Applied Energy 158 (2015) 44–54

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Performance analysis and optimum operation of a thermoelectric generator by Taguchi method

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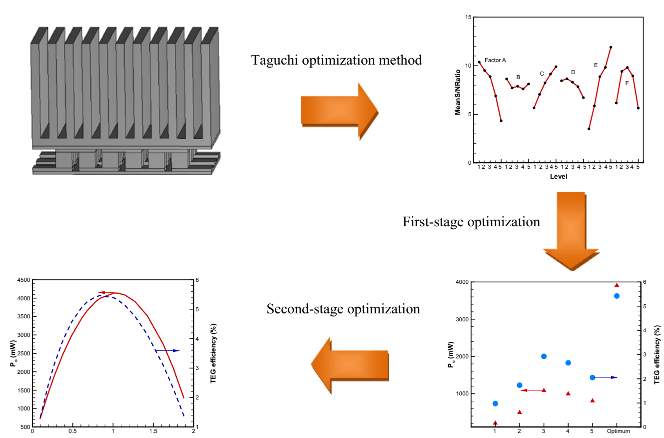
HIGHLIGHTS

- Performance of a thermoelectric generator is analyzed by the Taguchi method.
- Six factors with five levels are considered and a L_{25} (6^5) orthogonal array is employed.
- Hot side temperature is the most important factor in determining TEG performance.
- Two-stage optimization for the performance of the TEG is developed.
- The second-stage optimization can further improve the power by around 6%.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 March 2015
Received in revised form 21 July 2015
Accepted 12 August 2015

Keywords:
Thermoelectric generators
Output power and efficiency
Finite element scheme
Taguchi method
Heat sink
Two-stage optimization

ABSTRACT

The thermoelectric generator (TEG) is a promising device to convert waste heat into electricity. This work numerically simulates the performance of a TEG system in which a TEG module and heat sinks are considered. The heat transfer rate of the heat sinks is approximated by an analytical method. To maximize the efficiency of the system, the Taguchi method is employed. Six factors, including the length and width of heat sink, the height and thickness of fins, hot side temperature, and external load resistance, along with five levels are taken into account. The orthogonal array employed in the Taguchi method is able to significantly reduce the time for seeking the optimum operation. The analysis suggests that the hot side temperature is the most important factor in determining the output power and efficiency of the TEG system, whereas the heat sink width almost plays no role on them. The influences of the four geometric parameters on the heat transfer rate of heat sinks are also evaluated by the Taguchi method. The results indicate that the heat sink length has the largest effect on the heat transfer rate. Two-stage optimization for the performance of the TEG system is developed. The first-stage optimum operation is obtained from the Taguchi approach, and the second-stage optimization is performed from the power-current curve. After undergoing the second-stage optimization, the output power of the system in the first stage can be further improved by around 6%.

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http://dx.doi.org/10.1016/j.apenergy.2015.08.025
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Nomenclature

A	surface area (mm^2)
C_p	specific heat at constant pressure ($kJ\,kg^{-1}\,K^{-1}$)
D	depth (mm)
D_g	fin-to-fin spacing (mm)
$\vec{E}$	electric field intensity vector ($V\,m^{-1}$)
H	height (mm)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I	electric current (A)
$\vec{J}$	electric current density vector ($A\,m^{-2}$)
K	thermal conductance of the semiconductor couple ($W\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	length (mm)
n	number of modules
P_o	output power of TEG (mW)
Q	heat transfer rate (W)
Q_s	heat transfer rate for the fully developed flow limit (W)
$\dot{q}$	heat generation per unit volume ($W\,m^{-3}$)
$\vec{q}$	heat flux vector ($W\,m^{-2}$)
R	electric resistance (Ω)
R_e	external load resistance (Ω)
S	seebeck coefficient ($V\,K^{-1}$)
S/N	signal-to-noise ratio
T	temperature (°C)
T_f	surface temperature of the fins (°C)
T_∞	environment temperature (°C)
t	thickness (mm)
W	width (mm)
y	characteristic property

Greek letters

α	fluid thermal diffusivity ($m^2\,s^{-1}$)
η	efficiency (%)
μ	fluid viscosity ($N\,s\,m^{-2}$)
ν	fluid kinematic viscosity ($m^2\,s^{-1}$)
ρ	fluid density ($kg\,m^{-3}$)
ρ_e	electrical resistivity (Ω m)
ϕ	electric scalar potential (V)
Δp	pressure drop across the heat sink ($N\,m^{-2}$)

Subscripts

a	air
B	heat sink base
c	cold side of TE element
eff	effective
f	fin
HS	heat sink
h	hot side of TE element
n	n-type TE element
p	p-type TE element
TE	thermoelectric element

1. Introduction

The development and application of renewable energy are considered as the important routes to elongate fossil fuel reserve, abate anthropogenic CO_2 emissions, and mitigate deteriorating atmospheric greenhouse effect and global warming. Among the developing methods of renewable energy, thermoelectric generators (TEGs) are a promising device in that they can convert waste heat into electricity [1,2]. In recent years, the practical applications of TEGs through waste heat recovery have been reported in many studies. Martínez et al. [3] conducted an experiment to analyze the performance of a TEG system by recovering waste heat from a stainless steel chimney, and concluded that an extractor fan could be installed at the top of the chimney to optimize the TEG system. Hsu et al. [4] constructed a TEG system composed of 24 TEGs to convert waste heat from the exhaust pipe of an automobile to electrical energy, and found that the designed slopping block could make the thermal distribution more uniform than that without the slopping block. Gao et al. [5] numerically evaluated a TEG system driven by the waste heat of the exhaust gas from a high temperature polymer electrolyte membrane fuel cell (HTPEMFC) stack, and obtained an optimal system configuration. Zheng et al. [6] presented a thermoelectric cogeneration system to simultaneously generate electricity and preheat water where the primary heat source of the thermoelectric cogeneration was waste heat from boiler exhaust. Xiong et al [7] numerically established a two-stage thermoelectric energy harvesting system to generate electricity; the two-stage system, consisting of a top stage generator and a bottom stage generator with the same pairs of thermoelectric elements, was driven by the waste heat of blast furnace slag water.

To maximize the performance of thermoelectric devices, including TEGs and thermoelectric coolers (TECs), a variety of optimization methods have been developed. They include the simplified conjugate-gradient method [8,9], teaching-learning-based optimization algorithm [10], genetic algorithm [11], variational method [12], and so forth. Huang et al. [8] used a simplified conjugate-gradient method to optimize the combination of semiconductor pair number, leg length of semiconductor column, and the base area ratio of semiconductor columns for maximizing the coefficient of operation (COP) of a thermoelectric cooler. Rao and Patel [10] employed a modified teaching-learning-based optimization (TLBO) algorithm to optimize the arrangement of TECs for the maximization of cooling capacity and COP of the devices. Favarel et al. [11] used a genetic algorithm to find the optimal configuration of a TEG system for producing the maximum electrical power of the system at different temperatures and fluid flow rates. In the configuration, the position of the thermoelectric couples in the TEG system was considered. Stevens et al. [12] used a variational method to optimize a TEG system, and obtained an optimum number of thermoelectric leg pairs which could maximize the system power. When the leg pairs were beyond the optimum number, the performance of the system degraded.

In addition to the aforementioned methods, the Taguchi method is another noticeable tool to aid in designing experiments and find the optimum conditions. Mozdgir et al. [13] used the Taguchi method to design experiments and optimum the differential evolution algorithm parameters for minimizing the workload smoothness index in simple assembly line balancing. Chen et al. [14] employed the Taguchi method to find the optimum operating conditions for maximizing the cold gas efficiency of the co-gasification of torrefied biomass (eucalyptus) and coal in an entrained flow gasifier. Denneval et al. [15] adopted the Taguchi method to design experiments in association with the analysis of variance methodologies for predicting the photophysical properties (absorption and emission maxima) of a family of pyrimidine chromophores. They concluded that the method was useful to study the influence various parameters involved in the photophysical properties of a series of dyes and to quickly identify the optimized chromophore. Heng et al. [16] studied the dry powder