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Research Paper

Parametric study of thermoelectric power generators under large temperature difference conditions

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HIGHLIGHTS

- A simplified model that includes variable properties of thermoelectric materials is proposed.
- Variable properties of thermoelectric materials can be neglected in co-flow arrangement.
- Inlet temperature and properties of thermoelectric materials have a coupling effect on power.
- Counter-flow arrangement is recommended when the heat transfer coefficient is high.
- The maximum output power occurs at ratios of load resistance to internal resistance of about 1.5–1.8.

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ABSTRACT

To help study the performance of thermoelectric power generators in conditions where there are large temperature differences between the hot-side heat exchanger and the cold-side heat exchanger, this paper presents a simplified numerical model that includes temperature-dependent properties of thermoelectric materials. Specifically, the temperature difference is added into the calculations of the current across thermoelectric legs. The results indicate that the simplified numerical model could reduce calculation time without reducing calculation accuracy. The variable physical properties of thermoelectric materials should be considered in the counter-flow arrangement at high temperature, but they can be neglected in the co-flow arrangement. The inlet temperature of hot fluid and the variable physical properties of thermoelectric materials have a coupling influence on the performance of thermoelectric power generation, which could change the variation trend of output power. The performance of thermoelectric power generation for the counter-flow arrangement is better than that for the co-flow arrangement, especially with high heat transfer coefficients and long channel lengths. When the the various physical properties of thermoelectric materials are considered, the maximum output power and efficiency occur at ratios of load resistance to internal resistance of about 1.5–1.8 for output power and 1.7–2 for efficiency.

1. Introduction

Thermoelectric power generation is an energy conversion technology for directly converting heat into electrical power. It has been used in many applications, such as automobile engines [1], internal combustion engines [2], portable devices powered by body heat [3], and personal thermal management devices [4]. A typical thermoelectric power generation (TEG) is composed of thermoelectric (TE) modules, a hot-side heat exchanger, and a cold-side heat exchanger. The thermoelectric conversion efficiency is primarily determined by the performance of the TE materials and devices. Much attention has been devoted to the development of high-efficiency TE materials and novel heat transfer enhancement technologies. The dimensionless figure of merit (*ZT*) is used to characterize the thermoelectric conversion efficiency of TE materials. Tan et al. [5] and Zhao [6,7] proposed a (Sb, Bi)$_2$Te$_3$ nanowire array and single crystals of SnSe with a *ZT* of 1.72 at room temperature and 2.6 at 923 K. More work on TE materials, including SiGe [8], organic polymers [9], flexible n-type thermoelectric substances with organic intercalation of layered transition metal dichalcogenide TiS$_2$ [10], chemically doped macroscopic graphene fibers [11], and nano materials [12,13] had been done to increase *ZT* values and thus improve the performance of TEGs. The system performance is

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Nomenclature

Symbols

A	cross-sectional area, m^2
C_p	specific heat capacity, J/(kg·K)
H	height of leg, m
I	electric current, A
K	thermal conductance, W/K
L	length of channel, m
P	output power, W
Q	heat transfer rate, J
R	internal electric resistance, Ω
R_{lo}	load electric resistance, Ω
R_{sum}	total electric resistance, Ω
T	absolute temperature, K
W	width of channel, m
d	distance from entrance of the hot fluid, m
h	heat transfer coefficient, W/(m^2·K)
l	length of leg, m
m	mass flow rate, kg/s
r	row
t	time, s
w	width of leg, m

Greek symbols

α	Seebeck coefficient, V/K
λ	thermal conductivity, W/(m·K)
ρ	electrical resistivity, Ω·m

Subscripts

fh	hot fluid
fc	cold fluid
p	p-type thermoelectric material
n	n-type thermoelectric material
h	hot-side surface of TEG
c	cold-side surface of TEG
in	inlet fluid
ave	average absolute temperature

Superscripts

i	*i*th unit

not only determined by TE materials and devices, but it is also affected by the performance of the heat exchangers. Ma et al. [14,15] and Lu et al. [16] performed numerical simulations and experiments to investigate the performance enhancement of TEGs using longitudinal vortex generators. Refs. [17–20] described other heat transfer enhancement technologies used for TEGs, such as fins, channel inserts, and flow impeding panels.

For practical use of TEGs, the performances of TE modules and heat exchangers are dependent and interactive [18,21]. Thus, understanding the TEG performance by combining TE modules and heat exchangers is of importance for TEG design and optimization. Many theoretical and numerical methods have been developed to investigate the performance of TEGs. To obtain simple models, a lot of work had been based on a one-dimensional model. Tian et al. [22] proposed a mathematic model for a segmented TEG that consisted of low-temperature thermoelectric bismuth telluride and the medium-temperature thermoelectric skutterudite. The results showed that the segmented TEG had a greater potential compared to the traditional TEG. Yazawa and Shakouri [23] optimized the power and efficiency of TEGs with asymmetric thermal contacts. Zhang [24] proposed a new TE module design concept and analyzed it using an energy transport equation. Zhu et al. [25] found that optimizing the heat transfer area allocation ratio could enhance power generation by 8–30% and enhance efficiency by 40–60%. Gomez et al. [26] used a numerical method to predict the output power and optimum load resistance and found that the load resistance ratio for optimum conditions was larger than the traditional one. Ngondi [27] explored an economic analysis of TEGs. Moreover, based on a one-dimensional model, a non-dimensional number was used to effectively simplify the process of calculation. Chen et al. [28] investigated the two most important performance parameters, efficiency and thermal conductance. A new cycle model consisting of multi-couple TE devices and involving the key irreversibility of real TEGs was used to calculate the maximum efficiency and optimize structure parameters of TEGs. Lee [29] also used non-dimensional numbers to create a new mathematical method using dimensional analysis to determine important parameters of TE devices. This new method can be used to optimize the design for two given fluid temperatures for the heat sinks. Lu et al. [30] also used non-dimensional analysis to develop a theoretical model to study thermal resistance matching which is the relationship between thermal resistance allocation and the system cooling power under different operating currents. Yu and Zhao [31] established a numerical model to predict the performance of TEGs with parallel-plate heat exchangers. It can predict fluid temperature changes and the hot-side and cold-side temperatures of TEGs. Suzuki and Tanaka [32] analytically deduced output power generated by 15 TEGs with multi-panels. The effect of flow arrangement has usually been ignored. He et al. [33] used temperature gradient modeling to study four different cooling methods. It was found that the counter-flow arrangement produced higher output power than the co-flow arrangement.

However, with most one-dimensional analysis, the physical properties of TE materials are assumed to be temperature-independent, which may cause large errors when the TEG is used in conditions with large temperature differences between the hot-side heat exchanger and the cold-side heat exchanger. In this work, to study the performance of TEGs, a simplified numerical model that considers temperature-dependent physical properties of TE materials is proposed. Two iteration methods for solving the numerical model are compared. The effects of the flow arrangement, inlet temperature, heat transfer coefficient, channel length, and the ratio of load resistance to internal resistance are studied under large temperature difference conditions.

2. Physical and numerical models

Fig. 1(a) shows a physical model of a typical TEG. The TE modules are sandwiched between the hot-side heat exchanger and the cold-side heat exchanger. To simplify calculations, the heat conduction along the transverse direction is ignored. The temperature at each row (r) of the TEG is assumed to be the same, so the model is regarded as one dimensional, as shown in Fig. 1(b). The thermal contact resistance and heat losses, including radiation heat transfer, are ignored.

During the calculations, the TEG is divided into n units. Each unit includes one pair of p-type and n-type TE legs. In the i^{th} unit of the hot-side fluid channel, the heat transferred from the hot fluid to the hot-side wall (Q_h^i) can be calculated by:

$$Q_h^i = \frac{C_{p,fh}\cdot m_{fh}\cdot(T_{fh}^i - T_{fh}^{i+1})}{r} \tag{1}$$

$$Q_h^i = 2\cdot h_h^i\cdot A_h^i\cdot\left(\frac{T_{fh}^i + T_{fh}^{i+1}}{2} - T_{wall,h}^i\right) \tag{2}$$