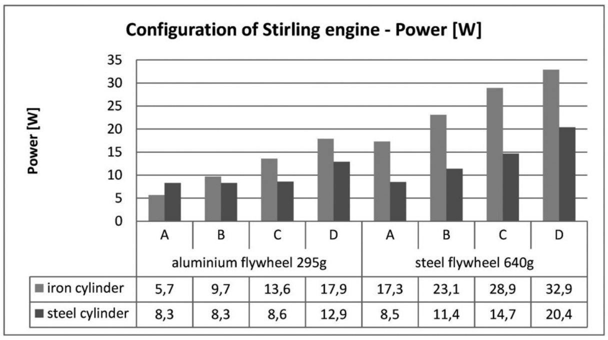

Fig. 8. Mechanical power of the engine in different configurations of replaceable elements.

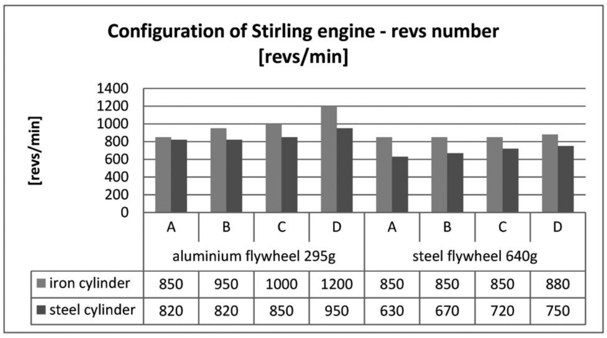

Fig. 7. Rotary speed of flywheels.

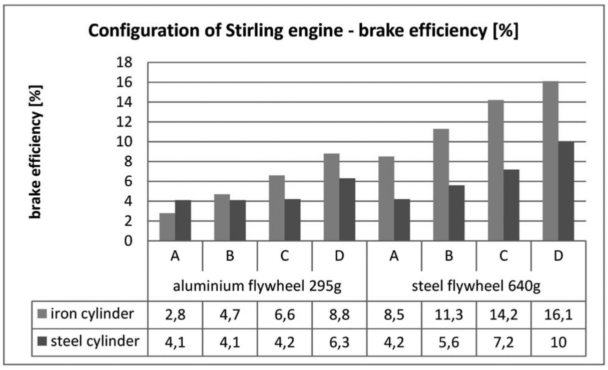

Fig. 9. Brake efficiency of the engine in different configurations of replaceable elements.

To start a laboratory model of Stirling engine shown in (Fig. 6.), it is necessary to turn on the gas burner and direct flame at the engine heater, then wait 10 minutes for the engine be thermally stable during the measurement.

To improve the engine there is a need to initiate movement of the piston by several revs of the flywheel. All the studies experimented on the Stirling engine were conducted at determined work state. Fig. 7 shows rotary speed of flywheels used for the above mentioned engine configuration.

As a result of one such study, there has been appointed the force F, needed to calculate the mechanical moment. Setting the number of revs n by the tachometer and converting to frequency f, the mechanical power P_m (2) has been appointed and is shown at the Fig. 8, where W_m stands for mechanical work:

$$P_m = W_m \cdot f \qquad (2)$$

On the basis of mechanical power there has been appointed brake efficiency e_b defined by the formula (3) and presented at the Fig. 9, where P_b signifies the power of burner:

$$e_b = \frac{P_m}{P_b} \cdot 100\% \qquad (3)$$

In the researches there were used two types of cylinders — iron and steel. When using an iron cylinder (spheroidal) the number of revs per minute, the efficiency and power were higher than with use of a steel cylinder.

Iron cylinder is characterized by possibility of reducing machining to minimum and good mach inability, abrasion resistance and first of all the low cost of production [7]. The choice of spheroidal iron is supported by the fact that it has the ability to accumulate the temperature for a longer time, that it is in the case of the steel cylinder, holding the engine work at a constant level. Significant influence on the engine performance has the flywheel. On the basis of the research it turned out the best parameters are obtained with use of the steel flywheel. The research also showed that better results are obtained using a steel cooler with a diameter of 76 mm than with a diameter of 60 mm. Also the use of radiators made of aluminum resulted in a worse performance, because they heat up quickly and retain heat, which does not give the desired cooling effect.

The aim of these researches was to determine the configuration assuring the best engine parameters: efficiency and mechanical power. The analysis of data showed that the best results were achieved with the following configuration: iron cylinder, steel flywheel, and steel cooler with the diameter of 76 mm.

However, using this iron cylinder, aluminum flywheel, aluminum radiator with a diameter of 60 mm, the engine has reached the lowest efficiency and mechanical power, because the centrifugal force of the flywheel which holds the engine in motion was lower. The radiator surface was too small and thus aluminum very quickly takes over heat from the cylinder. Due to the patent application the author is not able to give more detailed engine specifications [8].

Summary

During the construction of the model of engine one was guided by the criterion of minimizing material costs and maximizing the efficiency of conversion of heat energy into mechanical. Therefore, the model Stirling engine was designed and constructed in such a way that there is a possibility to exchange the particular components [6]: the flywheel, radiator and heater. On the basis of laboratory researches, there can be stated that the best parameters has the engine with steel flywheel, the heater made of spheroidal iron, steel radiator with a large diameter. For such a configuration the made Stirling engine model is characterized by brake efficiency of 16%. The next stage of research, in the section on construction of a Stirling engine, is to be devoted to design, build and test low speed neodymium generator integrated with the engine structure [8]. On the basis of knowledge and conceptual studies completed in the first part of the research, there will be built, optimized for the construction and used materials Stirling engine with a capacity of about 200–300 W.

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