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DIRECT AND INDIRECT HEAT ENERGY CONVERSION INTO ELECTRICITY

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Abstract

Conversion of heat energy into electricity is described.

Energy conversion is the process of changing one form of energy to another. There are two methods of conversion: direct, when heat energy is converted directly into electricity and indirect, when heat energy is converted into mechanical energy first and afterwards into electricity.

A principle of direct method is thermoelectric effect that includes three separately identified effects: the Seebeck effect, the Peltier effect and the Thomson effect. In case of heat energy conversion into electricity, we are talking about Seebeck effect.

For indirect method, first heat energy is converted to mechanical energy. The principle is gas compression and expansion due to temperature change that is used i.e.: steam engine, Stirling heat engine or polish engine WASE2. The engine is based on the fundamental physical phenomena. The next step is to convert mechanical energy into electricity. The principle is electromagnetic induction that produces an electromotive force across a conductor when it is exposed to a time varying magnetic field. Electromagnetic induction is used in i.e.: generators, alternators or American type generators.

Keywords: *heat energy, recovery, electricity, mechanical energy, Peltier effect, Seebeck effect, thermoelectric*

1. Introduction

Energy conversion is the process of changing one form of energy to another. As stated by the law of conservation of energy the total energy of an isolated system remains constant. Energy components of total energy may increase or decrease. There are two methods to convert heat energy into electricity:

- direct, when heat energy is converted directly into electricity,
- indirect, when heat energy is converted into mechanical energy first and afterwards into electricity.

2. Direct methods

It seems that direct method is better solution in scope of a losses and difficulty of the system, however there are indirect systems that are solutions more effective. Direct and indirect solutions of energy conversion are described below.

Direct methods

A principle of direct method is thermoelectric effect. That is outcome of temperature difference that occurs between two points. It generates electricity. Thermoelectric effect includes three separately identified effects: the Seebeck effect, the Peltier effect and the Thomson effect [1].

In case of heat energy conversion into electricity, we are talking about Seebeck effect. It is based on the creation of thermoelectric power in a closed circuit consisting of two different metals

− semiconductors, provide that the contact area of the metal is located in a different temperature than the opposite ends.

Currently there are such devices using the Seebeck effect:

2.1. Thermocouple,
2.2. Peltier / Seebeck cell,
2.3. Nanoantenna.

Below, a few words characterized each of mentioned solutions.

2.1. Thermocouple

Thermocouple is an electrical circuit element that uses the Seebeck effect, popularly used for temperature measurements. It is a device consisting of two different metals, usually in the form of wires, the ends are connected together. One connection is positioned at the measuring point and the other in the centre of constant reference temperature. By differences in temperature, occurring between the two points the potential difference is being created. It is the electromotive force, known as the thermocouples. In the case of thermoelectric power that is proportional to the temperature difference. Thermocouple usually is made out of iron and constantan.

The advantages for the use of thermocouples as equipment for the recovery of electricity from heat are:

- small size,
- simplicity of construction,
- high reliability,
- the possibility of use in wide range of temperatures depending on the materials used,
- the ability to perform on their own.

In contrast, disadvantages are:

- high trading price of thermocouples in the market,
- low value of the generated electricity,
- low efficiency.

2.2. Peltier / Seebeck cell

Writing two surnames characterizing various thermoelectric effects in one cell is conscious. The same cell can operate as a device using the Peltier Effect, as well as the Seebeck effect. These cells are more popular under the name of Peltier. These cells operate in three different ways:

- using the Peltier effect, when connected to a power source to heat is excreted into the environment,
- using the Peltier effect, when connected to a power source to cool is retrieved from the environment,
- using the Seebeck effect is used to generate electricity on the basis of temperature difference.

For use in this case ideal is the third method that is described in details below. A boundary condition is to put the Peltier batteries in areas with different temperatures. In this case, it is direct conversion of heat into electricity. Unfortunately, if you use the popular modules that are popularly used for cooling in fridges they are not sufficient. For the production of electricity there should be different materials used, that can operate at much higher temperatures. In addition, voltage and power derived from a single cell is small, so in order to obtain efficient energy values bigger quantity of cells has to be connected in one battery. There are also many parameters that influence on the applicability of such cells; e.g. the melting point of the solder, which cannot be lower than the temperature of a medium with higher temperature. Another drawback of the device is efficiency of thermal energy conversion into electricity, which is approx. 2-3%.

To improve the efficiency modules are placed one on top of another to form a so-called Peltier

pyramid. You have to keep in mind that while placing modules on each other next stage have to be able to work with:

- heat from the previous level,
- Joule heat of the previous stage, the heat that emits when current flows through a conductor, which has a nonzero resistance.

In summary, the advantages offered by the use of Peltier modules are:

- rigid structure (for mechanical strength),
- small dimensions,
- no moving parts in the cell,
- lack of coolant,
- cell may have any shape (the ability to adjust to the desired shape),
- the possibility of combining several modules (increase of efficiency),
- long life without service (approx. 200,000 Hours).

In contrast drawbacks of this method are:

- lack of ability to use in high temperatures,
- low voltage and low power value extracted from the cell,
- low efficiency of thermal energy conversion into electricity.

2.3. Nanoantenna

The newest invention is nanoantenns that can convert heat into electricity with very high efficiency, i.e. approx. 80-90%. By using nanotechnology, there were batteries that generate energy from the visible spectrum as well as the infrared range created. In this solution, a process of attaching small coils made of electrically conductive material onto a plastic plate is used. Once connected spirals creates a closed electrical circuit that is working in the electromagnetic resonance, which absorbs radiant energy of waves in a similar way as the TV antenna. Due to the fact that the device is small, it is able to absorb infrared energy in the range of the spectrum, which is invisible to the human eye [1].

The plates, on which those spirals are mounted, are flexible. You can perfectly fit them to the needed shape. Unfortunately, this technology has one big drawback. The voltage which is generated by the nanoantenna reaches the frequency around one GHz, which has to be secondarily converted. In addition, it is hard to "straighten out" this electricity and use it for example for battery charging. Currently there are experiments conducted to use micro capacitors directly on the structure in nanoantenna, which would improve this unfavourable phenomenon.

3. Indirect methods

Indirect methods are based on the initial conversion of heat energy into mechanical energy and in the next step conversion of mechanical energy into electricity.

3.1. Changing thermal energy into mechanical energy

There are many solutions known that enable the conversion of heat into mechanical energy. Looking into the history you will come across steam engines that meet this role. Already in the years, 140 BC there was built first equipment using this kind of energy. In the first half of the eighteenth century, these engines were used as source of power for machines [4]. The first use of the vehicle with steam engine took place in 1771. These engines were subject of continuous development and in the nineteenth century, they were used in ships, steam locomotives, kind of buses. However this technique due to lack of knowledge in materials used caused from time to time accidents and disasters [5]. The solution proposed by Robert Stirling, who built a heat engine,

characterized by high efficiency and does not require high pressure and steam as the working medium had changed the opinion about those engines.

3.1.1. Stirling engine

The engine is based on the fundamental physical phenomena. It involves compression and expansion of gases due to changes in temperature. If the sealed container is heated, the gas in the middle increases its volume, which would increase the pressure. If the container itself will be cooled – the gas volume will decrease, which will reduce the pressure. Robert Stirling placed in such a container a movable piston, which has no direct contact with the walls of the container. The work of the piston is moving air from the wall with cold temperature to the heated one. This type of "loose" piston is being called "sinker" [3].

The engine also uses the classic pneumatic actuator. It is also characteristic for the engine that combination of "sinker" with the pneumatic actuator is made by flywheels and connecting rods.

The design of this engine is quite complicated and due to the construction in classic solution (two connecting rods, flywheel, two pistons) it is quite expensive to produce. Over the years, the Stirling engine designs had changed. There were a lot of ideas and technical solutions to reduce these costs. Reviewing the existing proposals of these engines a lot of attention focus on motor made by Polish constructor called WASE 2. Due to reasons of size and technical, it might apply to the recovery of exhaust heat energy.

3.1.2. WASE 2

It is a non-piston, rotary Stirling engine. The WASE states from Wąsowski Andrew Stirling Engine 2.

The motor is composed of two hermetically closed cylinders. Each cylinder has eccentrically arranged rotary sinker. The cylinders together with the rotary sinkers may be arranged in series or in parallel systems. Sinkers are aligned out of phase. Therefore, if one side is heated, opposite is cooled, and axis with sinkers is being rotated, it gives overpressure in one cylinder and under pressure in other cylinder. Overpressure and under pressure in cylinders is "rectified" by a set of four pneumatic valves suitably configured to provide constant overpressure and under pressure on the output [2]. Method of rectification is similar to rectifying bridges to change AC voltage into DC voltage.

The pressure difference is constant and it is transferred to the motor, located on the same axis with two rotary pistons. In a consequence positive feedback is observed – mechanical work on a common axis and power depended only on the temperature difference between the walls of cylinder.

3.2. Changing mechanical energy into electrical energy

There are several solutions to convert mechanical energy into electricity. The principle is electromagnetic induction, which is directly related to Maxwell's equations that define the induction of currents. To use electricity, electromotive force has to be received in the system. An electromotive force is generated in an electrical conductor, which encircles a varying magnetic flux. The varying magnetic flux is formed through alternating magnetic field in the circuit or by changing the position of the circuit in constant magnetic field. Time varying magnetic field generates a wave electric field and conversely. This effect is the basis of operation of generators, power transformers, electric motors and radio. Solutions that can be used to convert mechanical energy into electrical energy are:

- Classic Generator,
- Alternator,
- American type of Generator.

3.2.1. Classic Generator

The generator (power generator) is a simple device that is used to convert mechanical energy in the current flow. The main components of the generator are a stator (stationary part connected to the housing) and a rotor (rotating part within the stator). A stationary structure provides the magnetic field, winding coil of the rotor cross the magnetic field and varying electromotive force is induced. To the ends of winding coil, there are attached commutators – conductive rings connected to the external circuit unit.

There are many types of generators, differing only in technical details. These solutions are quite similar to the types of electric motors. In fact, the electric motor can work as a generator and the generator may be a motor. However, generators have many disadvantages; and have been replaced by alternators in motor vehicles with combustion engines. The main disadvantages are:

- large size,
- low efficiency,
- low reliability level,
- periodical carbon brush replacement.

The advantages are:

- simple design,
- easy access to the brush holders,
- no rotating or fixed electronic components,
- voltage stability.

3.2.2. Alternator

The alternator is a generator of alternating current. In the alternator, current is produced in the fixed stator windings by the rotating magnetic field of the rotor. It is commonly used as a power source for vehicles. The alternator is more efficient and more reliable than current generator. The main difference between alternator and generator is that the main working windings are placed in the stator, not on the rotor, so there is no need for a commutator. The alternator is operating similarly to the AC generator through the windings of the rotor. In addition alternator has one winding axially wound and a ferromagnetic elements form magnetic field to have varying magnetic field through the stator winding (stator) during rotation of the rotor.

To ensure co-operation with a battery that requires a DC voltage, alternator has a built-in silicon rectifier diodes. Sometimes it also includes a built-in voltage regulator. The advantages of this solution are:

- lightweight construction,
- receiving the maximum current value even at low rotation speed,
- smaller size than conventional generators,
- good efficiency.

The disadvantages are:

- very high rotation speed needed to get voltage higher than the battery voltage,
- voltage-dependent speed (the possibility of damage of electrical equipment),
- difficult design.

3.2.3. American type of Generator

American type of generator is currently very popular in industrial applications. Its construction is based on neodymium magnets and coils. Voltage is generated by the movement of the electrical conductor (wire) in the magnetic field, which is formed by pair of magnets. There are numerous solutions differing in number, shape and arrangement of both the magnets and coils.

There are also few construction solutions:
- stator with windings outside and the rotating rotor inside,
- stator inside and a ring shape rotor outside,
- stator between the rotating disks with embedded magnets.

The advantages of these generators are:
- simple design,
- slow movements,
- permanent and stable design,
- trouble-free operation,
- low internal resistance,
- self-realization possibility.

The disadvantages are:
- very high components cost,
- cannot be used to get a high current value (above 10 kW).

4. Conclusion

There are many solutions for direct and indirect methods of energy conversion from heat to electricity well known. Nevertheless, there are no perfect solutions and this is area that can be used for further searching and development. Current solutions do not meet all customer requirements, so it is worth to find a way to combine best practices and develop one device that fulfil installation needs.

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