STUDY OF THE INFLUENCE OF THE THERMAL RESISTANCE IN A THERMOELECTRIC GENERATION SYSTEM

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Abstract

In this research, we have made a computational study of the thermal resistance influence (both in the hot and the cold side) in the efficiency of a thermoelectric generation device.

With this purpose, we have developed a computational model. This model uses the numeric method of the finite differences and simulates (transitory and permanent regimen) the complete behavior of the thermoelectric generation system, including the heat exchangers and the thermal focal points. The accuracy of this computational model has been experimentally checked, with the construction and test of a prototype, obtaining a maximum error of 5%.

1. INTRODUCTION

The thermoelectric generation system is based on the transformation of the calorific energy, directly in electric energy, so a part of the contributed heat, from the hot focal point to the system, is transformed into electric current, while the rest of the heat is transferred to the cold focal point, usually the ambient. The system performance depends, mainly, on the temperatures reached in the sides (hot and cold) in the thermoelectric module, which depends on the focal points temperatures and the thermal resistance between the thermoelectric module side and the thermal focal point.

The use of the residual heat in the thermoelectric generation represents an application with a great prospect of future [1], [2] y [3] taking into account the current energetic crisis. The main inconvenient of this application is the low temperature available in the thermal focal point, what makes that the efficiencies are small. This fact shows the significance of the heat exchanger thermal resistances, in both cold and hot sides.

The main objective of this research is to study and assess this significance with a computational model.

2. COMPUTATIONAL MODEL

The model inputs are: the geometric data, the materials properties, the number and type of Peltier modules and the value of the thermal energy given to the system. After the simulation, the model outputs are: the performance values, voltage, intensity, power, temperatures and generated heat flows, all of them depending on time.

The model solves the thermal conduction equation in transitory regimen for the one-dimensional case:

$$\rho c_p \frac{\delta t}{\delta \tau} = k\left(\frac{\delta^2 t}{\delta x^2}\right) + q^* \quad (1)$$

Discretized and applied to node i, is:

$$\frac{T_{i-1}' - T_i'}{R_{i-1,i}} + \frac{T_j' - T_i'}{R_{i,j}} + \dot{Q}_i = \frac{C_i}{\delta\tau}(T_i' - T_i) \quad (2)$$

The heat generation or absorption of node i is represented by $\dot{Q}_i$ and its expression is given by the thermoelectricity expressions:

$$\dot{Q}_h = -N2\alpha_h I T_h + I^2 R_{cont} \quad (3)$$

$$\dot{Q}_c = N2\alpha_c I T_c + I^2 R_{cont} \quad (4)$$

$$\dot{Q}_J = I^2 R_0 = NI^2 2\rho L/A \quad (5)$$

$$\dot{Q}_\tau = \tau I \Delta T_0 \quad (6)$$

The expressions of the thermal resistance between nodes i,j and the thermal capacity of node i are:

$$R_{i,j} = \frac{L_{ij}}{k_i * A_i} \quad (7)$$

$$C_i = V_i \rho_i c_p \quad (8)$$

The thermal capacity and thermal resistance of the Peltier modules is studied the same way that was studied in [4].

If we join the terms depending on the nodes temperatures and the heat flows, we obtain the equation:

$$-\frac{\delta\tau}{C_i}\frac{1}{R_{i-1,i}}T_{i-1}' + \left[\frac{\delta\tau}{C_i}\left(\frac{1}{R_{i-1,i}} + \frac{1}{R_{i,j}}\right) + 1\right]T_i' - \frac{\delta\tau}{C_i}\frac{1}{R_{i,j}}T_j' = T_i + \frac{\delta\tau}{C_i}\dot{Q}_i \quad (9)$$

Introducing the Seebeck coefficient as a function of the temperature we get the following expressions:

$$\Delta V = \left(\frac{m}{1+m}\right)2N\left((\alpha_h T_h - \alpha_c T_c) - \sum_{i=1}^{10}\tau_i (T_i - T_{i+1})\right) \quad (10)$$

$$I = \frac{1}{1+m}\frac{A}{\rho L}\left((\alpha_h T_h - \alpha_c T_c) - \sum_{i=1}^{10}\tau_i (T_i - T_{i+1})\right)\frac{1}{(1+2\rho_c/\rho L)} \quad (11)$$

$$P_{out} = \Delta V I \quad (12)$$

Regrouping terms is posed the following matrix system of equations, which is solving repetitively.

$$[M][T_i'] = [T_i] + \frac{\partial\tau}{C_i}\left[\dot{Q}_i\right] \quad (13)$$

3. VALIDATION OF THE COMPUTATIONAL MODEL

In order to know the accuracy of the developed computational model, we constructed a thermoelectric generator prototype. It has the following parts: An electric resistance that simulates the thermal energy source; Heat extender; A Peltier module Marlow DT12-6; A dissipater for the cold side of the Peltier module; A decade box CAM METRIC R420 that allows us to vary the load resistance; Temperature probes in all elements.

In Figure 1 is showed, as an example, the comparative results corresponding to a heat flow of 30W. We can see that the model precision is good (The model error is below 5%.), obtaining the maximum generated power when the load resistance is the same as the internal resistance of the Peltier module, as it is analytically demonstrated in [5]. However, as it is noticed in Figure 2, the module reproduces the influence of the heat flow in the optimum value of the load resistance. The bigger the introduced heat flow is, the higher the module temperature will be, and the same happens with its internal resistance, because it varies with temperature. In consequence, the optimum load resistance increases when the provided heat is increased.

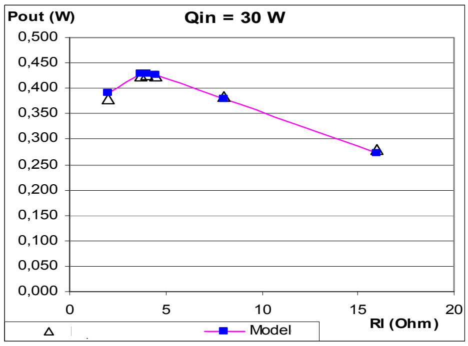

Figure 1. Generated power for 30W of heat inflow. Comparison between model and prototype.

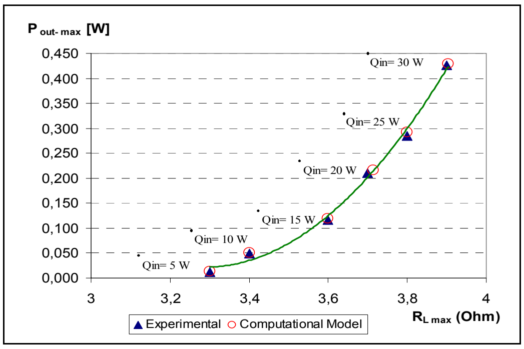

Figure 2. Generated power and optimum load resistance, for each heat inflow.

4. METHODOLOGY AND STUDY CASE

For this study we have considered the thermoelectric generation by means of the use of the smoke heat of a combustion boiler in a paper industry, with the characteristics showed in Table 1:

Heat source	Combustion smokes
Flow	60000 m^3/h
Speed	17,78 m/s
Pipe dimensions	1,25m x 0,75m
Specific heat	0,26 kcal/kg ºC
Density	1,254 kg/m^3
Smokes temperatures	200ºC

Table 1. Chimney characteristics

For this study, we shall take as unit, one meter of the chimney, assigning each Peltier module a dissipater base area of 110*100mm, so we shall put 320 Peltier modules in each meter of chimney. For the environment temperature we shall consider 15ºC.

In order to know some thermal resistance values, we have made some simulations with the CFD Fluent software. The studied cases have been:

1. Aluminum flat plate of 10mm that surrounds the pipe.
2. Aluminum plate of 10mm with fins of 2mm thick and 35mm long.

Knowing that the heat focal point (smokes) temperature is 200ºC, we have selected the thermoelectric materials TAGS-85, formed by an alloy of Ag, Sb, Te, Ge, and whose properties, as a function of temperature, are given by the following expressions, obtained from the adjustment of the curves showed in [5]:

$$\alpha = -0.000476T^2 + 0.761779T - 108.781667 \text{ in [microV/K]} \quad (14)$$

$$\rho = -0.00000001^2 + 0.00002298T + 0.00097131 \text{ in [Ohm*mm]} \quad (15)$$

$$k = 4E\text{-}9T^3 - 4.998E\text{-}6T^2 + 0.002446297T + 1.11558381 \text{ in [W/m*K]} \quad (16)$$

Each Peltier module is composed of 127 pairs of these semiconductor materials, 1.5mm high, and with a transversal section of 1.96mm^2.

We have design a DOE with two factors and five levels, in order to find out the influence of the dissipaters thermal resistances on the maximum generated electrical power. The two factors are: R_h (thermal resistance of the dissipater, which is in touch with the hot side of the Peltier module) and R_c (thermal resistance of the dissipater, that is in touch with the cold side of the Peltier module). The maximum level and the minimum level have been obtained with Fluent (Table 2).

5. RESULTS AND DISCUSSION

We can calculate the thermal resistance of each dissipater because we obtain the temperature distribution, the velocity distribution and the heat fluxes with Fluent simulations. In Figure 3, we can see the temperature distribution in a quarter of the heat-exchanger-with-fins.

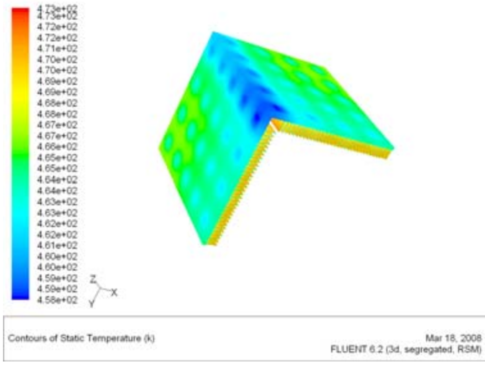

Figure 3. Temperature distribution in the heat-exchanger-with-fins.

Table 2 is a summary of the Fluent simulations about the two studied designs.

Heat exchanger	$T_p(K)$	*R(K/W)*	*ΔP(Pa)*
Flat plate	325,8	4.90	6.2
Plate with fins	462.8	0.338	32.1

Table 2. Heat exchangers results

In Figure 4, we have represented the maximum generated electrical power against the thermal resistances of the two dissipaters. This electrical power increases very much if the thermal resistances are small. Because of this result, we declare that good heat exchanger designs are completely indispensable in electrical generation devices.

See that this electrical generation application is really important because 3kW of electrical power can be generated in only one meter long of chimney. We think that this device has a long future because it uses chimney smoke, which usually is thrown away.

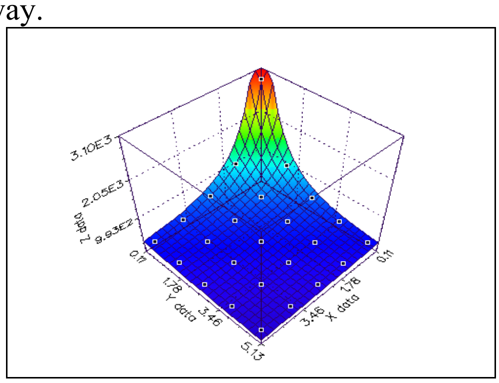

Figure 4. Maximum generated electrical power (Z) against thermal resentence of the dissipater in hot side (X) and in cold side (Y).

According to the methodology presented in section 4, we have obtained a fitting model with a $R^2 = 99\%$.

$$1/P_{out}=0{,}000122441 + 0{,}000268206.\ R_h + 0{,}000241703.R_c + 0{,}0000794218.R_h^2 + 0{,}000115985.\ R_c^2 + 0{,}000192486.\ R_h.R_c \qquad (17)$$

From the results showed in Figure 5, we infer that is essential to minimize the thermal resistance of both dissipaters in order to increase the generated power.

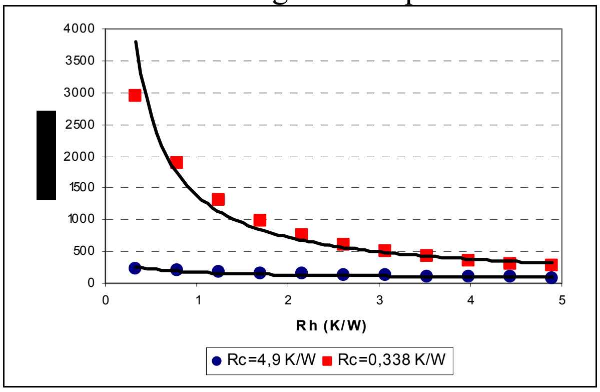

Figure 5. Maximum generated electrical power against R_h, with R_c= maximun (blue) and R_c= minimun (red).

Besides, from Figure 6, we infer that both dissipaters' thermal resistances have the same influence on the generated electric power because heat flux in cold side is very similar than heat flux in hot side.

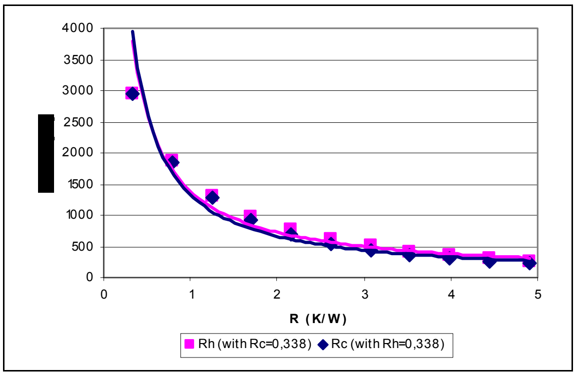

Figure 6. Generated power against R_h and R_c

6. CONCLUSIONS

We have developed a computational model that simulates the behaviour of a complete thermoelectric generator, including the heat exchangers and the thermal focal points. Its accuracy has been experimentally checked and we can declare that maximum relative error is smaller than 5%.

We have studied a thermoelectric generation device that uses the smoke of a real chimney as a thermal focus. We think that this application has a long future because the maximum electrical power that the device can generate is 3kW per one chimney meter long.

We have proved that good dissipater designs are completely indispensable in electrical generation devices. For example, in our case, the maximum electrical power increases 46% if the thermal resistances improve from 0.6 K/W to 0.4 K/W.

7. ACKNOWLEDGMENTS

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NOMENCLATURE

A	*Section*	m^2
C	*Calorific capacity*	*W/s.K*
c_p	*Specific heat at constant pressure*	*J/kgK*
I	*Electric current*	*A*
k	*Thermal conductivity*	*W/mK*
P_{out}	*Electric power*	
$\dot{Q}$	*Heat flux*	*W*
R	*Electric resistance*	*K/W*
R_h	*Hot side dissipater thermal resistance*	*K/W*
R_c	*Cold side dissipater thermal resistance*	*K/W*
T	*Absolute temperature*	*K*
V	*Voltage*	*V*
α	*Seebeck coefficient*	*V/K*
ρ	*Electric resistivity*	*Ohm. m*
ρ	*Density*	kg/m^3