NEW MODIFIED BETA TYPE STIRLING ENGINE COMPARISON WITH CLASSICAL STIRLING ENGINE LAYOUT

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Abstract. In the paper the main aspects of the “classic“ beta type Stirling engine and a new design with unidirectional gas flow configuration are described and compared. A principal layout description of the working principle is presented and later differences in the main engine parts are described. General differences in the thermodynamic cycle for the new engine configuration are presented and explained. In the development process, special attention has been devoted to heat transfer intensity and the possibilities of operating at low temperature difference.

Keywords: new engine design, Stirling engine, unidirectional flow, thermodynamic cycle.

Introduction

Stirling engines are known as heat engines which can use almost any heat source. The technology they use can be described as a thermodynamic system where the working fluid is permanently contained within the system. The high theoretical working efficiency is one of the most important advantages of this type of the engines. However, in real life it is hard to achieve theoretical efficiency. Time after time bigger and smaller companies are working on development of Stirling engines. There are many cases in history when Stirling engines have been widely used in some specific areas, but due to different reasons they gave up to inner combustion or electric engines. However, development of Stirling engines continues.

Nowadays, interest for Stirling engines is coming back thanks to development of computer simulating programs and the request for use of renewable resources. There are many different designs of Stirling cycle engines [1-3]. One of the new designed constructive solutions is a one-way flow beta type Stirling engine. In accordance with Kirkley-Walker classification [4; 5] engines can be divided for the location of the piston into alpha, beta and gamma types. In the beta type engine that is used as basis for modified engine displacer and power pistons are located on one axis in the common cylinder. The operating cycle of such type of the engine is well described also by G. Walker [6].

The efficiency of Stirling engines is one of most attractive things in this engine but it depends on different parameters. Many scientists have studied the influence of different mechanical characteristics and operation conditions on the engine efficiency [7]. In the opinion of the author, two of the most important scientists, after Stirling himself, in the development of the theory of Stirling engines are G.Walker and G. Schmidt. But there are also many others who have played an important role in the development of Stirling engines. For example, important research was made by C. Cheng et al on experimental investigation of beta type Stirling engines in different operation conditions. The effect of the working fluid, pressure and temperature was examined and an adiabatic model was built. [7]. The work done by Cinar C. et al presents the effect of hot-source temperature on the engine power [8]. Nuance of exploitation conditions and Stirling engine design using a low temperature heat source is show in the research done by Karabulut H. et al. [10]. The effect of flow parameters on the heat transfer is presented by Kuosa M et al. [11]. They are just some of the scientists on the basis of whose work presented in this paper the new modification of the Stirling engine was created.

Return of Stirling engines

There are still many new variations of the Stirling engine construction, new technology and new materials as well that brings us closer and closer to the very promising theoretical efficiency of the engine. As a sample of successful development of the constructive solution of Stirling engines the following information will be given.

Large parabolic mirrors have found their way into several installations worldwide, most notably the recent (2005) joint venture between the electricity supplier Southern California Edison and Stirling engine manufacturer Stirling Energy Systems. This agreement will see the installation of some 20,000 solar Stirling dishes into a 1,800 ha area of the Mojave Desert, for a total power generating capacity of

500 MW – the largest of its type in the world at the time of the agreement (until the 900 MW project in Imperial County, Southern California was announced). More recently the project was expanded up to 34,000 dishes totalling 850 MW. The advantages of solar Stirling systems are the high efficiency (exceeding that of parabolic troughs and non-concentrated photovoltaics), relatively low cost per kW compared with other solar technologies and high life expectancy (Stirling engine used is the 25kW unit, and has been tested for 26,000 hours of continuous operation) [12].

Description of the engine and its working principle

A Stirling Engine has 5 main characteristic parts that determine its operation – displacer piston, power piston, heater, cooler and regenerator. Figure 1 below schematically shows the location of the main parts and designation of the characteristic parameters of a "classic" beta type Stirling engine. This makes it simple to see and understand the working principle of the engine.

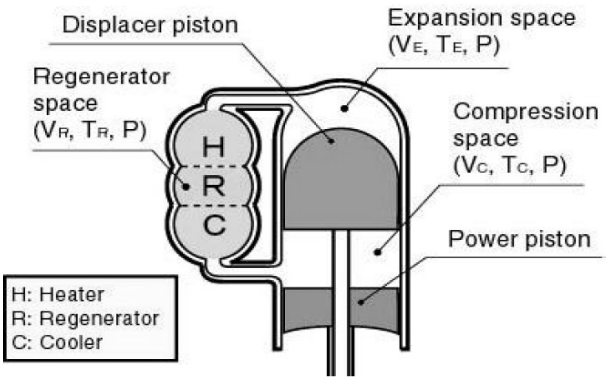

Fig. 1. **Schematic illustration of beta type Stirling engine [13]**

The work of a classic Stirling engine in idealized situations with little simplification can be described by 4 phases. At the first phase the power piston moves upwards and compresses the working gas. In the phase two the displacer piston by moving upwards moves masses of the working fluid form the expansion space to the compression space though the heater, regenerator and cooler. In this phase the working gas is heated, so the pressure inside the engine rises. Despite the fact that the working gas is moved though the heater, regenerator and cooler the main influence on the working gas parameters is done by the heater and regenerator. In the third phase useful work is done be heated working gas so raised pressure pushes the working piston downwards. In the fourth phase the displacer piston by moving downwards pushes the working gas through the cooler, regenerator and heater but in this time the main influence on the working fluid is done by the cooler and regenerator. So, in the classical Stirling engine layout the working fluid is pushed back and forth through the heater, regenerator and cooler. As it is easy to see, we would like to avoid to push the working gas through the cooler when we are heating gas and reversely. So, one of the main differences in the offered new Stirling engine is that the gas flow is arranged that way that when heat energy is added to the working gas the gas flows only through the heater and when it needs to be cooled it is pushed only though the cooler [14-16].

To see how it is achieved let us look at the schematic layout of the engine in Figure 2. There are 5 main parts and to help describe the engine there are also some other parts presented. The main parts in the new engine modification are just like in the classical Stirling engine – the power piston, displacer piston, cooler and heater but instead of the regenerator as the fifth we have a valve.

To describe the working principle of the new engine modification we will need to subdivide two phases into two parts. Let us start as previously with the movement of the power piston upwards. The difference from the previous variant is that due to the different crankshaft offset angle (explained later) and different cooler passages at the first part when the power piston is moving upwards it continuous to push the working gas out of the compression space into the cooler. From the cooler, thanks to the open valve, the cooled working gas is pushed into the expansion space. When gas is pushed out from the compression space the valve closes the cooler passage but the power piston with its body closes the other opening of the cooler passage and just like in the previous variant compression begins. Gas cooling continues up to 80 degrees after the BDC of the power piston and the phase compression is respectively 100 degrees, but those numbers are matter for engine optimisation. In the expansion space heat is not added to the working gas. At the second phase the displacer piston is pushing gas from the expansion space through the heater into the compression space. At the third phase the raised pressure of the working gas pushes the working piston downwards but at the lower part of the phase the power piston opens the cooler inlet and the valve opens the cooler outlet (timing can be varied to optimise the flow parameters). So, at the second part of the phase cooling of the gas begins. At the fourth phase the displacer piston is pushing the working gas out of the compression space into the expansion space.

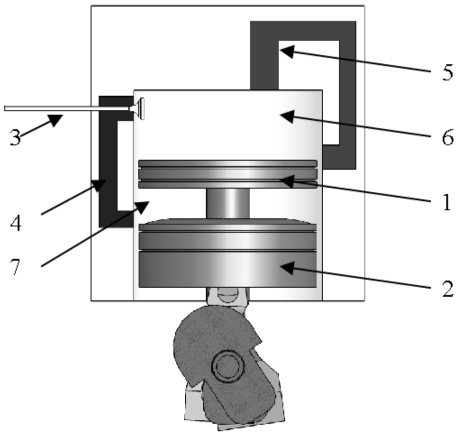

Fig. 2. **Schematic illustration of designed engine:** 1 – Displacer piston; 2 – Power piston; 3 – Valve; 4 – Cooler; 5 – Heater; 6 – Expansion space; 7 – Compression space

The main differences of the presented engine if compared to the classical beta type Stirling engine, if we compare them from the point of view of gas thermodynamics, are the following: there is no regenerator in the new presented engine, in engine channels the working gas flows in one direction, and the volume of the cooler or cooler space is separated after cooling of the working gas is done. In the new engine there is no regenerator and as the first impression might be that it is not good to lose the regenerator because then we should lose some cycle efficiency, but as it will be discussed later it is not so bad as it might look [17; 18].

Heat exchangers

The heat exchangers are responsible for transferring all the heat into and out of the engine. There are always two heat exchangers, one to heat the working gas and one to cool it. There are many different types of heat exchangers and countless configurations possible, but the basic principle is to have two fluids, one hot and one cold, interacting by some thermally conductive configuration that will cause the outlet temperature of both fluids to approach some point in between both inlet temperatures. Usually there is no direct contact between the fluids; they are separated by some medium, usually a metal of high thermal conductivity [19].

In our case the cooler of the designed engine is illustrated schematically in Fig. 2 and shown in blue. The working gas flow is unidirectional from the lower part to the upper part of the cylinder. The design of the new engine allows separating the cooler from other engine volume and this solution allows using large coolers without sacrificing of the engine efficiency and power. If we do not separate all of the coolers volume then it will become a part of the so called dead volume. Dead volume is defined as the total void volume in the Stirling engine. In general, the dead volume is referred to as the volume of the working fluid contained in the total dead space in the engine, including the regenerator and transfer port. In normal Stirling engine design practice, the total dead volume is approx. 58 % of the total volume. The dead volume will decrease both, the engine network and the thermal efficiency and will increase both, the external heat input and output. However, a real engine must have some unavoidable dead volume [20]. In our modification by implementing a cooler separation mechanism we can reduce the amount of dead volume by approximately 50 %. In our design, a valve mechanism that is added to separate the cooler consumes some energy but the overall effect of cutting off a large part of dead volume is worth it.

The heater of the designed engine is shown in red in Figure 2. The heater channels (2) start from the cylinder head and end in the upper part of the cylinder but below the lower edge of the displacer piston in the upper position so that the volume above the displacer is connected with the volume between the pistons through heater channels. The power piston in the upper position is still lower than the exit of the heater and cooler channels. The direction of the working gas flow in the heater also is unidirectional and it is clockwise in our schematic drawing.

One of important parts of the classic Stirling engine is the regenerator. The regenerator design is very complex and it will not be described here in details but the main factors that characterise the design of the regenerator are the necessity of reducing dead space and flow restriction while maintaining a high level of effectiveness. These criteria are by their very nature contradicting – a high value of effectiveness necessarily means that the regenerative matrix is able to store a lot of heat in it, meaning that it must have a significant amount of material within it. To have a significant amount of material the regenerator must either be large and sparsely packed, meaning a large dead volume is inherent, or else the regenerator must be small and densely packed, meaning a high flow resistance is unavoidable [21]. So, after all effectiveness of regenerators in real life conditions is far from theoretical. In the new engine design there is no regenerator and it helps decrease dead volume of the engine and achieve higher rpm because regenerators usually at high flow rates reduce their effectiveness and increase aerodynamic resistance.

Pistons

As it was shown in Figure 1 there are two kinds of pistons in Stirling engine. In the classical engine the purpose of the displacer piston is to simply move the working gas around inside the engine. The heat exchangers create two distinct regions inside the engine; a hot region and a cold region. These regions occupy the majority of the volume inside the engine. It is the role of the displacer to shuttle the working gas alternately between these regions in order to alternately heat and cool the gas giving rise to the necessary expansion and contraction that facilitates the operation of the engine [21]. But in the described here new engine variant the displacer moves the working gas only through the heater and in one direction- from expansion to compression space when it is in the upper region of the cylinder and assists to push out the working gas from the compression space through the cooler into the expansion space when it is in the lower region of the cylinder.

The power piston in the classical Stirling engine is similar to that of a piston found in an internal combustion engine. Its job is to transmit power created by pressure acting on the piston face to the crankshaft of the engine. The piston slides within a cylinder and is tightly sealed against the cylinder walls by the piston rings in order to maintain the necessary pressure differential across the piston for motive power [21]. But in the new engine the power piston works also as a valve that opens and closes the inlet of the cooler.

The maximum heat energy supply in the presented one way flow Stirling engine is achieved after the power piston starts to move downwards after the top dead centre (can be varied with location of the heater outlet and phase shift), and that helps to increase the power output of the engine because no heat energy is wasted while the working gas is compressed when the power piston moves upwards. Intensive heat energy supply through the heater continues up to 45-50 degrees after UDC, but the working phase lasts up to 105-110 degrees from UDC of the power piston.

Theoretical thermodynamic cycle

Modification of the beta type Stirling engine not only allows us to decrease the dead volume of the engine and apply the heat energy more precisely when it is needed, but also allows to partly realize isobaric compression. Many of design changes of the new engine improve the characteristics of the real cycle of the Stirling engine, but there are also important changes in the ideal Stirling cycle. To show the effect of the design changes on the ideal thermodynamic cycle of the Stirling engine the following assumptions are made [22]:

1. Working substance is perfect gas.
2. Flow resistance everywhere is zero: pressure always uniform throughout the engine.
3. Regenerator loss zero: the gas enters the hot end at exactly the heater temperature and
4. enters the cold end at exactly the cooler temperature.
5. Zero heat loss by conduction, etc.; all heat added to the engine passes to the gas.

6. Isothermal expansion and compression for classical Stirling engine; zero temperature drop across heat-exchange surfaces. At each point in the engine the temperature has some constant value.
7. Volumes of expansion space and of compression space vary in the ideal discontinuous
8. (non-sinusoidal) manner.
9. Mechanical friction assumed zero.
10. Dead space is assumed to be zero.
11. The thermodynamic cycles are shown in Figure 3. With cross-hatch areas are depicted that are different if we compare these two engines. As we know, in the pressure – volume coordinate system the enclosed area inside the cycle is useful work done by the engine and if it is larger than theoretically we have more power out of the engine. In the temperature- entropy coordinate area inside a closed cycle we have heat energy needed to realise such cycle. Less area means less energy needed.

In Figure 3 a classical Stirling cycle is shown in P-V coordinates with numbers 1-2-3-6 and in T-S coordinates 1-2-4-6 but the new designed engine cycle with numbers 1-2-3-4-5 and 1-2-3-5-6 respectively. The difference between two cycles in P-V coordinates starts in the compression phase when the classical Stirling cycle has isothermal compression that starts from point 3 and continues to point 6 but in the new engine cycle we have at first isobaric compression from point 3 to 4 and at the second part of the compression phase we have isothermal compression. In T-S coordinates this difference in the compression phase characterises with points 3-5-6 for the new engine design. As we can see, intensive cooling of the working gas continues also in the first part of the compression phase (points 3-4 that characterises isobaric compression).

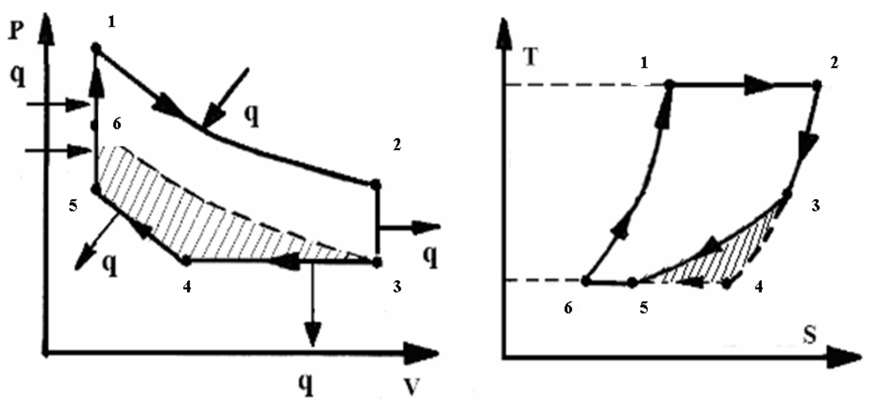

Fig. 3. **Ideal Stirling cycle for classical and new Stirling engine modification**

As we can see from Figure 3, for the same changes of volume and pressure of the engine the new modified engine has a larger area inside the cycle and so should produce more net work per cycle. The reason of such net work increase is easy to understand because we need to waste less energy on compression if we instead of isothermal have isobaric compression. If we have the same differences in temperatures for both engines then the area inside the cycle will be less for the new engine, so to realize a full cycle in the new modified Stirling engine we need to use less heat energy [14-16].

Approximate calculations indicate that in a real new engine we should have power increment about 35 % but loss of the cycle effectiveness should be about 0.3 % [23].

Conclusions

The new design of the beta type Stirling engine does not only allow us to decrease the dead volume of the engine, to supply heat energy at more effective way, to have much larger coolers and less aerodynamic resistance for the working gas inside the engine but also allows to partly realize isobaric compression. Many of design changes of the new engine improve the characteristics of the real cycle of Stirling engine, but there are also important changes in the ideal Stirling cycle because isothermal compression is partly substituted with isobaric compression.

Only approximate calculations yet are made, but they indicate that in the real new engine we should have power increment about 35 % but loss of the cycle effectiveness should be about 0.3 % if compared with the classical Stirling engine layout.

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