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Optimization of thermoelectric generator module spacing and spreader thickness used in a waste heat recovery system

Jiin-Yuh Jang*, Ying-Chi Tsai

Department of Mechanical Engineering, National Cheng-Kung University, 1 University Road, Tainan 70101, Taiwan

HIGHLIGHTS

► We provided a 3D numerical model of a TEG module used in a waste heat recovery system.
► The effects of temperature difference and waste gas heat transfer coefficients were investigated.
► The power density for a TEG module is the objective function to be maximized.
► The numerical data are in good agreement (within 8%) with the experimental data.
► The optimum TEG module spacing and spreader thickness are strongly dependent on the waste gas heat transfer coefficient.

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ABSTRACT

When thermoelectric generator (TEG) modules are attached to a rectangular chimney plate for venting hot flue gases, the power generated per unit surface area (power density) is strongly dependent on the TEG module spacing. The thermoelectric module consists of a hot plate, a spreader, a thermoelectric generator and a cold plate based on water cooling. In this study, the optimization of TEG module spacing and its spreader thickness as used in a waste heat recovery system is investigated and solved numerically using the finite difference method along with a simplified conjugate-gradient method. The power density for a thermoelectric module is the objective function to be maximized. A search for the optimum module spacing (S) and spreader thickness (H_{sp}), ranging from 40 mm < S < 300 mm and 1 mm < H_{sp} < 30 mm, respectively, is performed. The effects of different operating conditions, including the temperature difference between the waste gas and the cooling water (ΔT = 200–800 K), and effective waste gas heat transfer coefficients (h_h = 20–80 W/m^2 K) are discussed in detail. The predicted numerical data for the power vs. current (P–I) curve are in good agreement (within 8%) with the experimental data.

1. Introduction

Thermoelectric generators present potential applications in the conversion of low level thermal energy into electrical power. Especially in the case of waste heat recovery, it is unnecessary to consider the cost of the thermal energy input, and there are additional advantages, such as energy saving and emission reduction, so the low efficiency problem is no longer the most important issue that we have to take into account [1]. In general, a TEG consists of a number of semiconductor pairs that are connected electrically in a series and thermally in parallel, and each pair includes a p-type and an n-type element. Although in theory, a single piece of semiconductor material could work, a series connection is used to meet the high voltage potential requirements. p-Type and n-type elements are alternated to assure that the carriers transport in the same direction.

Most of the reported performance data of TEGs is analyzed using conventional non-equilibrium thermodynamics [2,3]. With reference to the structure of a TEG, a significant increase in the power output from a module can be achieved by modifying the geometry of the thermoelectric elements [4,5]. In subsequent research, Rowe [6,7] provided efficiency in a couple of solar-powered TEGs and reviewed applications of nuclear-powered TEGs in space. Chen et al. [8] used an irreversible model to study the performance of a TEG with external and internal irreversibility. The optimal range of the parameters for the device-design was determined, and the problems relative to the maximum power output and maximum efficiency were discussed. Xuan et al. [9] employed

* Corresponding author. Tel.: +886 6 2757575x62148; fax: +886 6 2088573.
E-mail address: jangjim@mail.ncku.edu.tw (J.-Y. Jang).

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Nomenclature

A	TEG module area (mm^2) $A = S \times S$
D_h	hydraulic diameter (m)
E	electric field (V/m)
h	effective heat transfer coefficient (W/m^2 K)
H	height (mm)
I	electric current (A)
$\vec{J}$	electric current density (A/m^2)
J_{obj}	objective function
k	thermal conductivity (W/m K)
L	length (mm)
n	pairs of p-type and n-type semiconductor
P	power output (W)
P_{max}	maximum power output (W)
P_{max}/A	maximum power density (W/m^2)
Q	heat transfer rate (W)
R	residual sum
S	TEG module spacing (mm)
T	temperature (K)
ΔT	temperature difference between the waste gas and the cooling water (K)
V	electric potential (V)
v	velocity (m/s)
V_{oc}	open circuit voltage (V)
x_i	design variable vector
x, y, z	Cartesian coordinates

Greek symbols

α	Seebeck coefficient (V/K)
β	descend direction coefficient
ε	flue gas emissivity
η	TEG conversion efficiency (%) $\eta = P_{max}/Q_h$
ϕ	general dependent
ρ	electrical resistivity (Ω m)
σ	Stefan Boltzmann constant (W/m^2 K^4)
ξ	search directions

Subscripts

c	cold side
cer	ceramic substrate
cond	conductive copper
conv	convection
f	fluid
gas	flue gas
h	hot side
hp	hot plate
opt	optimal design
P–N	p- and n-type thermoelectric semiconductor
rad	radiation
sp	spreader
TEG	thermoelectric generator
water	cooling water

a phenomenological model to study the effects of internal and external interface layers on thermoelectric module performance. Sets of general performance formulas have also been derived. Pramanick and Das [10] performed a study on the structural design of a thermoelectric module. A model for a cascaded TEG was developed, which was based on finite time thermodynamics.

Recently, there has been a growing interest in TEGs using various heat sources in such applications as combustion of waste, geothermal energy, power plants, and other industrial heat-generating processes [11,12]. Khattab and Shenawy [13] studied the possibility of using a solar TEG to drive a small thermoelectric cooler (TEC). Crane and Jackson [14] studied numerical heat exchanger models integrated with models for Bi_2Te_3 thermoelectric modules which were validated against experimental data from previous cross-flow heat exchanger studies as well as experiments using thermoelectric modules between counter-flow hot water and cooling air flow channels. Dai et al. [15] provided a new type of TEG system based on liquid metal which served to harvest and transport waste heat. The experimental results for the TEG system were discussed and a calculated efficiency of 2% in the whole TEG system was obtained. Champier et al. [16] reported a study conducted in order to investigate the feasibility of using a TEG in an improved biomass fired stove. The maximum power reached by each module varied between 1.7 W and 2.3 W, resulting in a temperature difference between the two sides of 160 °C.

Furthermore, in the application of TEGs for waste heat recovery power generation, there have been many conceptual designs for a power conversion system that are potentially capable of being applied in this area. Hsiao et al. [17] constructed a mathematic model to predict the performance of a TEG module attached to a waste heat recovery system. The results showed that the TEG module presented better performance on an exhaust pipe as opposed to a radiator. Thacher et al. [18] investigated the feasibility of waste heat recovery from exhaust in a light truck by connecting a series of 16 TEG modules, which showed good performance at high speeds. Niu et al. [19] constructed an experimental TEG unit, which was used to examine the influences of the main operating conditions, the hot and cold fluid inlet temperatures, flow rates and the load resistance on the power output and conversion efficiency. Karri et al. [20] studied the power and fuel savings produced by TEGs placed in the exhaust stream of a sports utility vehicle (SUV). The optimized quantum-well (QW) based TEG stack generated about 5.3–5.8 kW, resulting in a fuel savings of about 3%.

According to the literature survey [21], it is recognized that most of the previous theoretical models have been limited to one dimensional problems. However, in these existing models, the *P–N* element pair is simply treated as a single bulk material so that the difference in thermal behavior between the two semiconductor elements was not possible to evaluate. Only a few studies have been conducted for three-dimensional TEGs. For example, Chen et al. [22] proposed a three-dimensional TEG model and implemented it in a computational fluid dynamics simulation environment (FLUENT) and its user-defined functions (UDFs). Cheng et al. [23] provided a three-dimensional numerical model to predict transient thermal behavior of TECs. It was observed that both the temperatures of the hot and the cold ends increased with the cooling load, and the value of the COP (coefficient of performance) linearly increased with the cooling load. Recently, Sidek et al. [24] provided a numerical study on temperature uniformity of thermal spreader integration with microcombustor for TEG. The results show the effect of thermal conductivity, specific heat capacity and thickness, and the mutual relation between the magnitude of heat source and thermal spreader temperature profile. Jang et al. [25] used a numerical optimization technique in a geometrical optimization for spreaders to obtain efficient power output balancing with reasonable material costs. The results showed the optimum spreader length and thickness with the fixed module spacing for Pareto-optimal configurations.