STUDY OF STIRLING ENGINE FOR INDUSTRIAL APPLICATIONS

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Abstract: In this paper is studied the possibility of using the Stirling engine in order to reduce environmental pollution. Constructive types, operating principle, main advantages and disadvantages are presented. Finally, the stages of the practical realization of such an engine are presented.

Key words: stirling machine, mechatronics of stirling engines, stirling thermodynamic cycle.

1. INTRODUCTION

The Stirling engine defines a regenerative closed-cycle hot-air heat engine. In this context, "closed cycle" means that the working fluid is in a closed space called a thermodynamic system; "regenerative" refers to the use of an internal heat exchanger which significantly increases the potential output of the Stirling engine.

Usually, the Stirling engine is classified as an external combustion engine, although the source of thermal energy can be not only the combustion of a fuel, but also solar energy or nuclear energy. A Stirling engine operates by using an external heat source and a heat sink, each of which is maintained within predetermined temperature limits and a sufficiently large temperature difference between them [1], [7], [9].

The Stirling engine achieves the highest efficiency in the process of converting thermal energy into mechanical work, theoretically up to the maximum efficiency of the Carnot cycle, although in practice this is reduced by the properties of the gas and materials used.

As an external combustion engine, it can be adapted to use various fuels, such as biofuels, alcohols, hydrogen, vegetable oils (from seeds, from soybeans, from peanuts, or extracted from various plants), or biofuels extracted from seaweed and oceanic, etc. [8], [10]

These thermal engines are strong, robust, dynamic, compact, noxious, oil-free, smoke-free, working with high efficiencies (not only mechanical but also thermal) [2].

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2. STIRLING ENGINE USES

2.1. Cogeneration applications (CHP - Combined Heat and Power)

Through cogeneration, from a pre-existing energy source, usually an industrial process, with the help of an installation, in addition to the delivered mechanical or electrical power, heat necessary for heating is provided. Normally the primary heat source is the input to the Stirling engine heater and as such will be at a higher temperature than the heat source for the heating application which is the exhaust energy from the engine [3], [11].

Fig.1. Stirling engine at the Hochhut Technical Collection in Frankfurt am Main

The power produced by the Stirling engine is often used in agriculture in various processes, resulting in biomass waste that can in turn be used as engine fuel, thus avoiding the costs of transporting and storage the waste. The process in general is plentiful in energy resources being in its entirety advantageous from an economic point of view (figure1).

2.2. Solar electricity generators

Placed in the focus of a parabolic mirror, a Stirling engine can be used as an electric current generator with an efficiency higher than simple solar panels with photovoltaic cells and comparable to that solar panels with concentrator photovoltaic cells.

2.3. Refrigeration installations Stirling - Cryocooler

Any Stirling machine can work in reverse as a heat pump: if the mechanical work is introduced by driving the machine, a temperature difference appears between the cylinders [12]. One of the modern uses is in the cold industry as refrigeration and cryogenic installations (cryocooler).

The main components of a cryocooler are identical to those of the Stirling machine. The rotation of the motor shaft will compress the gas, increasing its temperature. By pushing the gas into an exchanger, heat will be delivered. In the next phase, the gas will be subjected to expansion, after which it will cool down and will be circulated to the other exchanger where it will take heat. This exchanger is located in a thermally insulated space such as a refrigerator [13], [15].

2.4. Heat pumps

A Stirling heat pump is very similar to a Stirling cryocooler, the difference being that the heat pump works at room temperature and its main role is to pump heat from outside the building inside to provide cheap heating. As with other Stirling machines and in this case the heat passes from the expansion zone to the compression zone, however, unlike the Stirling engine, the expansion zone is at a lower temperature than the compression zone, so instead of producing work mechanically, it is necessary to provide it by the system to satisfy the requirements of the second law of thermodynamics.

2.5. Nuclear energy

In nuclear power plants, there is the possibility of using Stirling machines for the production of electricity. By replacing steam turbines with Stirling engines, construction complexity can be reduced, efficiency can be achieved, and radioactive waste can be reduced. Certain uranium enrichment reactors use liquid sodium as a coolant by design. If the thermal energy is still used in a steam plant, water/sodium heat exchangers are needed, which increases the degree of danger due to the possibility of a violent reaction of sodium with water in case of direct contact. The use of the Stirling engine means that water can be removed from the cycle [14].

2.6. Automobile engines

In the automotive industry, the non-use of Stirling engines for driving vehicles is often argued by the power-to-weight ratio being too low and the start-up time being too long. The biggest problems appear in the long start-up time, slow acceleration, stopping and load response for which no immediately applicable solutions have been found. Some researchers believe that the hybrid drives would eliminate these shortcomings, but so far, no vehicle has been built on this basis.

3. PRESENTATION OF THE STIRLING ENGINE

3.1. The advantages and disadvantages of the Stirling engine

The main advantages of the Stirling engine are [3]:

- waste heat is easily usable so Stirling engine can be used in combined systems such as WhisperGen;
- it can use any heat source without modification, not only those based on a combustion process, such as solar, geothermal, biological or nuclear energy;
- the combustion process can be continuous, significantly reducing the level of polluting emissions, in the case of the fuel-based source;
- most Stirling engines have their drives and seals on the cold side, so its require less lubricant and have longer service intervals than other types of machines;
- actuation mechanisms are simpler than in other types of reciprocating machines, valves are not required and the combustion system can be simpler.
- Stirling engine uses a non-changing working fluid that is under close to nominal pressure, so there is no danger of explosion in normal use.
- in some cases, the low pressure may allow using very light weight cylinders.
- it can be built for very quiet operation without air supply, for propulsion without air consumption in submarines or in space technology.

- it start easily (yet slowly after a warm-up period) and run more efficiently in cold weather, compared to internal combustion engines that start quickly in hot weather and hard in cold weather.
- it are very flexible and can operates as cogeneration plants (CHP - Combined Heat and Power) in the winter and as a refrigeration plant in the summer.

The main disadvantages of the Stirling engine are:
- by construction, the Stirling engine is equipped with heat exchangers both for absorption and for its release, exchangers that must withstand the pressure of the working fluid, which in turn is proportional to the engine power. In addition, the heat exchanger on the expansion side is subject to very high temperatures, which is why the material must resist strong corrosive effects and have reduced deformations. Usually these requirements increase the cost of the material.
- thermodynamic cycles require large temperature differences in order to function efficiently. This means that high strength materials are required.
- the removal of waste heat is quite complicated because the cooler must be kept at a temperature as low as possible to increase efficiency.

Because of this, large radiators are needed that increase the volume. Along with the cost of the material, this was one of the reasons that prevented the use of Stirling engines for motor vehicles. Other applications, however, such as ship propulsion and stationary micro-power plants using cogeneration (CHP), do not require a large liter power.

3.2. Motor cycle

Since the cycle of the Stirling engine is closed, it contains a certain amount of gas called "working fluid", usually air, hydrogen or helium. During normal operation, the engine is sealed and there is no gas exchange with its interior. Unlike other types of engines, valves are not required.

The gas in the Stirling engine, similar to other heat engines, goes through a cycle consisting of 4 transformations (times): heating, expansion, cooling and compression.

The cycle occurs by moving gas back and forth between the hot and cold heat exchangers. The hot heat exchanger is in contact with an external heat source, for example a fuel burner, and the cold heat exchanger is in contact with an external radiator, for example an air radiator.

A change in the temperature of the gas causes a change in pressure, while the movement of the piston contributes to the alternate compression and expansion of the gas [4], [5].

In conclusion, the Stirling engine uses the temperature difference between the two zones, the hot and the cold, to create an expansion-contraction cycle of a given mass of gas inside a machine to convert thermal energy into mechanical work. The greater the difference between the temperatures of the two zones, the greater the efficiency of its cycle.

3.3. The theoretical reversible cycle of the Stirling engine

The theoretical cycle of a Stirling engine is the same regardless of whether the engine has one or two cylinders and consists of two isotherms and two isochores (fig.2.).

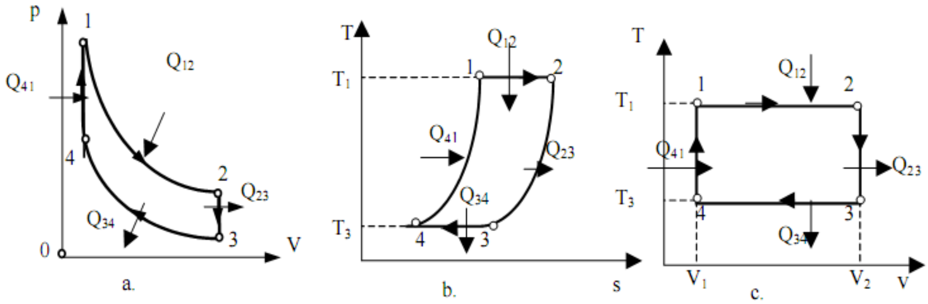

Fig.2. The theoretical reversible cycle of the Stirling engine
a - in P-V coordinates; b - in T-s coordinates; c - in coordinates T-V

For the description of the reversible Stirling cycle, it is assumed that the engine has two cylinders (figure 3).

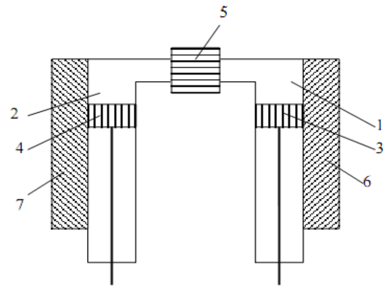

Fig.3. Scheme of the two-cylinder Stirling engine:
1,2 - the hot, respectively cold cylinder; 3,4 - hot and cold piston;
5 - heat regenerator; 6.7 - the source of hot, respectively cold heat

When the hot piston 3 moves down, the isothermal expansion 1-2 of the working agent takes place. In this transformation, the system receives heat from the hot source:

$$Q_{SC} = Q_{12} = mRT_1 LN \frac{V_2}{V_1} = mT_1(s_2 - s_1)\ [kJ] \qquad (1)$$

Where: m - is the mass of the working agent [kg]; R- perfect gas constant of the working agent [kJ/kgK].

Simultaneously with the up movement of the piston 3 on the first portion, the cold piston 4 moves down. In this way, the passage of the working agent takes place through the heat regenerator 5 which receives the heat Q_{23} by heating the copper wires that compose it. Due to the synchronization of the movement of the two pistons, the transformation to which the working agent is subjected is isochore 2-3. As a result, the evolved gas decreases its temperature and pressure at T_3, respectively p_3. Next, the cold piston 4 performs the isothermal compression 3-4, being in contact with the cold source, it gives up its heat:

$$|Q_{sr}| = |Q_{34}| = mRT_3 ln\frac{V_3}{V_4} = mT_3(s_3 - s_4) \quad [kJ] \tag{2}$$

By reversing the direction of movement of the two pistons, the 4-1 isochore transformation is achieved during which the evolutionary medium absorbs the heat from the regenerator Q_{41}, and the active elements of the regenerator cool down. It is easy to see that, under the conditions that $T_1 = T_2$ and $T_3 = T_4$, and points 2,3 and 4,1 are found on two isochores:

$$|Q_{23}| = |Q_{41}| = mc_v(T_2 - T_3) = mc_v(T_1 - T_4) \quad [kJ] \tag{3}$$

The mechanical work produced is:

$$L = Q_{sc} - |Q_{sr}| = mR\left(T_1 ln\frac{V_2}{V_1} - T_3 ln\frac{V_3}{V_4}\right) = m\,(T_1 - T_3)(s_2 - s_1) \quad [kJ] \tag{4}$$

The thermal efficiency of the reversible Stirling cycle will be:

$$\eta = \frac{L}{Q_{sc}} = 1 - \frac{T_3}{T_4} \tag{5}$$

4. CASE STUDY – BUILDING A STIRLING ENGINE MODEL

4.1. Introduction

The two-piston Stirling engine is a heat engine that operates through compression and decompression cycles of a working fluid, based on temperature differences, and which, in the end, directly transforms thermal energy into mechanical energy (figure 4).

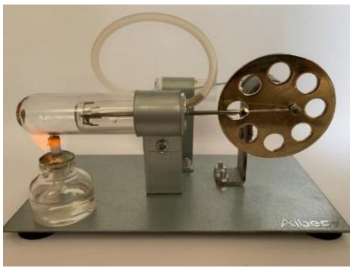

Fig.4. The two-piston Stirling

This engine can operate on the basis of a heat source regardless of its quality, be it solar, chemical or nuclear energy. Stirling engines are quieter and more economical than internal combustion engines, can be safer to operate, and do not have high maintenance requirements.

4.2. The practical realization of the Stirling Engine (with two pistons)

The two-piston Stirling engine has a very simple construction, being built almost entirely of galvanized sheet iron and glass. It can have a speed of up to 200 rpm. The base is a galvanized iron plate, which has a rectangular shape placed on four rubber feet to have a well-defined stability (fig.5).

Fig.5. Stirling Engine base and piston

In each of the racks, one by one, carefully fix the cylinders of the pistons and at the same time insert the pistons into them (fig.6). After mounting the cylinders in the racks, connect each piston with the connecting rod, respectively the engine crank. Rotate the connecting rod to ensure that there is not a large frictional force between the pistons and cylinders and adjust a 90^0 offset between the connecting rod and the engine crank. After adjustment it is noticed that a smoother rotation occurs [6].

Fig. 6. Fixing the cylinders in the racks and connecting the pistons to the engine

Now the engine is ready, carefully assembled all the details. The lighter is ignited and clamped under the end of the hot piston (fig.7).

Fig.7. The two-piston Stirling engine

It is allowed to burn and heat the piston air for about 60 s. After this time interval we give a small impulse to the crank, the hot steam from the hot cylinder being pushed by the piston travels through the silicone tube to the piston the cold cylinder pushing the piston, thus the engine ours is in constant motion as long as the heat source exists [4].

5. CONCLUSIONS

Stirling engines have a simpler construction than internal combustion engines and are quite efficient. They can only be put into operation by the presence of a heat source. Any type of raw material that has the property of burning and releasing heat can be used as a heat source for the Stirling engine. An ecological example would be the straw left on grain fields after they are harvested. The energy capacity of straw has a ratio of approximately 1/3 of the energy capacity of average quality coal that is used to heat houses in winter.

Stirling engines are considered "external combustion" engines with relatively high efficiency. These observations represent decisive arguments in favor of the use of Stirling engines in industrial applications, since they present a very low percentage of pollution compared to internal combustion engines.

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