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Effect of pulsed heat power on the thermal and electrical performances of a thermoelectric generator

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HIGHLIGHTS

- A transient simulation model of a thermoelectric generator (TEG) was presented.
- The heat flux in periodically rectangular form was applied to TEG system.
- The effect of pulsed heat power on the performances of a TEG was investigated.
- The ratio of the maximum to minimum input heat flux value influenced the efficiency.
- A linear correlation of the steady-state efficiency with the input power was proposed.

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ABSTRACT

This paper presents a transient simulation model based on the coupling of electric conduction and heat transfer in order to (1) quantify the conversion efficiency enhancement of a thermoelectric generator (TEG) under periodic heating and (2) predict the thermal and electrical performances of a TEG. Joule heating, the Peltier effect, and the Thomson effect are included in the transient model, which is experimentally validated using a commercial bismuth-telluride-based thermoelectric device under both steady state and transient conditions. In contrast to an alternate temperature gradient (ATG), which has been adopted in previous studies and is difficult to maintain in a regular square form, pulsed input power is considered herein as an effective parameter for investigating its influence on the thermal and electrical performances of a TEG. In particular, the output power and temperature difference across a TEG under pulsed input power are compared with those under constant input power, where the time average of a pulsed heat source is equivalent to the heat flux under a constant heat source. In the case of periodic heating, a rectangular input heat flux with 10% duty cycle is applied to the TEG system, with average values of 40,000 W/m^2, 30,000 W/m^2, 20,000 W/m^2, and 10,000 W/m^2; its time period ranges from 60 s to 2000 s. It is found that pulsed heat power yields better results than an ATG in terms of improving the conversion efficiency under the same input power condition; specifically, a maximum efficiency enhancement of 8.6× is achieved. In addition, it is found that the ratio of the maximum input heat flux to the minimum input heat flux under periodic heating, a/b, plays an important role in improving the conversion efficiency. For a given time period and average input power, a larger a/b value leads to higher efficiency enhancement. Moreover, it is observed that the efficiency enhancement is independent of the average input power under a given a/b value and fixed time period. Finally, we show that the efficiency under steady state heating is linearly proportional to the input heat flux, and the linear coefficient is 2.05×10^{-7} [$1/(W/m^2)$]; this result can facilitate the prediction of TEG performance.

1. Introduction

A thermoelectric module (TEM) is a semiconductor-based electronic device that converts temperature differences across its elements into electrical voltage; conversely, the application of an electrical voltage to a thermoelectric (TE) device induces a temperature difference across its elements. A TEM consists of several small elements composed of p-type and n-type semiconductor materials; the p-type and n-type elements are arranged alternately and connected in series. An applied temperature gradient causes either electrons in an n-type element or holes in a p-type element to migrate from the hot side to the cold side, thereby generating an internal electrical field due to the accumulation of carriers in the

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Nomenclature

A	area (m^2)
a, b	heat flux ($W\,m^{-2}$)
C	heat capacity ($J\,kg^{-1}\,K^{-1}$)
E	electric field ($V\,m^{-1}$)
f	function
J	electric current flux ($A\,m^{-2}$)
k	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
P	electric power (W)
P'	Peltier coefficient
Q	heat power (W)
Q'	density of Joule heating energy ($W\,m^{-3}$)
q''	heat flux ($W\,m^{-2}$)
$\langle q'' \rangle$	average heat flux ($W\,m^{-2}$)
R	electrical resistance (Ω)
S	Seebeck coefficient ($V\,K^{-1}$)
T	absolute temperature (K)
t	time (s)
V	voltage (V)
Abbreviations	
ATG	alternating temperature gradient
DAQ	data acquisition system
EE	efficiency enhancement
PH	periodic heating
SSH	steady-state heating
TE	thermoelectric
TEG	thermoelectric generator
TEM	thermoelectric module
ZT	figure of merit
Greek letters	
Δ	difference
η	conversion efficiency
κ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
ρ_c	charge density ($C\,m^{-3}$)
ρ_e	electrical resistivity ($\Omega\,m$)
σ	electrical conductivity (S m)
τ	time period (s)
Subscripts	
c	cold side
h	hot side
in	input
in-PH	input under periodic heating
int	internal
L	load
oc	open-circuit
out	output
out-PH	output under periodic heating
out-ss	output under steady-steady heating

cold side. Thus, the temperature difference is converted into electrical energy, and therefore, a TEM can be employed as a thermoelectric generator (TEG). A TEG has no moving parts and it can convert heat energy into electrical energy in a reliable and eco-friendly manner; therefore, it is used to transform geothermal energy and solar energy into electrical energy [1–4]. Further, it can be employed at a nuclear power plant for micropower generation to ensure that sensors or indicators function properly in the event of severe accidents [5]. In fact, a system consisting of a TEG and a heat restore unit has been tested as a power supplier for a wireless sensor node to be used in aircraft [6,7]. Recycling waste heat and transforming it into usable electrical energy is a practical approach to efficient heat utilization, which can ease the global energy shortage [8–10]; some research groups have extensively investigated methods for heat recovery from automotive engines [11–13]. Thermoelectric systems that can produce several hundred watts of electric power have been constructed [2,11,14], and many simulation models for analyzing the performances of thermoelectric devices have been proposed [15–19]. Owing to their advantages, TEGs are attracting considerable research attention; thus, the development of several promising industrial and civilian TEG applications is expected.

Conversion efficiency is a critical factor that influences the practical applications of an energy-conversion system. The conversion efficiency of a TEG-based system is significantly lower than that of other energy conversion systems such as nuclear power plants, solar cells, and wind turbines. The highest TEG conversion efficiency achieved in previous studies is 4.75% when the hot-fluid inlet temperature is 150 °C and the cold side is maintained at 20 °C [9]. In order to enhance the potential of this technology for various applications, it is necessary to improve its conversion efficiency significantly by using a new technique. Contemporary research is focused on developing materials to enhance the conversion efficiency by increasing the thermoelectric figure of merit, which evaluates the performance of a TE material and is defined by $ZT = S^2T/\rho_e\kappa$, where S, ρ_e, κ, and T are the Seebeck coefficient, electrical resistivity, thermal conductivity, and absolute temperature, respectively. The figure of merit can be improved by synthesizing new semiconductor materials [20–22] or by reducing the dimensional structure from bulk structure to nanowire or quantum well structure [23,24]. However, the high cost of new materials and techniques for fabricating TEGs with a smaller dimensional structure have limited their market applications thus far.

On the other hand, Thonhauser et al. found that current pulse shape influences the figure of merit; in their study, the effective figure of merit under Peltier cooling was increased to around two times that under the steady-state condition by superimposing a transient current pulse on the steady-state current [25]. Some researchers investigated transient TE cooling operation, and they succeeded in reducing the temperature of the cold side [26–28] and improving the conversion efficiency [29]. Yamashita et al. applied a similar approach to the case of a TEG and studied the role of an alternating temperature gradient (ATG) in improving the conversion efficiency [30–32]; however, owing to heat dissipation into the surroundings, the maximum efficiencies obtained over an optimum period were 0.37% and 0.27% for two different TEGs, which were 3.54 and 5.66 times as high as the efficiencies at $1/T = 0\ s^{-1}$, respectively. McCarty et al. [33] used a "thermal switch" physically located between a heat source and a TE device to modulate heat flow through the TE device; the switch permits heat flow from the source to the device only when the source temperature is near maximum. Thus, a higher time-averaged temperature drop across the TE device, and therefore, a higher efficiency (>5×), could be achieved. Yan and Malen [34] showed that a sinusoidal or square-wave periodic temperature gradient can optimize the figure of merit and improve the conversion efficiency of a TEG. They conducted an experiment in a vacuum chamber to avoid heat dissipation; a TEG with 32 pairs of p and n elements and an extremely thin Kapton Joule heater were selected as the module and the heat source, respectively. Thus, they achieved 140% and 180%