EXPERIMENTAL PERFORMANCE OF THERMOELECTRIC MODULES APPLIED TO POWER GENERATION

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Abstract. *It is known that thermoeletric and eletric effects are detected in a circuit made of semiconductor materials kept in different temperatures. This phenomenon called Seebec effect and Peltier effect can be used to generate eletric power and cooling. The Seebeck effect was first observed by the phisician Thomas Johann Seebeck, in 1821, when he was studying thermoeletric phenomenon, and consists in the production of a eletric power between two semiconductors join of different materials when they are under different temperatures. The thermoeletric modules are made of several thermoeletric pairs made of semiconductors materials joined in series and sealed between two surfaces of ceramic material, one covers the hot joins and the other covers the cold ones, through which a continuous current flows and, according to its way, one board becomes hot or cold, and the dissipated power is fuction of the eletric current flowing through the module. This paper presents, initially, the theoretical equations that allows evaluating the thermoeletric modules' performance applied in the eletric power generation and the experimental results of this elements association. During the tests there were used thermopairs to evaluate the temperatures in the thermoeletric module's hot and cold sides, thermo-anemometers to mesure the air speed and temperature measurements in the heat sink and a software to obtain, store and analyze this data. The main objective is to know the behavior of the most important project parameters that are the efficiency and the electric power generated by the thermoelectric system.*

Keywords*: thermoelectric module, Seebeck effect, thermoelectric power generation*

1. INTRODUCTION

It has been known for over a hundred years that reversible thermal and electrical effects can be detected in a circuit consisting of two dissimilar wires having their junctions at different temperatures. That these thermoelectric effects could be used for the production of electric power and refrigeration has been realized for almost an equal length of time; however, the problem has been, and is, the development of the appropriate materials and the development of the best engineering techniques for their utilization. This paper presents the theoretical equations that allow evaluating the performance of a thermoelectric power generator system based on the thermoelectric effect and also presents the experimental results of tests applied on a thermoelectric device composed by modules used for simulation of a small power generator.

Basically, thermoelectric power generation is a solid state means of converting heat flow directly into electrical power via the Seebeck effect. High temperature energy sources have historically been utilized because of the inherent higher efficiency at high temperature differences. However, there are many low level energy sources plentiful in nature which are candidates for thermoelectric conversion, for example, ocean thermals, solar energy, steam and various forms of waste heat. TE modules normally designed for cooling are the best choice for these applications because they are manufactured from materials of highest efficiency at these nominal temperatures. As such, they represent the highest efficiency devices possible for use as thermoelectric power generations for low intensity energy sources (Buist and Lau, 1997).

Thermoelectric devices offer several advantages over other technologies (Riffat and Ma, 2003): they have no moving parts and, therefore, need less maintenance; they contain no chlorofluorocarbons; the direction of heat pumping is reversible, i.e., changing the polarity of the DC power supply a cooler can then become a heater; they can work in environments that are too severe, too sensitive or too small for conventional refrigeration and are not position-dependent. Due to these advantages, thermoelectric devices have found very extensive applications in wide areas, such as military, aerospace, medical, microelectronics, laboratory, instrument and sensors, industrial and commercial products.

Several authors presented technical papers in this field. Wu (1995) presents a real thermoelectric power generator using waste heat. The generator is treated as an external and internal irreversible engine, comparing the system with a Carnot engine. Chen et al (2002) present the power output and efficiency expressions for thermoelectric generators which is composed of multi-elements. Numerical examples are provided. Luo et al (2003) applied the theory of finite time thermodynamics to analyze and optimize the performance of a multi-elements thermoelectric refrigerator.
Bass et al (2004) present a paper that discusses a new technology named MLQW (multi-layer quantum well) thermoelectrics that should increase four times he COP of thermoelectric coolers used in electronic cooling applications. Chen, Sun and Wu (2005) investigate the performance of multi-element thermoelectric generators

assuming heat-transfer irreversibilities and combining finite-time thermodynamics with non-equilibrium thermodynamics. The performance characteristics are described by numerical examples. Chen, Li, Sun and Wu (2005) analyze the performance of the generator assuming Newton's heat-transfer law and present the effects of design factors on the performance. Gamathy and Elsner present life tests data of a Si/SiGe films used to produce a thermoelectric module. Figure 1 shows a schematic of the Seebeck effect (thermoelectric power generator).

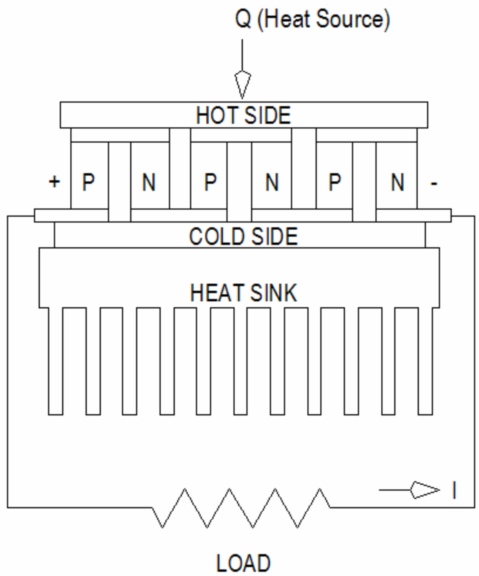

Figure 1. Schematic of a thermoelectric power generator

2. THEORY OF OPERATION

A thermoelectric device consists of several N & P pellets connected electrically in series and thermally in parallel sandwiched between two ceramic plates. When the thermoelectric module is operating as a refrigerator, the bottom plate is bonded to a heat sink and, with the application of DC current of proper polarity, heat is pumped from the top plate to the bottom plate and into the heat sink, where it is dissipated to ambient. The resultant is that the top surface becomes cold. The top surface can also supply heat by simply reversing DC polarity. The same unit can be converted into a thermoelectric power generator by simply replacing the DC source with the load, or item to receive power, and apply heat to the top surface of the TE modules as illustrated in Fig. 1. Electrical power is derived from the movement of electrical carriers brought on by heat flow through the thermoelectric pellets. Holes, or positive carriers, move to the heat sink side of the P–type pellet making that junction electrically positive. Similarly, electron flowing through the N-type pellets results in a net negative charge at the heat sink side of the N-type pellet.

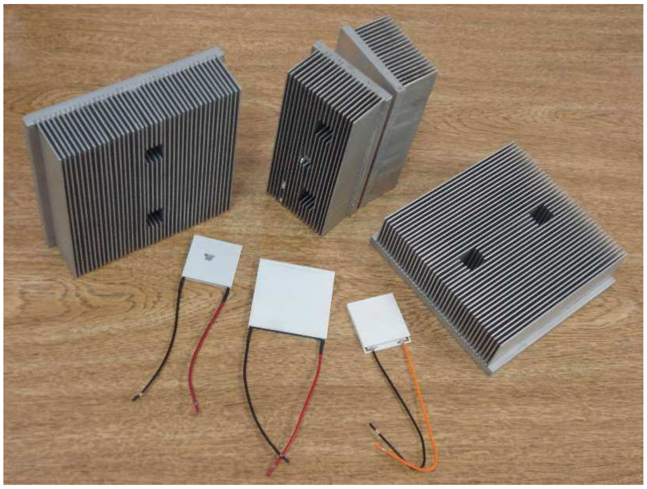

Figure 2. Thermoelectric modules and heat sinks

Figure 2 shows thermoelectric modules and heat sinks.

According to Buist and Lau (1997) "there are some important practical considerations that should be made before attempting to use thermoelectric coolers in the power generation mode. Perhaps the most important considerations is the question of survivability of the module at the anticipated maximum temperature. Many standard thermoelectric cooling modules are fabricated with eutectic Bi/Sn solder which melts at approximately 138ºC. However, there are some coolers being offered employing higher temperature solders designed for operating at temperatures of 200ºC, even approaching 300ºC. In any case, consideration should be given to operational lifetime of a thermoelectric module exposed to high temperatures. Contaminants or even constituents of the solder can rapidly diffuse into the thermoelectric material at high temperatures and degrade performance and, in extreme cases, can cause catastrophic failure. This process can be controlled by the application of a diffusion barrier onto the TE material. However, some manufactures of thermoelectric coolers employ no barrier material at all between the solder and the TE material. Although application of a barrier material is generally standard on the high temperature thermoelectric cooling modules manufactured, they are mostly intended for only short-term survivability and may or may not provide adequate MTBF´s (Mean Time Between Failures) at elevated temperatures. In summary, if one expects to operate a thermoelectric cooling module in the power generation mode, qualification testing should be done to assure long-term operation at the maximum expected operating temperature".

3. MATHEMATICAL MODEL

The important design parameters for a power generator are the efficiency and the power output. The efficiency is defined as the ratio of the electrical power output P_o by the thermal power input q_h to the hot junction

$$\eta = \frac{P_o}{q_h} \tag{1}$$

The power output is the power dissipated in the load. The thermal power input to the hot junction is given by

$$q_h = \alpha T_h I + \frac{1}{2} I^2 R + K\Delta T \tag{2}$$

where: α is the Seebeck coefficient, T_h is the hot side temperature of the thermoelectric module, I is the current, R is the electric resistance (Ω) , K is the total thermal conductance of the thermoelectric cooling module and ΔT is the temperature difference between hot and cold sides (T_{h} - T_{c}). In the discussion of power generators, the positive direction for the current is from the p parameter to the n arm at the cold junction. The electrical power output is

$$\mathrm{P_0} = \mathrm{I^2 R_L} = \mathrm{V\,I} \tag{3}$$

where R_L is the load resistance. The current is given by

$$I = \frac{\alpha\Delta T}{\left(R + R_L\right)} \tag{4}$$

Since the open-circuit voltage is $\alpha\Delta\mathrm{T}$. Thus the efficiency is

$$\eta = \frac{I^2 R_L}{\left(\alpha T_h I + \frac{1}{2} I^2 R + K\Delta T\right)} \tag{5}$$

4. EXPERIMENTAL THERMOELECTRIC DEVICE

To analyze the mathematical model aiming to evaluate the performance of the system, an experimental thermoelectric device for power generation was build. Figure 3 shows the schematic of the experimental system.

The apparatus consist of a thermoelectric modules physically coupled in the cold side to a micro channel heat sink and this finned plate heat exchanger is inserted inside a duct made from aluminum with 0,065 x 0,035 m cross section, and have thermal insulation of polystyrene and fiberglass. The micro channel heat sink is made from aluminum, measuring 150x80x40mm, with 19 fins with a width of 2mm. The base of heat sink is 6mm thin. The hot side is coupled to a heat source. In this experiment it is a type plate electric resistance.

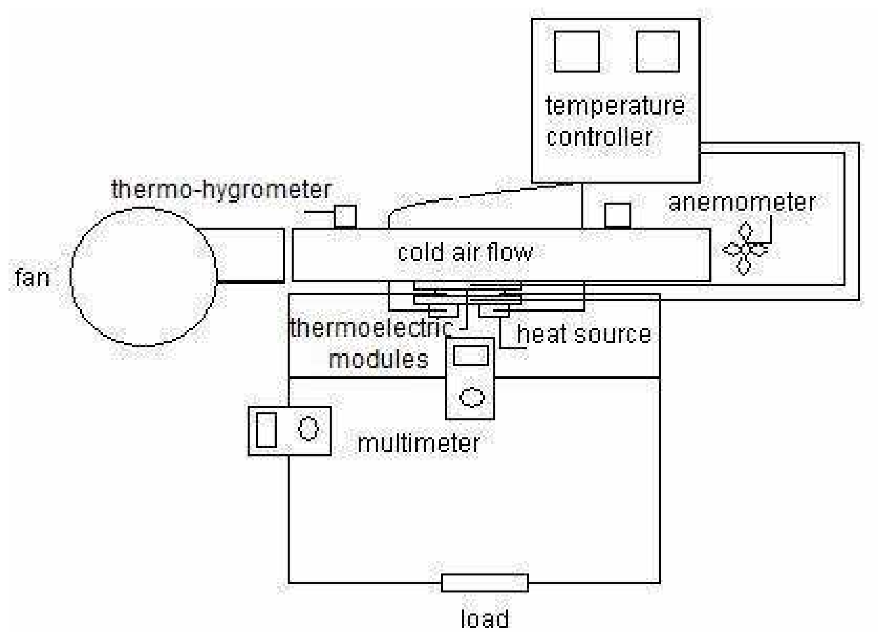

Figure 3. Schematic of the experimental system

The cold side fan has adjustable power and flow. The cold air flow is controlled by an air flow generator model "Marotec 8203-B". The air temperature and humidity are measured with thermo hygrometers model "Instrutherm HT-210". The speed of the cold air flow is measured with digital hot wire thermo-anemometer model "Instrutherm TAFR-180". The electric current and voltage are measured with multimeters "Minipa ET-1502 and ET-2052". The thermoelectric modules is a model TE Tecnology 0,04x0,04m, 16,5 V that can operate at maximum temperature equal to 80^{o}C. The temperature controller and measurement of the plates are made with thermocouples and a temperature controller model "Gefran 600, 220V". The characteristics of the thermoelectric modules are presented in Table 1.

Table 1. Characteristics of the thermoelectric module

Thermal conductance (K)	0.46 W/K
Seebeck coefficient (α)	0.0513 V/K
Thermal conductivity (k)	0.0151 W/ºC m
Electrical resistivity (ρ)	0.00101 Ω cm
Dimensions	40 x 40 x 3.6 mm
Number of associations (N)	127
Total resistance (R)	2.12 Ω

2.1. Methodology

Thermoelectric modules were connected in series with a resistance, making an electric circuit. An amperimeter and a voltmeter were connected to the circuit in order to measure the electric current and voltage supplied by the thermoelectric modules. Thermoelectric modules were isolated in order to avoid heat lost. Fan was adjusted to reach, helped by an anemometer, a constant velocity close to 8 m/s in the outlet of the cold air duct, resulting in 0,0182 m^3/s air flow. The heat source was connected to the temperature controller. There were monitored and measured: the temperature in the hot side of the thermoelectric modules (T_h), the temperature in the cold side of the thermoelectric modules (T_c), cold side inlet air temperature, cold side outlet air temperature, air speed in the duct of the cold sides of the thermoelectric module, electric current supplied by the thermoelectric modules and voltage supplied by the thermoelectric modules when the temperature in the hot side of the thermoelectric modules reach 50°C, 60°C and 70°C. The tests are according to ISO 5725-1 (1994) and ISO 5725-2 (1994). The accuracy characteristics of the measurement instruments are presented in Table 2.

Table 2. Characteristics of the measurement instruments

INSTRUMENT	MANUFACTURER/MODEL	RESOLUTION/ACCURACY
Thermo-higrometer	Instrutherm/HT-210	1°C / ± 0,05 %
Multimeter	Minipa/ET 2052	0,0005V / ± 0,5%
Multimeter	Minipa/ET 1552	0,005A / ± 0,5%
Hot wire thermo-anemometer	Instrutherm/TAFR 180	0,1 m/s / ± 5%
Temperature controller	Gefran/ 600	1°C / ± 0,5%

3. RESULTS

The performance of the thermoelectric power generator device is presented in Figs. 4 to 9. Figure 4 shows the voltage as function of hot side temperature (open circuit). Figure 5 shows the voltage as function of hot side temperature (load = 51 Ω), Fig. 6 shows the current as function of hot side temperature (load = 51 Ω), Fig. 7 shows the power output as function of hot side temperature (load = 51 Ω) and Fig. 8 shows the efficiency as function of hot side temperature (load = 51 Ω).

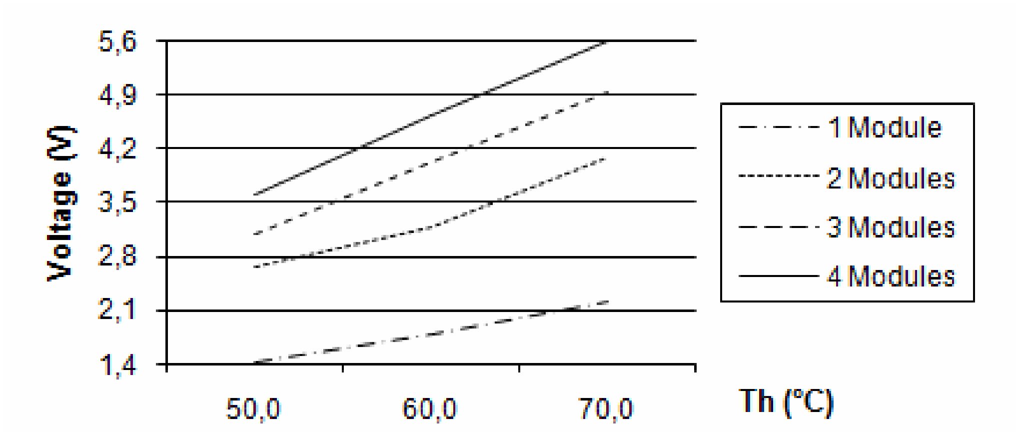

Figure 4. Voltage as function of hot side temperature (open circuit)

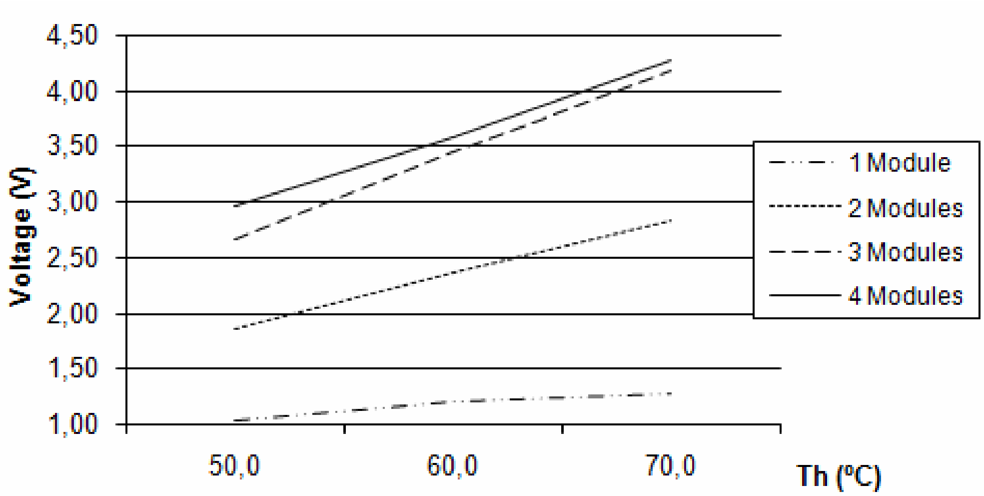

Figure 5. Voltage as function of hot side temperature (load = 51 Ω)

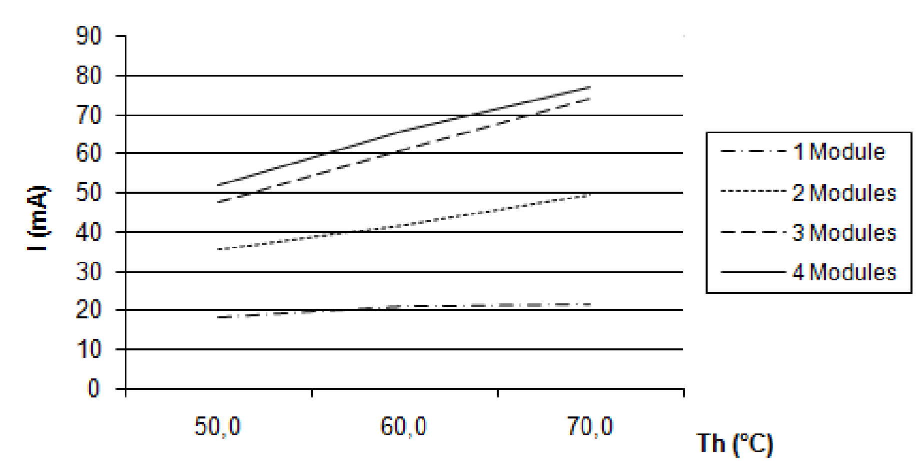

Figure 6. Current as function of hot side temperature (load = 51 Ω)

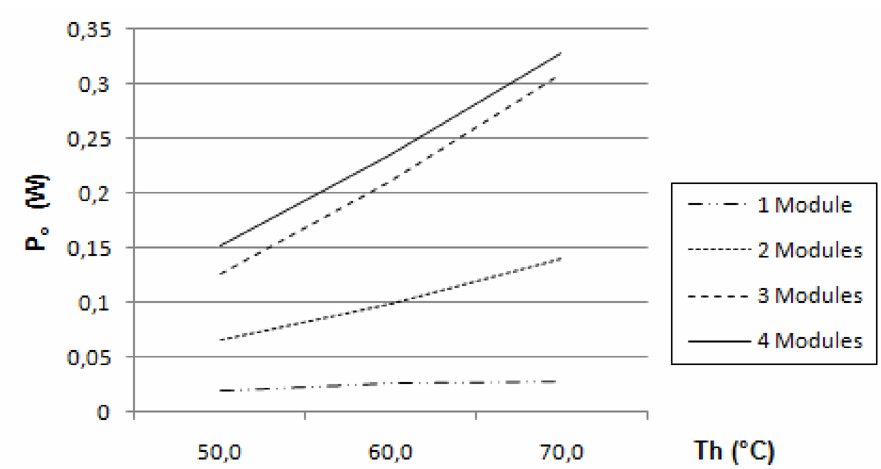

Figure 7. Power output as function of hot side temperature (load = 51 Ω)

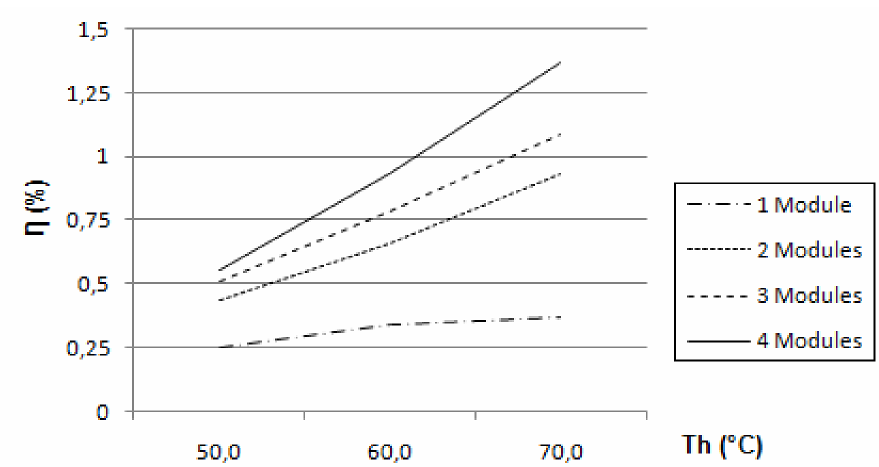

Figure 8. Efficiency as function of hot side temperature (load = 51 Ω)

It can be seen, analyzing the graphs above, that the most important design parameters for a power generator, that are the power output and the efficiency, increase when the hot side temperature increases.

It was also performed one test using a thermoelectric module designed to operate at higher temperatures. The result is shown at Fig. 9.

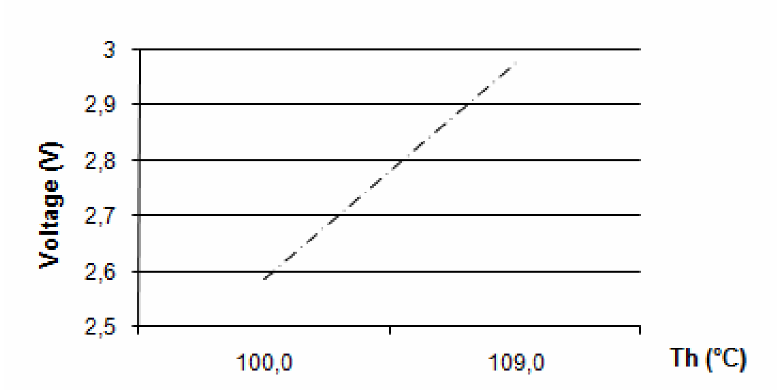

Figure 9. Voltage as function of hot side temperature

4. CONCLUSION

A thermoelectric application was investigated in this paper and it was presented the experimental results of tests applied on a thermoelectric device composed by modules used to convert heat flow to DC power for simulation of a small power generator. Generation of electrical power via thermoelectric devices has been a subject of interest for decades. This paper presents some of the unique features of these versatile devices together with some limitations and precautions. Finally, some performance curves are presented. It can be seen that the electric voltage and current generated is a direct function of the hot side temperature and that by coupling several thermoelectric modules it is possible to reach electric power commercially applicable. However, this application is only feasible commercially if waste heat is used as heat source, for example, automotive engine exhaust gases, garbage burning plants, camping stove burner, among others, once the conversion efficiency from heat directly to electricity is very low.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), Proc. 303301/2006-6.

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