The Experimental Study of Heat Waste Conversion into Useful Electric Power

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Abstract ***– This paper presents the practical results of the design solutions, executing and experimental testing of a prototype model of o thermoelectric generator, based on the conversion of residual thermical energy into electric power, by improving the Seebeck effect. To this purpose, high performance thermoelectric modules have been used, taken from the recent production of the American Corporation Hi-Z Technology. The prototype thermoelectric generator built for a demonstrative purposes has got the low efficiency category. The results taken from the tests and experimental measurements have shown theimportance of the constructive solution of materials and technologies that have been used. These results direct the functional reliability growth and energy conversion efficiency. The functional performance and conversion capability evolution are directly conditioned by progress that will be registered through heavy research for the performance of the semiconductive materials with thermoelectric characteristics stressed out by the so-called high figure of merit.***

Keywords: ***Seebeck Coefficient, thermoelectric module, figure of merit, performance coefficient, recovery, re-conversion.***

I. INTRODUCTION

In the present, approximately one third of the consumed energy for thermic end processing is dissipated in the atmosphere as losses, which are particularly due to the users' lack of efficiency and ability to manage the energy excess.

The biggest part of the energy losses is however of low quality and therefore, impossible to economically recovered.

Still, it is possibly for approximately 20% of the option for energetic recovery and reconversion by using various technologies which also include today the thermoelectric ones in the purpose of reconversion as common electric power [2].

Thermoelectric materials have initially been used in applications imposing smaller spaces for thermal energy conversion into electric power with an efficiency of 2% - 5% [2].

The development of advanced semiconductor materials offers new opportunities for thermal energy loss conversion with higher efficiency and more advantageously economic – in conditions of higher reliability and with relatively passive systems which do not produce vibrations and toxic gas.

Great part of the industrial thermal waste is contained in gasses evacuated at ~150ºC, a temperature that represents low quality heat and thus, lacking in recovery interest. Furthermore, this temperature field is too low for the thermoelectric generator (TEG) to function efficiently. The new thermoelectric materials offer economic efficiency to the conversion, from 15% up to 25%, with the sole condition that, during operation, the temperature on the heating side is between 450ºC÷750°C [2].

The recent progress in the field of the nano-sciences and nano-materials brings forth the future possibility that the present figure of merit of $ZT \sim 2$ to rise to the higher value of $ZT \sim 4$ [2].

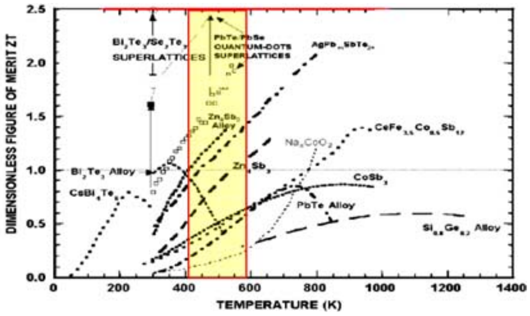

Figure 1 – The Environmental Factor for Various Thermoelectric Materials and Temperature Field [2]

TABLE 1. Types of thermoelectric materials for different uses

Temperature Level [K]	Used Material
Low Temperatures (150÷200),	Mostly used alloy are $Bi_{1-x}Sb_x$ with good thermoelectric properties only for N type, which reduces the conversion efficiency (the type P material is inefficient at this temperature) [2].
Ambiant Temperatures	Bi_2Te_3 and Sb_2Te_3 are alloy (type P samples identical with those type N with small variations of composition). In both cases, ZT ~1, at ambient temperature due to the low thermic conductivity λ (~1,1 $W.m^{-1}.K^{-1}$) [2].
Middle Temperatures 550÷750	One very used material is PbTe and its alloy (PbSn)Te. The problem is that PbTe cannot become a thermo element for both P and N types [2].
High Temperatures > 1000	Alloy based on Si and Ge have good thermoelectric qualities, especially for producing energy in the aeronautics field [2].

These materials offer possibilities for to build pilot systems with the purpose of fundamenting basic knowledge, of obtaining valid information and of gaining practical experience in the design solutions and functioning conditions. The knowledge may be successfully used in high thermal flux TEG systems equipped with ZT ~ 2 modules.

Research on interfacing systems for the thermoelectric generating systems with process equipment can generate important opportunities for the integration thermoelectric generating systems in numerous industrial applications.

As such, there is an important interest in perfecting the thermic losses efficient conversion systems, because regenerating energetic alternative can arise with continuous use possibilities for co-generating or even three-co-generating in useable energy forms such as heat, cold and electric power in randomly spaces or distributed on mobile systems as a portable energy.

II. THEORETICAL NOTES

A. *Constructive particularities*

Thermoelectric generating modules consist of several hundreds of P/N type thermocouples connected in series from the electrical point of view and in parallel from the thermal point of view. They are standardized for specific I/V outlets.

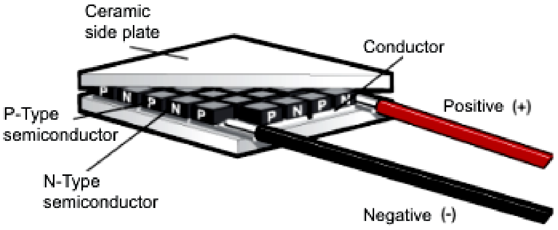

Figure 2: Construction of a Thermoelectric Module [5]

The thermoelectric effect unites the thermal flux that passes through a material with the intensity of the electric current that goes through that material. The thermoelectric characteristic of a material is shown by the Seebeck coefficient [1]:

$$S_{ab} = \frac{dV}{dT}\left[\frac{\mu V}{K}\right] \tag{1}$$

or :

$$S_{ab} = S_a - S_b \tag{2}$$

where S_s and S_b are Seebeck coefficients of the two materials corresponding to the junction.

B. *Thermoelectric Materials' Efficiency: Figure of Merit(ZT)*

Thermoelectric materials are caracterized by fowlling main properties:

• a high electric conductivity, in order to minimize the Joule effect over the variation of the resistivity;

• a the high Seebeck coefficient maximizes the heat conversion from electricity to thermal energy;

• low thermic conductivity makes difficult the thermal conduction through a material.

These three properties come together in an unique measure, whith represents the global performance of a thermoelectric device called material figure of merit. This is noted with Z and is defined by the following equation [2]:

$$Z = \frac{\alpha^2 * \sigma}{\lambda}\left[\frac{1}{K}\right]$$

$$where: \begin{cases} \alpha - Seebeck's\ coefficient\left[\frac{V}{K}\right] \\ \sigma - electrical\ conductivity \\ of\ material\left[\frac{A}{V*m}\right] \\ \lambda - heat\ conductivity \\ of\ material\left[\frac{W}{m*K}\right] \end{cases} \tag{3}$$

In order for thermic resistance to be minimized, the device must have high electric conductivity, while for maintaining a high temperature gradient a low thermal conductivity is necessary.

By modifying electric conductivity, there appears a proportional modification of the thermal conductivity and the other way around, fact which limits ZT growth.

The maximum thermal efficiency of an electric generating device is here given by the following equation [2]:

$$\eta_{max} = \frac{T_c - T_r}{T_c} * \frac{\sqrt{1+Z^* * \bar{T}} - 1}{\sqrt{1+Z^* * \bar{T}} + \frac{T_r}{T_c}}$$

$$where: \begin{cases} Z^* - optimal\ Z\ of\ p-n\ couple \\ T_c - hot\ side\ temperature[K] \\ T_r - cool\ side\ temperature[K] \\ \bar{T} - average\ temperature\ between\ T_c\ and\ T_r \end{cases} \tag{4}$$

This equation illustrated in the graphic below suggests that the efficiency amplitude varies with ZT and with temperature difference. This first term of the equation emphasizes the fact that the maximum efficiency is associated with the difference between T_c and T_r, similar with the Carnot cycle efficiency [2].

$$COP_{max} = \frac{Q_r}{P} = \frac{T_c - T_r}{T_c} * \frac{\sqrt{1 + Z^* * \bar{T}} - \frac{T_c}{T_r}}{\sqrt{1 + Z^* * \bar{T}} + 1} \quad (5)$$

$$where: \begin{cases} Q_r - capacitance\ of\ cooling\,[W] \\ P - electric\ input\ power\,[W] \end{cases}$$

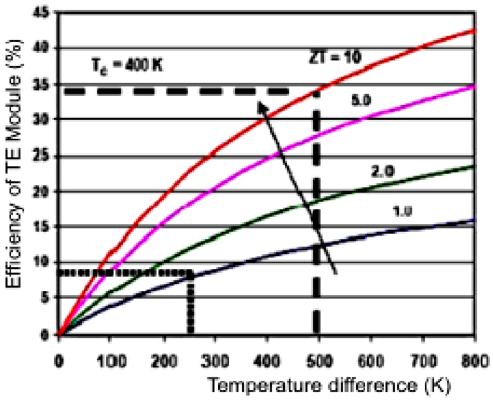

Figure 3 – Thermoelectric module efficiency depending on the temperature difference and figure of merit [3,4]

A good thermoelectric material will simultaneously have a high Seebeck coefficient, high electrical conductivity and low thermal conductivity.

C. Estimating the Generated Electric Power

The flux of the resulted heat extrated from the cold source is here defined by the following equation [1]:

$$Q_c = (S_p - S_n) * I * T_c - K * \Delta T - \frac{R * I^2}{2} \quad (6)$$

$$where: \{K - total\ heat\ conductivity$$

The electric power dissipated in the module through the Joule and Seebeck effect is [1]:

$$W = I * [(S_p - S_n) * \Delta T + I * R] \quad (7)$$

The output electric current value is determined through the following equation [1]:

$$I = (ZT)_{ave} * \frac{2K * (T_c - T_r)}{(S_p - S_n) * (T_c + T_r)} \quad (8)$$

For a given ΔT temperature difference the P-N junction efficiency used in electricity generating will exclusively depend on the given electric current, which will have to insure maximum of energy resulted from the cold source for two values [4].

$$\eta = \frac{I * [(S_p - S_n) * \Delta T + I * R]}{(S_p - S_n) * I * T_c + K * \Delta T - \frac{(R + r) * I^2}{2}} \quad (9)$$

Maximizing the conversion efficiency depends not only on the T_r şi T_c but also on the "figure of merit", where T_M represents the middle temperature of the system [2]:

$$\bar{T} = \frac{T_r + T_c}{2} \rightarrow Z^*_{pn} = \frac{(S_p - S_n)^2}{R * K} \quad (10)$$

IV. THE STRUCTURE OF THE EXPERIMENTAL MODEL

The experimental model was done with type HiZ 20 thermoelectric modules, having the following constructive-functional characteristics:

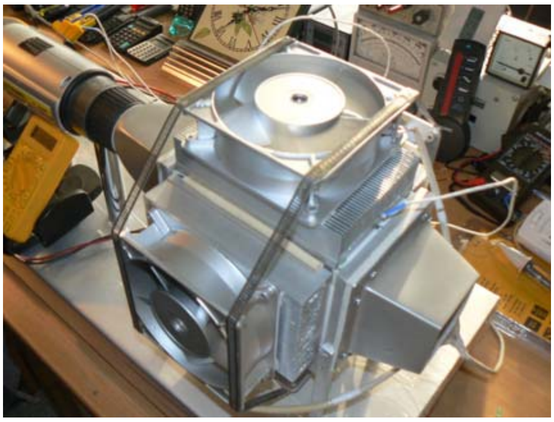

Figure 4: Construction of the thermic recovery of warm gasses and conversion into electric energy

TABLE 2. Properties of the HiZ-20 Type Module [5]

Physical Properties	Value	Tolerance
Constructive Properties		
Figure of Merit (Z)	~2	
Thermic Properties		
Nominal temperature on the heating side	230 ^{0}C	±10 ^{0}C
Nominal temperature on the cooling side	30 ^{0}C	±5 ^{0}C
Thermic conductivity (at nominal temperature value)	0.024 W/cm*K	+0.001 W/cm*K
Thermic flux (at adjusted load)	9.54 W/cm^2	±0.5 W/cm^2
Electric Properties of the Generator		
Power (at adjustable load)	19 W	Minimum
Voltage in load	2,38 V	±0.1 V
Internal resistance	0.3 Ω	±0.05 Ω
Current intensity	8 A	±1 A
Voltage without load	5 V	±0.3 V
Efficiency	4,5 %	Minimum
Seebeck coefficient (α)	0,0238 (V/K)	
Electric resistivity (ρ)	2x10^{-3}(Ω.m)	

An entire construction has been done for tests modeling an exhausting of burned gas pipe. The burned gasses have been assimilated by an air heater with levels of adjusting the temperature. The inside chamber of heat recovery the gas temperature has been equipped with Al heat sink with maximum thermic change surface.

Spreading the heat towards the exterior is done by another Al thermic heat sink with very good performance.

Furthermore, for growing the heat spreading performance and for maximizing temperature difference between the cooling and heating sizes of the thermoelectric module, the outer thermic change has been amplified by a ventilator.

TABLE 3 Components and characteristics produced by the prototype thermoelectric generator

Characteristic Parameter	Maximum Value	Tolerance
Gas maximum temperature (^{0}C)	250	
Thermic radiator temperature (^{0}C)	230	±10
Ambient temperature (^{0}C)	30	±5
Temperature difference (^{0}C)	< 200	Minimum
Voltage without load (V)	40	±2,5
Load voltage (V)	19	±0.8
Maximum internal resistance (Ω)	2,4	±0.4
Electric current intensity (A)	8	±1
Power (adjusted load) (W)	152	Minimum
Transferred thermic flux (W)	4293	±0.5
Maximum conversion efficiency (%)	4,5 %	Minimum

In the table bellow can be analyzed the electric loads used in the experiment:

TABLE 4: Apparatus characteristics used as load

Consumer type	Apparatus type	Characteristics
1+2	Lighting bulb	4,8 $V_{c.c.}$; I=0,5 A;1,1 Ω
3	Walkman	3 – 5 $V_{c.c.}$;Z= 8Ω
4	Lighting bulb	12 $V_{c.c.}$; P=5 W;2,4 Ω

V. SIGNIFICANT RESULTS

TABLE 5: Type 1 consumer measured data

ΔT module determination			
Heating side temperature	T_c [^{0}C]	Measured	140,9
Cooling temperature	T_r [^{0}C]	Measured	56,8
Temperature fall	ΔT [^{0}C]		84,1
Middle temperature	T_{med}[^{0}C]		98,85
Validating module integrity			
Precision of the resistive load	R_s [Ω]	Measured	1,1
Load voltage	V_s [V]	Measured	6,94
Voltage without load	E_0 [V]	Measured	6,97
Power consumed on load	P_s [W]	Measured	3,851
Efficiency	%	See graphic	0,85
Pumped heat on the cooling side	(W)	Calculated (eq.6)	1384
Optimum electric current intensity	(A)	Calculated (eq.7)	0,965
Optimum COP (calculated with I_{opt})	(%)	Calculated (eq.5)	0,528

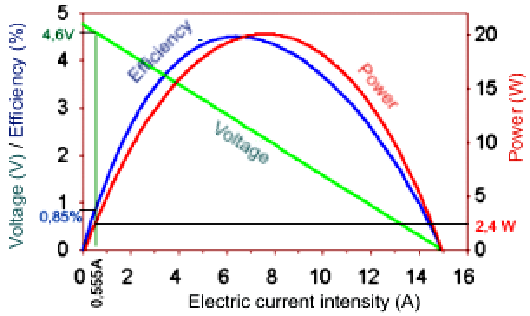

Figure. 6: Power, voltage on load and on module [5]

VI. CONCLUSIONS

The experimental model has brought to light a series of designing suggestions, thus:

- Output voltage, together with conversion efficiency and available power are significantly influenced by the temperature difference between the heating side and the cooling side of the thermoelectric generator;
- The generator's performances are affected by improper thermic isolations, even on relatively isolated areas;
- Performances of thermic transfer and the generator's output parameters grow together with the warm gas debit growth as well;
- The generator's maximum performances correspond to the situation when the resistance of the connected load is close to the individual resistance of the thermoelectric equipment;
- Nominal performances of the thermoelectric generator correspond to a temperature difference of < 200 ^{0}C.
- The maximum exit power can be obtained only in the case of an efficient system of forced cooling on the cold side and of the use of cooling fluid.

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