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Proposal of a Thermoelectric Microgenerator based on Seebeck Effect to Energy Harvesting in Industrial Processes

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Abstract.

This paper presents a study of the national electric power, showing the Brazil consumes electricity in a year and how much you could save if thermoelectric modules were used in some industries and new cars and planes to capture and transformation of residual thermal energy into electrical energy. The conclusion appears really attractive economically, given the fact that many processes generate residual thermal energy and also energy cogeneration using thermoelectric modules is totally clean, which prevents the emission of greenhouse gases to the environment.

Key words

Green Energy, Energy Harvesting; Microgeneration, Seebeck Effect and Thermoelectric Modules.

1. Introduction

As technological development and concern about global warming, the quest for power generation through alternative sources is increasing [1]. Today, electricity is a pretty basic for the development of the population, which improves the quality of life by providing social and economic growth.
Currently we live in an energy crisis that has been evidenced by the limits of energy supply required for the demand of the development, which is based primarily on non-renewable sources [2]. Along with the great dependence of these types of sources, has also the environmental impact, mainly due to the pollution that is a result of production activities that use these types of energy resources.
In view of this, the energy issue has become vital for all countries of the world, are extremely important to reduce dependence on fossil fuels, which today is the most widely used form of generation, finding sustainable solutions to help energy matrix of all countries and minimize the overall environmental impacts, prioritizing the need to replace this by other renewable energy source [3].
To Brazil, the stakes are high for the energetic exploitation of natural resources, as they are scattered unevenly in various regions of the country. Often, the Brazilian potential for generating energy through renewable resources is touted as one of the largest in the world [4].
With the increasing need for clean energy sources, renewable energy from the thermoelectric phenomenon, has emerged as an alternative among the possibilities. This is due to the fact the thermoelectric modules present certain advantages, such as high durability, high accuracy and low volume, besides being a way of Green Energy.
Thus, this paper presents the advantages and applications of thermoelectric modules in the domestic market, using the residual energy harvesting for power cogeneration. Thus, the analysis of their impact on the electricity sector and improving the overall energy efficiency of electrical systems will be shown, proving environmental and economic benefits of the use of thermoelectric modules.

2. Thermoelectricity

The thermoelectricity is the conversion of thermal energy into electrical energy through a temperature gradient. This phenomenon is reversible and is mainly based on the Seebeck effect and the Peltier effect [2,5,6].
The Seebeck effect was discovered accidentally in 1821 by Thomas Seebeck, verifying that two conductors of different states at their tips and a temperature difference between them, metal materials made with a needle that was between them was shifted [5]. Between 1822 and 1823 Thomas Seebeck published his findings stating that conductors (or semiconductors) produce a different

voltage when they are united with the ends and subjected to a temperature gradient [7].
In 1834 Charles Jean Peltier discovered another thermoelectric effect known as Peltier effect, which unlike the Seebeck effect, when electric current (direct current) flowing in the circuit made up of different conductors causes the conductors coupling the cool or warm, depending on the direction of the current. The amount of heat consumed is proportional to the current flowing in the conductors [1,5].

3. Thermoelectric Modules

A thermoelectric module converts thermal energy into electrical energy and vice versa consisting of a matrix formed by multiple bimetallic junctions connected in series to increase output voltage, and in parallel to increase output current. [2]
These are able to operate as generators temperature gradient or as generators of electricity in direct current [2]. Each bimetallic junction element is constituted by a p-type semiconductor and n-type, they are connected in series and grouped in pairs surrounded by a sheath ceramics. The ceramic plates have copper busbar that allows linking semiconductors electrically in series and thermally in parallel [1].

Currently, we use many joints to maximize the power delivered by the module. In Figure 1 presents a series of junctions grouped in matrix form, forming a set, known thermoelectric module [1].

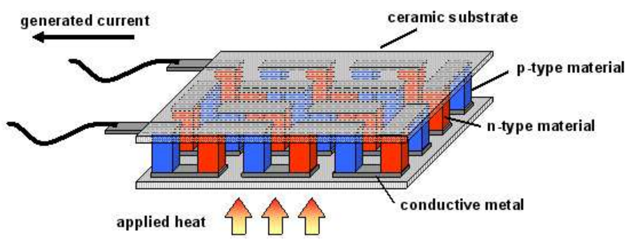

Fig. 1 – Thermoelectric modules

The modules are in their datasheet specifications and temperature information relating to voltage, current and power modules can provide, beyond the dimensions and other characteristics necessary for their use. It is observed that as there is a high temperature gradient, the values of voltage and current increase proportionally.

4. Thermoelectric Generation

The thermoelectric power generation is based on the Seebeck Effect. When heat is applied to the junction of two different conductors, a voltage is generated. The temperature difference between the hot side and the cold face is directly proportional to the voltage generated.
When heat is applied to a surface of the thermoelectric generator, electrons from the n-type semiconductor and the gaps of the p-type semiconductor will move away from the heat source. This movement of electrons and holes gives rise to an electric current. The current direction is opposite to the movement of electrons, so in the same sense that the movement of the gaps. [3]
The performance of a system for generating electrical power using thermoelectric modules depends not only on the characteristics of the thermoelectric modules used , but a number of factors directly influence , like for example the temperature gradient , the converter used and charge on which to feed. [8]
The temperatures at which the system is exposed to influence the overall yield of the system because the greater the temperature difference, the greater is the voltage output of the modules. In addition, they generate oscillations in the output voltage of the thermoelectric modules, which will be mitigated by the converter responsible for decrease or increase the output voltage. This converter, in turn, also has certain income that affects the system. The charge also influences the yield, since the maximum energy transfer is obtained when the electric resistance inside of the module is equal to the electrical resistance of the load.

5. State of the Art

With the discoveries made by Thomas Seebeck and Jean Charles Peltier, a story about the thermoelectric phenomenon began to be deepened and further studies and research began to emerge. Due to the findings of the ideal characteristics of a thermoelectric material, various semiconductor materials have been investigated and some alloys with higher efficiency have been created [5].
In the '60s, the thermoelectric phenomenon was at its height when it was thought that soon all refrigeration applications would be replaced by thermoelectric modules [6]. But over the past five decades the development was not expected because the coefficient of performance of devices for cooling by Peltier effect is still 4-5 times lower than that for conventional cooling systems [7].
Even with the low performance considered, applications for higher powers are growing, such as in automobiles, airplanes and industries, and the results of its application are amazing, as will be shown below. The reason are the advantages such as high durability, high precision and small occupation space, besides being a totally clean source of energy.

A. Applications to Combustion Vehicles

In the car the reuse of part of the thermal energy released in the exhaust began to be studied and show progress recently. The first thermoelectric generator was built and published by Neild in 1963. In 1993, the Hi-Z succeeded, after a series of improvements, generating 1068W in a truck [7].
In 2005, BMW was able to generate 500 Watts with a temperature gradient of 207 ° C and 3000 engine displacements. This power can be used to power systems such as air conditioning, radio, or even GPS. This company claims that this technology can improve the fuel usage up to 10% without producing any CO_2 emissions [7].
Based on results obtained by General Motors, the future of thermoelectric generators will replace the alternator of the motor, and the next 3 years will appear the first cars without alternator [7].
Some studies indicate that using thermoelectric converters with an efficiency of 5% would increase by

6% (1% of the cooling system and the exhaust 5%) to power a car [9].

B. Applications in the aeronautical industry

For higher powers the first applications of thermoelectric modules were in the Voyager I spacecraft developed by the National Aeronautics and Space Administration - NASA, today several spaceships using this technology for their "space missions". As these missions require security and reliability for a long term energy and heating of spacecraft nuclear batteries that convert heat into electricity via thermoelectric principle are used [10].
Today, aviation also these generation systems are used. The applications of thermoelectric effects are experienced in the areas of refrigeration, air conditioning, cooling of embedded electronics and power generation [11]. Studies of Boeing Research and Technology show that the application of modules is still limited due to efficiency and cost, but show a reduction in weight of the airplane, and a reduction of more than 0.5% combustible [12].

C. Residential Applications

Because of the need of conservation of energy, increasingly often studies for the application of thermoelectric modules. Accordingly, many alternatives arise. In industries have not yet found such studies, but the sites of application are many, such as in ceramics, thermoelectric plants, foundries, and others that use some kind of system involving thermal differences.
One such application is in wood stoves where some tests have been made. The first study ara this application was developed by Hi-Z technology in 2002. The same is 20W and capable of generating an output voltage Vcc from 12 to 14 [13].
Knowing that the tension generated by the system can then feed loads or battery charging, this model of generator can produce attractive results in energy savings. In industries can be constructed models with larger powers and, since the application sites are larger and varied. In these places, you can also find higher temperatures which increases the efficiency of thermoelectric generators.

6. Proposal for Microgenerator

A thermoelectric microgenerator to energy harvesting based on the Seebeck Effect with heat transfer system interchangeably. Composed of two heat transfer systems, one for capture of waste heat from industrial processes consisting of a module called the heat captor interchangeably. This being responsible for making the convective heat transfer process to the heat transfer block where they are Thermoelectric modules. While the second it is a hybrid system consisting of cooling fins and cooling block planned to improve the area of contact with the thermoelectric modules.
In Figure 2 we present the design prototype conceived microgenerator that is characterized by being a Regenerative System Full aiming Cogeneration of Electricity by capturing the waste heat (energy harvest) of industrial processes transforming thermal energy directly into electrical energy through the thermoelectric effect.

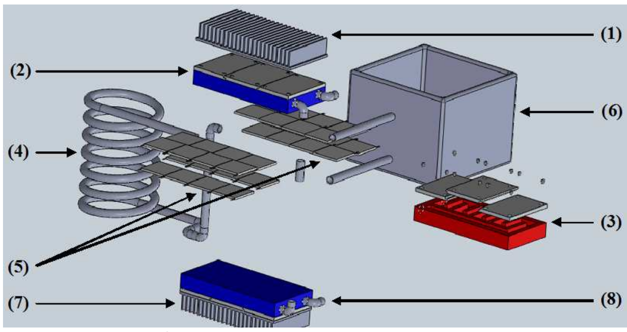

Fig. 2 - Drawing of the proposed prototype microgenerator

As can be seen in Figure 2 the prototype consists of two heat transfer systems, one for capture of waste heat from industrial processes consisting of a heat transfer module (3) and interchangeable heat sensor (4). Which is responsible for making heat transfer (4) of the convection process to block heat transfer (3) where are the arrangement of thermoelectric (5) modules.
The second system is in a hybrid system composed of cooling fins (1, 7) and planned cooling (2, 8) block to improve the area of contact with the thermoelectric modules. In the reservoir (6) is used cold water for cooling. This water can also be porveniente other industrial open cases circulated to the cooling blocks (2). This thermal system developed also allows adaptation to the process by replacing the heat sensor (4) optimizing the thermal transfer to the microgenerator.
Subsequently, we have the electrical system that is preconceived by a calculation methodology for the design and dimensioning of electrical micro sources of power generation based on the Seebeck effect, from curves of theoretical performance of thermoelectric modules and temperature gradients predetermined scale industrial processes enabling and determine the best arrangement of thermoelectric modules (5) and signal conditioning (voltage and power) is better suit the operating condition of the load to be supplied, and the conditions of operation any industrial process (temperature gradient), enabling the optimization of the thermoelectric power generation microgenerator.
As a product has been the design and sizing of a system of interchangeable heat transfer, which together with the methodology for calculating electric, results in a thermoelectric prototype microgenerator based on Seebeck effect to harvesting energy. It is noteworthy that the thermoelectric microgenerator this is a new and innovative development as the modular design and reconfigurable topology microgenerator thermoelectric harvesting energy
The Figure 3 shows a picture of the prototype developed microgenerator.
This thermal system developed allows its adaptation to the process by changing the sensor heat optimizing heat transfer to microgenerator. While the electrical system is prearranged through a calculation methodology for the design and dimensioning of micro electric power generation sources based on the Seebeck effect , from theoretical performance curves of thermoelectric modules and temperature gradients predetermined processes allowing industrial scale and determine the best arrangement of thermoelectric modules and signal conditioning (power and voltage) that best fits the

operating condition of the load supplied as well as the operating conditions of any industrial process (temperature gradient), which enables optimization of power generation thermoelectric microgenerator.

Fig. 3 - Demonstration of the prototype developed microgenerator

How has the product design and scale of a heat transfer system that interchangeably with the methodology of calculation results in electric prototype based on thermoelectric microgenerator Seebeck effect to capture residual energies for experimental validation.
It is noteworthy that the thermoelectric microgenerator it is a novel development and innovative about the design modular and reconfigurable topology of thermoelectric microgenerator to energy harvesting.

7. Validation microgenerator

The prototype has been designed to be able to supply a load of approximately 40W, the output voltage of 10VDC to a gradient of average temperature of 500 ° C. For this we used 40 inbC1-type thermoelectric modules 127.08HTS, Thermomanic the mark on the electrical arrangement comprising twenty modules serial number associated with two sets in parallel, and the modules 40 are arranged in two layers per side, where each layer consists of 10 modules (thermal pool).
Assays were performed with the lower limit of operation of the cogeneration desenvuelto (2000ºC) system gradients due to safety laboratories and limitations of pumping heat (1000°C) system available.

A. No-Load Test

The no-load test consists of applying a certain temperature gradient sobreos thermoelectric modules and measure the magnitudes thermal (hot and cold source temperature) and the voltage generated at the output terminals.
In Figure 4 the results obtained from the application of thermoelectric modules model inbC1-127.08HTS, possible to verify the ascending ramp gradient system temperature to its stability are presented.
Based on the data in Figure 4, it is seen that the voltage generated varies constantly with the temperature gradient generated by the system, emphasizing the need to use a DC-DC converter on the output to maintain a fixed voltage generated by system. Moreover, it is noticed that the average voltage generated after entering the cogeneration system in steady state is about 29.07V for a temperature gradient of 62.81°C.
In order to have a benchmark was performed testing the prototype using thermoelectric module TEC1-12706 model. Their results are shown in Fig 5.

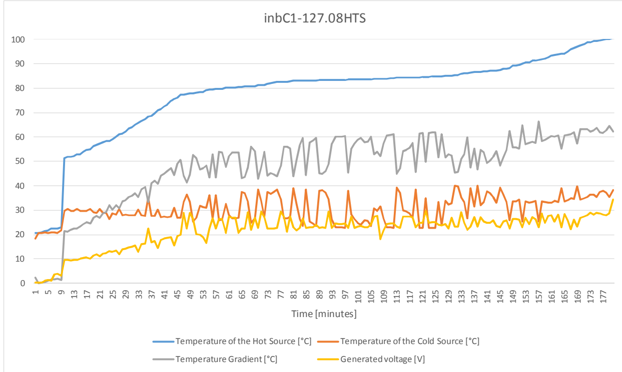

Fig. 4 - Statement of the results obtained in the no-load test (inbC1-127.08HTS)

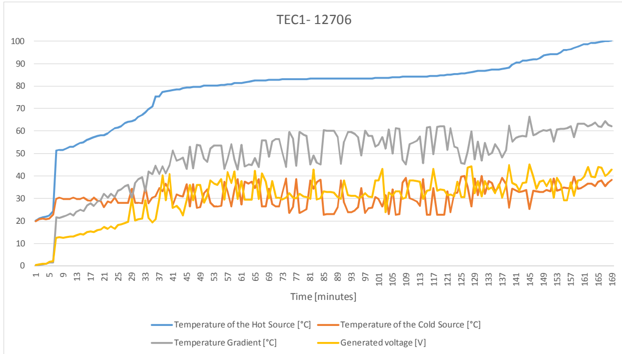

Fig. 5 - Statement of the results obtained in the no-load test (TEC1 - 12706)

Looking at Figure 5, we note that the voltage generated by the thermoelectric module TEC1-12706 model behaves analogously to the thermoelectric module inbC1-127.08HTS model, varying with the temperature gradient generated by the system. However, it is noticed that the average voltage generated after entering the cogeneration system in steady state was approximately 37.80V for the same temperature gradient of 60.84°C.
Therefore, it is stated that the thermoelectric module TEC1-12706 model features a performance of generated voltage higher than 30% when compared to model-inbC1 127.08HTS, being subjected to small temperature gradients.

B. Load Test

The load test is to apply a particular temperature gradient on the thermoelectric modules and measure the thermal quantities (hot and cold supply temperature). However, in this essay, it is necessary to connect a load to the terminals of the modules, so that the electrical parameters are also measured at the output terminals that feed the load.
The purpose of this test was to measure the maximum load that the system could supply without varying the voltage at the output terminals (10 V). Therefore, we used a varistor 0-100Ω load as a variable, thus obtaining the maximum power generated by the system as a function of the temperature gradient.
The results obtained using the thermoelectric module inbC1-127.08HTS model are presented in Figure 6.

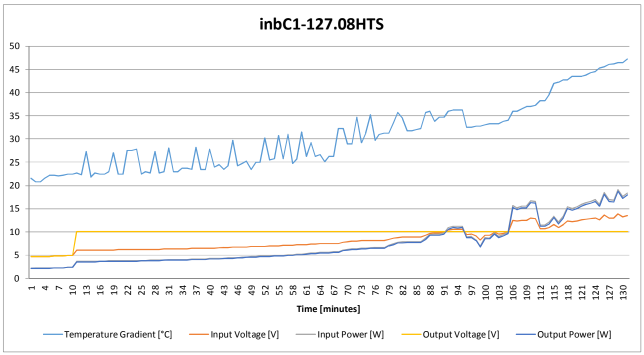

Fig. 6 - Statement of the results obtained during testing under load (inbC1-127.08HTS)

Similarly, the results obtained for the model TEC1-12706 thermoelectric module shown in Figure 7, measuring from the ascending ramp up the temperature gradient in the thermal stability of the prototype transfer.

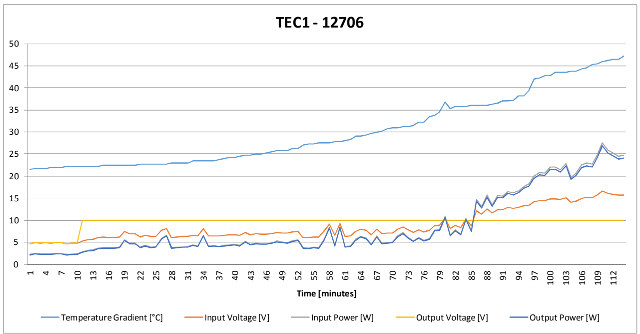

Fig. 7 - Statement of the results obtained during testing under load (TEC1 - 12706)

From the results shown in Figure 6 and Figure 7, it is seen that the output voltage of the DC-DC converter remains stable and fixed at 10V (yellow line) throughout operation of the system, unlike the voltage generated (orange line) by the arrangement of thermoelectric modules, which varies proportionally with the gradient system temperature. The only time that the output voltage remains fixed at 10V and when the tension is generated (orange line) is less than 5V, this occurs because the DC-DC converter was designed to operate with input voltages from 5V to 35V.
As regards the powers generated (gray line) by the arrangement of the modules and the power delivered to the load (dark blue line), there is a small decrease in power load for the power generated by microgenerator. This variation is owed to the performance of signal conditioning (DC-DC converter) system, ranging from 0.92 to 0.98, causing some difference between the powers.
In Figs 6 and 7, it is also possible vizualisar the increased power output (gray line) with increasing temperature gradient (light blue line), that is, the greater the temperature difference between the hot and cold sources, proportionally greater the net power provided by the system.
The microgenerator developed with thermoelectric module model inbC1-127.08HTS could provide a power of about 17.46W, with a temperature gradient of 46.33°C. Since the microgenerator developed with the thermoelectric module TEC1-12706 model generated a power of approximately 24.81W, with a temperature gradient of 46.18°C.
When comparing the results obtained under test with the theoretical results (present in the datasheet), which for a temperature gradient of 50 ° C we obtain 40W of power, one realizes that the microgenerator developed with thermoelectric module inbC1-127.08HTS model has a value lower than expected performance.
It is noteworthy that this range of values is due, in large part, by varying the temperature at the contact surface of the modules possess a temperature difference of up to 7°C from one end to the other.
Therefore, given the different actual weathering to which the system is exposed both in the generation and in the signal acquisition system, means that the results obtained are suitable for an experimental prototype bench and which in turn demonstrate the functionality and effectiveness of the proposed microgenerator.

8. Analysis and Discussion of Results

In initial tests in order to prove the values of voltage and current in a circuit with a combination of sources in series and parallel, we could see that the result was also validated for thermoelectric modules, and when they are associated in total range of their values when the potential difference and are associated in parallel, the same has the current split circuit between them in proportion to their voltages.
The test to validate the application of the cogeneration system, some difficulties were encountered. First, the temperature gradient was not so high due to limitations of the bench system, and when the temperatures have stabilized the difference between the hot side and the cold side was close to 46°C. Even so, with this temperature difference, the answer regarding the system voltage was done as expected, since with the temperature read each module generated about 1.32V, as presented in the manufacturer's datasheet, generating a sufficient total voltage feed the DC-DC converter used.
Thus, it was proven that the system serves to capture losses in industrial processes and generate electricity to power small loads. Analyzing broadly, the thermoelectric microgenerator proposed, if implemented on a large scale, can help improve the energy efficiency of processes and reducing energy consumption.

9. Final Considerations

Based on the research and informations exposed, it is clear that cogeneration power using thermoelectric modules is a promising source and presents results feasibly economical with their use, especially if implemented on a wide scale. The results were very significant, considering that only a few systems have been analyzed in this model can be applied cogeneration.
It is also considered that studies and researches are made constantly to improve their efficiency and the requirements for reducing emissions of gases that cause global warming, as well as the need to use renewable sources are increasing, making the applications of thermoelectric modules become increasingly interesting and most sought after because arouses the interest of the government and industries to utilize this technology.
It is noteworthy that it is possible to achieve the application of the proposed microgenerator in various processes may well achieve high levels of power, with

the implementation of a cogeneration system in large scale and high temperature gradients. It is known today that the application of these thermoelectric modules and often tied to use in cooling systems, but they also bring economic returns when used for power generation by capturing losses.

Ends up emphasizing that there are other industries with great potential to capture energy waste to energy cogeneration. Among these are the power plants (8.5% of the national power generation) processes, foundries and potteries, and especially the fleet of buses and trucks.

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