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Study of the influence of heat exchangers' thermal resistances on a thermoelectric generation system

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A B S T R A C T

In this paper, a computational study of the influence of the heat exchangers' thermal resistances (in both the hot and cold side) on the efficiency of a thermoelectric generation device has been carried out.

For this purpose, a computational model has been developed. This model uses the numerical method of finite differences to simulate the performance of the thermoelectric generation system, including the heat exchangers, the heat source and the heat sink. The accuracy of this computational model was experimentally verified, by constructing and testing a prototype. It was obtained that the maximum error between experimental and simulated values of electric power generated is lower than 5%.

The generation of thermoelectric power, using as heat source the heat of the smoke from a paper mill's combustion boiler, has been studied too. The results demonstrated that it is possible to generate about 1 kW per meter of chimney height, that is, about 300 W/m^2. Therefore, it can be stated that this device has good prospects for the future.

1. Introduction

Thermoelectric generation systems transform thermal energy directly into electric energy. Thus, part of the heat transferred from a heat source to the system is transformed into electric power, whilst the rest is transferred to the heat sink, usually the environment. The efficiency of the system depends, to a great extent, on the temperatures at both sides (hot and cold) of the thermoelectric modules. These, in turn, depend on the temperatures of the heat source and heat sink, and on the heat exchangers' thermal resistances.

Considering today's energy crisis, the use of waste heat for thermoelectric generation is an application with good prospects for the future, as was stated by Riffat [1] and Rowe [2]. Also, hybrid generation devices, such as those presented by Yodovard [3] and Min [4], are becoming increasingly important. The main problem of these applications is usually the low temperature of the heat source, which leads to low system efficiencies. This fact shows the significant role that the heat exchangers' thermal resistances play. The main aim of this research project is to study and quantify this influence using a computational model.

Most of the models used to simulate thermoelectric generation systems need, at least, the temperature at one side of the thermoelectric modules as boundary condition. This fact can be seen in Lau's papers [5,6]. However, this temperature cannot be determined a priori, since it depends on the heat exchangers used. Therefore it is necessary to simulate the whole system, that is, the thermoelectric modules, the heat exchangers, the heat sink and the heat source. For this purpose, a computational model has been developed, which is capable of simulating the performance of thermoelectric generation systems.

2. Objectives

- To implement a computational model capable of simulating the performance of the whole thermoelectric generation system.
- To experimentally validate this model by constructing and testing a prototype.
- To study the influence of the heat exchangers' thermal resistances on the generation of electric power with thermoelectric generators.
- To study, with the model validated, the possibility of producing electric power using the heat of the smoke from of a combustion boiler.

3. Computational model

The computational model is based on a previous one developed by Vián [7,8], which was capable of simulating thermoelectric cooling systems. This new model solves the non-linear system

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Nomenclature

A	Area (m^2)
A_{leg}	Base area of a semiconductor leg (m^2)
A_{smoke}	Base area of the original chimney (m^2)
C	Thermal capacity (J/K)
c_p	Specific heat under constant pressure (J/kgK)
$c_{p,smoke}$	Specific heat under constant pressure of the smoke (J/kgK)
I	Electric current (A)
k	Thermal conductivity (W/mK)
L	Length (m)
L_{leg}	Length of a semiconductor leg (m)
m	Load ratio (m)
$\dot{m}_{smoke}$	Smoke mass flow rate (kg/s)
N	Number of thermocouples in a thermoelectric module
P_{out}	Electric power generated (W)
P_{max}	Maximum electric power generated (W)
$\dot{Q}$	Heat flux (W)
$\dot{Q}_c^{module}$	Heat flux transferred from each module to the cold side heat exchanger (W)
$\dot{Q}_h^{module}$	Heat flux absorbed by each module from the smoke (W)
$\dot{Q}_h$	Heat flux produced at the hot end of the semiconductor legs (W)
$\dot{Q}_c$	Heat flux produced at the cold end of the semiconductor legs (W)
$\dot{Q}_{Joule}$	Heat flux produced by Joule effect in the semiconductor legs (W)
$\dot{Q}_{Thomson}$	Heat flux produced by Thomson effect in the semiconductor legs (W)
$\dot{Q}_{in}$	Heat flux introduced by the heat source (W)
q^*	Rate of internal heat generation (W/m^3)
R	Thermal resistance (K/W)
R_{cont}	Electric contact resistance of a soldered joint (Ω)
R_c	Thermal resistance of the cold side heat exchanger (K/W)
R_h	Thermal resistance of the hot side heat exchanger (K/W)
R_l	Electric load resistance (Ω)
R_0	Internal electric resistance of a thermoelectric module (Ω)
T	Temperature at a particular time τ (K)
T'	Temperature at a particular time $\tau + \delta\tau$ (K)
T_c	Temperature at the cold end of the semiconductor legs (K)
$T_{environment}$	Average environment temperature (K)
T_h	Temperature at the hot end of the semiconductor legs (K)
T_{smoke}	Temperature of the smoke (K)
T_h^{module}	Temperature at the hot side of the thermoelectric modules (K)
T_c^{module}	Temperature at the cold side of the thermoelectric modules (K)
V	Volume (m^3)
v_{smoke}	Velocity of the smoke (m/s)
Greek symbols	
α_h	Seebeck coefficient at the hot end of the semiconductor legs (V/K)
α_c	Seebeck coefficient at the cold end of the semiconductor legs (V/K)
ΔT_{smoke}	Temperature drop of the smoke per meter of chimney height (K/m)
ΔV	Voltage (V)
$\delta\tau$	Time interval (s)
η	System efficiency
π	Peltier coefficient (V)
ρ	Density (kg/m^3)
ρ_{smoke}	Smoke density (kg/m^3)
ρ_e	Electric resistivity of the semiconductor material (Ohm × m)
ρ_{cont}	Specific electric contact resistance of a soldered joint (Ohm × m^2)
σ	Thomson coefficient (V/K)
τ	Time (s)

formed by the thermoelectric and the heat transfer equations, using the implicit finite differences method.

The model inputs are: geometric data, material properties, number and type of thermoelectric modules, temperature of the heat sink and heat flux introduced into the system. The model outputs are: efficiency, voltage, electric current, electric power generated, temperatures and heat fluxes, all of them time-dependent.

In the one-dimensional case, the model solves the thermal conduction equation in transitory state:

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

The first and second derivatives in finite differences form, for $T = T(\tau,x)$, are as follows

$$\frac{\delta T}{\delta \tau} = \frac{T(x,\tau+\delta\tau) - T(x,\tau)}{\delta\tau} \quad (2)$$

$$\frac{\delta^2 T}{\delta x^2} = \frac{T(x+\delta x,\tau+\delta\tau) - 2T(x,\tau+\delta\tau) + T(x-\delta x,\tau+\delta\tau)}{(\delta x)^2} \quad (3)$$

Equations (1)–(3), when applied to node i:

$$\frac{\rho_i c_p}{\delta\tau}(T_i' - T_i) = \frac{k_i}{(\delta x)^2}(T_{i+1}' - 2T_i' + T_{i-1}') + {}^*q_i \quad (4)$$

After multiplying by the volume of node i ($V_i = A_i\,\delta x$):

$$\frac{V_i \rho_i c_p}{\delta\tau}(T_i' - T_i) = \frac{A_i k_i}{\delta x}(T_{i+1}' - 2T_i' + T_{i+1}') + \dot{Q}_i \quad (5)$$

The thermal resistance between nodes i and $i+1$, as well as the thermal capacity of node i are

$$R_{i,i+1} = \frac{L_{i,i+1}}{k_i A_i} \quad (6)$$

$$C_i = V_i \rho_i c_p \quad (7)$$

Therefore, Eq. (1) is

$$\frac{C_i}{\delta\tau}(T_i' - T_i) = \frac{T_{i-1}' - T_i'}{R_{i-1,i}} + \frac{T_{i+1}' - T_i'}{R_{i,i+1}} + \dot{Q}_i \quad (8)$$

After grouping the terms based on the temperatures of the nodes i, $i+1$ and $i-1$, the following equation is obtained: