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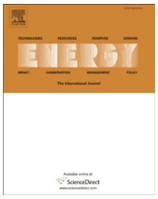

Modeling and simulation for the design of thermal-concentrated solar thermoelectric generator

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ABSTRACT

The performances of thermal-concentrated solar thermoelectric generators (TEGs) at three different geometric types are investigated numerically to aid in designing practical devices. The temperature-dependent properties of the commercial thermoelectric material are taken into account, and an equivalent model based on the three-dimensional finite element scheme is developed to simplify and accelerate simulations. The constriction thermal resistance and thermal spreading resistance are considered in the equivalent model. Increasing substrate area increases the thermal concentration ratio; this improves the performance of the solar TEG. In the three geometric types, the smallest element with the substrate area of 90 × 90 mm^2 provides the maximum system efficiency of 4.15%. For a TEG at a given element length, decreasing the cross-sectional area of the thermoelectric element is a feasible route to improve the performance. Under the situation of forced convection, varying convection heat transfer coefficient has an ignorable effect on the performance. For equal convective heat transfer coefficients, water cooling is better than air cooling for the net output power of the TEG because of its increased specific heat. Therefore, water cooling is recommended for the cooling of the solar TEG.

1. Introduction

Thermoelectric generators (TEGs) are energy conversion devices, which unlike convectional heat engines, are entirely solid-state, environmentally friendly, extremely reliable, simple, compact, and safe [1,2]. When a temperature difference across a TEG exists, it will generate electrical power through the Seebeck effect [3,4]. Although the principle of thermoelectricity was discovered in 1834, there were few practical applications until the middle 1950s [5]. Since the first and the second energy crises occurred in the 1970s, considerable interest has arisen in the development of thermoelectric power generation [6]. The applications of TEGs are limited due to their relatively low conversion efficiency [7,8]. Waste heat is extensively encountered in many industrial and manufacturing processes [9,10] and it is low-cost and even no-cost if waste heat can be recovered. Therefore, the low efficiency problem of TEGs is not a critical issue when they are applied in such settings [7] if waste heat is used as the heat source of the TEG. Moreover, the energy conversion process of TEGs is totally green [11] so that they are able to abate greenhouse gas emissions.

A number of practical applications of thermoelectric devices through waste heat recovery can be found in literature. Hsiao et al. [12] proposed a theoretical model to predict the performance of a TEG module by recovering waste heat from an automobile engine. Their results showed that the performance of the TEG installed on an exhaust pipe was better than that installed on a radiator. Hsu et al. [13] constructed a thermoelectric system, which comprised 24 TEG modules to recover waste heat from the exhaust pipe of an automobile, to find its optimum operating conditions. Chen et al. [14] investigated the characteristics of thermoelectric modules used for power generation by recovering low-temperature waste heat at various operating conditions. They discovered that the effects of the flow pattern of the heat sink and the water flow rate on the performance of the modules were not significant, whereas the heat source or the heating temperature played an important role on the performance.

Another low-cost heat source is the solar energy which has been widely applied in industries, such as solar thermal systems and photovoltaic systems [15]. In recent years, solar-driven TEGs have received a great deal of attention and a lot of studies have been carried out. One of the common designs of solar thermoelectric

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Nomenclature

A_c	cross-sectional area of the collector (mm^2)
C_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
C_{opt}	optical concentration ratio of solar thermoelectric generator
C_{th}	thermal concentration ratio of solar thermoelectric generator
D	depth of thermoelectric element (mm)
D_g	fin-to-fin spacing (mm)
$\vec{E}$	electric field intensity vector (V m^{-1})
F	area factor
G	curve fitting functions of relative error
H_f	fin height (mm)
h_L	convection heat transfer coefficient at the TEG's cold side (W m^{-2} K^{-1})
I^L	electric current load vector (A)
$\vec{J}$	electric current density vector (A m^{-2})
K^{TT}	thermal stiffness matrix
$K^{\varphi T}$	Seebeck stiffness matrix
$K^{\varphi\varphi}$	electric stiffness matrix
k	thermal conductivity (W m^{-1} K^{-1})
L	length of thermoelectric element (mm)
L_{HS}	length of heat sink (mm)
$\dot{m}$	mass flow rate of fluid (kg s^{-1})
m	constant for the curve fitting function
N	element shape function
n_f	number of fins
n	constant for the curve fitting function
$P_{equivalent}$	output power of equivalent model (W)
P_{out}	output power (W)
P_{pump}	pumping power (mW)
P_{real}	output power of real model (W)
q_s	solar irradiance (W m^{-2})
Q	heat transfer rate (W)
Q_H	heat transfer rate at the solar TEG's hot side (W)
Q_{in}	input energy of solar thermoelectric generator (W)
Q_L	heat transfer rate at the solar TEG's cold side (W)
Q^L	thermal load vector (W)
T	temperature (°C)
T_e	vector of nodal temperatures (°C)
T_f	surface temperature of fins (°C)
t_f	fin thickness (mm)
T_∞	environment temperature (°C)
U	mean velocity of fluid (m s^{-1})
W	width of thermoelectric element (mm)
W_{HS}	width of heat sink (mm)

Greek letters

α	Seebeck coefficient (V K^{-1})
γ	electrical conductivity (S m^{-1})
ε	emissivity of the solar absorber
η_a	absorptivity of the collector coating
η_{opt}	optical efficiency of the Fresnel lens
η_T	total efficiency of the system
η_{TEG}	conversion efficiency of the TEG
μ	fluid viscosity (N s m^{-2})
ρ	fluid density (kg m^{-3})
ρ_e	electrical resistivity (Ω m)
σ^2	coefficient of determination
σ_{SB}	Stefan–Boltzmann constant ($= 5.67 \times 10^{-8}$ W m^{-2} K^{-4})
ϕ	electric scalar potential (V)
φ_e	vector of nodal electric potentials (V)
Δp	pressure drop across the heat sink (N m^{-2})

Subscripts

a	air
f	fin
H	hot side
HS	heat sink
L	cold side
rd	radiation
w	water

systems is the optical-concentrated solar TEG which uses an optical concentration system to focus sunlight on the hot side of the TEG. Li et al. [16] designed a prototype optical-concentrated solar TEG and used a numerical method to evaluate its performance. Their results showed that the efficiency of the TEG could reach up to 9.8, 13.5, and 14.1% when Bi_2Te_3, skutterudite, and LAST alloys were employed as the materials of the TEG, respectively. Fan et al. [17] fabricated and experimentally tested an optical-concentrated solar TEG system along with a parabolic dish concentrator. The system was able to produce electric power up to 5.9 W under the temperature difference of 35 °C with the hot-side temperature of 68 °C. Yang et al. [18] developed a numerical model to analyze the performance of a TEG module with optical concentration. Their results suggested that the efficiency of the TEG decreased to 3.85% and had a relative drop of 61.3% when the contact resistance and all heat losses were considered. Xiao et al. [19] analyzed the performance of a multi-stage solar TEG by means of a numerical method. They pointed out that that the efficiency of the solar TEG system could reach 10.52% based on a three-stage thermoelectric module.

As far as the thermal-concentrated solar TEG is concerned, a flat-panel solar absorber on the hot side of the TEG is used to concentrate the solar heat through heat conduction. Kraemer et al. [20] designed a flat-panel solar TEG system with high thermal concentration; the system with the conditions of a thermal concentration ratio of 299 and AM1.5G (1 kW m^{-2}) could attain a peak efficiency of 4.6%. Chen [21] developed a theoretical model to evaluate the efficiency of a TEG pair in association with thermal concentration and optical concentration. His results suggested that the efficiency of the TEG pair under thermal concentration but with little or no optical concentration could be larger than 5% when the hot-side temperature was between 150 and 250 °C.

According to the above literature review, the two routes of optical concentration and thermal concentration can be utilized to improve the performance of solar TEGs. The optical concentrator is generally costly [22]. On the other hand, very little research has been performed on the thermal-concentrated solar TEG, especially in numerical simulation. For this reason, the objective of this study is to numerically investigate the performance of a solar TEG with thermal concentration. A three-dimensional finite element scheme will be employed to model the TEG system. In some studies [12,13,21], the properties of thermoelectric materials were assumed to be constant. This may induce a numerical deviation at high temperatures. Consequently, the temperature-dependent properties of the thermoelectric materials are considered in this work. In particular, an equivalent model is developed to simplify and accelerate the numerical approach. The effects of substrate area and thermoelectric element geometry on the performance of the TEG will be explored. Eventually, the power consumption for the cooling of the TEG is predicted via a theoretical method to evaluate the net output power of the TEG system.

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