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Thermoelectric generator sandwiched in a crossflow heat exchanger with optimal connectivity between modules

Simon Bélanger, Louis Gosselin *

Département de génie mécanique, Université Laval, 1065, avenue de la Médecine, Québec City, QC, Canada G1V 0A6

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ABSTRACT

The design of a thermoelectric generator sandwiched in the wall of a crossflow heat exchanger was optimized. A numerical model has been developed and validated. The objective function was the total power output. The design variables were the number of modules and the current in each control volume of the mesh. We also optimize directly the electrical topology of the system. A genetic algorithm was used to perform the optimizations. Complex optimal electrical topologies were achieved due to the non-uniform temperatures distributions in the heat exchanger.

1. Introduction

A thermoelectric generator is a device that converts thermal energy into electrical power. The problem that has plagued the industry for many years is the low conversion efficiency of thermoelectric generators. A lot of research is being conducted in that field with promising results. New developments of thermoelectric materials indicates that the efficiency of thermoelectric systems is likely to improve in the years to come [1], with the development of new materials and thin films with a higher figure of merit [2–5], thus making the use of thermoelectric generators more interesting in a variety of applications. Producing electrical power with a thermoelectric generator has many advantages. For example, it requires no moving parts, thus making it a very reliable system. Even though the conversion efficiency is low, the use of thermoelectric generator could be interesting for waste heat recovery, as there is no cost associated with the heat used for power production [6].

In the past, authors have developed models for thermoelectric generators while treating it as an irreversible heat engine [7]. Many others have explored the influence of various parameters on the performances of thermoelectric generators including the effect of multiple layers of modules [8,9]. Some research was also performed to optimize the geometry of the thermoelectric modules used in the generator [10]. While many of the works in that field were theoretical, some authors have studied experimentally real generators in order to validate their numerical models [11,12].

The ultimate goal of the development of such devices is to use them in various applications, in particular for waste heat recovery. For example, thermoelectric generators could be used in regions with unreliable electric supply when collecting heat from heating stoves [13]. Recently, Yu and Zaho have developed a numerical model for a thermoelectric generator within a parallel plate heat exchanger [14]. Also, some authors have explored the possibility of wearable thermoelectric generators for body-powered devices [15].

In this paper, we present a model and optimize the internal structure of a thermoelectric generator sandwiched in a crossflow heat exchanger. Crossflow heat exchangers are popular for waste heat recovery because of their low cost and easiness to manufacture and operate. First, we describe the model, along with a method to represent the various electrical connections between the thermoelectric modules. Then, we present the optimization results performed on the system for various operating conditions.

2. Modeling of a one-stage generator in a crossflow heat exchanger

In this section, we describe how the generator was modeled. We considered one layer of single-staged thermoelectric modules sandwiched between a hot and a cold flow in a crossflow heat exchanger, as seen in Fig. 1. The heat exchanger wall was divided in small control volumes (mesh) labeled in Fig. 1 by the index *i*. In our model, four temperatures in each control volume (T_H, T_C, T_1, T_2) need to be evaluated. The temperature must be evaluated in each fluid (i.e., T_H, T_C) and at the top and bottom surfaces of the thermoelectric modules (i.e., T_1, T_2). The fluid-to-fluid temperature

* Corresponding author. Tel.: +1 418 656 7829; fax: +1 418 656 7415.
E-mail address: Louis.Gosselin@gmc.ulaval.ca (L. Gosselin).

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Nomenclature

A	area, m^2
B	area to length ratio, m
C	conductance matrix
c_p	heat capacity, J/kg K
D	incidence matrix
F	heat capacity rate, W/K
I	current, A
k	thermal conductivity, W/mK
K	thermal conductance, W/K
L	length, m
m	number of thermoelectric modules
P	electrical power, W
q''	heat flux, W/m^2
R	electrical resistance, Ω
S	source term
T	temperature, K
u	velocity components, m/s
v	potential at each node, V
x, y, z	Cartesian coordinates, m
Greek symbols	
α	Seebeck coefficient, V/K
ρ	density, kg/m^3
σ	electrical resistivity, Ω m
Subscript	
C	relative to the cold fluid
H	relative to the hot fluid
1	relative to the surface with the hot fluid
2	relative to the surface with the cold fluid

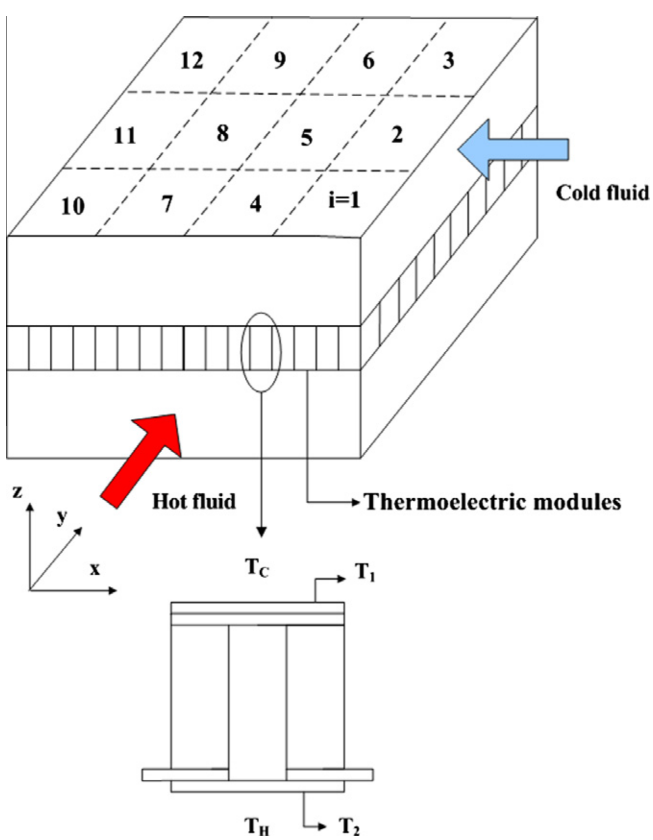

Fig. 1. Representation of a thermoelectric generator sandwiched in a crossflow heat exchanger with 12 control volumes.

difference in the heat exchanger will drive a current in the thermoelectric modules. The model evaluates the electrical power generated under various conditions for such a system.

In each control volume, the hot fluid transfers heat to the wall by convection and similarly the cold fluid receives heat from the wall. This yields the following equations for the local heat flux in the ith control volume.

$$q_{Hi} = h_{hi}(T_{Hi} - T_{1i})\Delta x \Delta y \quad (1)$$

$$q_{Ci} = h_{ci}(T_{2i} - T_{ci})\Delta x \Delta y \quad (2)$$

where h_{hi} and h_{ci} are the local convection coefficient on the hot and cold sides respectively. When fins are present in the heat exchanger, one would need to replace h in Eqs. (1) and (2) by $h\eta_f A_f/(\Delta x \Delta y)$ where η_f is the efficiency of the fin system, and $A_f/(\Delta x \Delta y)$ is the ratio of areas of the fin surface to the wall surface. Therefore, whenever we vary h later in this paper, this could be seen as equivalent to varying the design of the fin system.

The thermal conductance K and the electrical resistance R of the thermoelectric elements in the wall can be defined locally, and depend on the thermoelectric properties (thermal conductivity, k, and electrical resistivity, σ) and on the geometry of the legs,

$$K_i = k_n B_n + k_p B_p \quad (3)$$

$$R_i = \frac{\sigma_n}{B_n} + \frac{\sigma_p}{B_p} \quad (4)$$

where $B_n = A_n/L_n$ et $B_p = A_p/L_p$ are the n and p-legs cross-sectional area to length ratios (shape factor). A variable number of thermoelectric elements can be included in each control volume. We labeled m_i the number of modules in the ith control volume.

The local heat flux introduced in Eqs. (1) and (2) can be determined based on the geometry and properties of the modules [8],

$$q_{Hi} = \left(m\alpha I T_1 - \frac{mRI^2}{2} + mK(T_1 - T_2) \right)_i \quad (5)$$

$$q_{Ci} = \left(m\alpha I T_2 + \frac{mRI^2}{2} + mK(T_1 - T_2) \right)_i \quad (6)$$

where α is the Seebeck coefficient, and I is the electrical current flowing through the module. Eqs. (1), (2), (5) and (6) form a set of 4 equations with 6 unknowns (T_H, T_C, T_1, T_2, q_H, q_C) for each control volumes. Here, the current I has to be specified by the user and is not considered as an unknown. Specifying I is equivalent to specifying the load electrical resistance. Therefore, two additional relations between the six unknowns are required. These relations describe how the fluid temperatures vary according to the heat fluxes. Assuming that the velocities of the fluids are known, it is possible to perform an energy balance on each control volume. The heat removed from the hot stream will cool it. Therefore, a heat balance on the warm side yields, in the ith control volume:

$$q_{H_i} = F_H(T_{H,i-1} - T_{H,i}) \quad (7)$$

and similarly on the cold side