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Performance analysis of a passively cooled thermoelectric generator

Ahmed S. El-Adl[a,*], M.G. Mousa[b], A.A. Hegazi[b]

[a] Department of Mechanical Engineering, Higher Technological Institute, Tenth of Ramadan City, Egypt
[b] Department of Mechanical Power Engineering, Mansoura University, Mansoura, Egypt

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ABSTRACT

Performance of a passively cooled thermoelectric generator (TEG) under different operating conditions is experimentally investigated in this study. The effect of input heat rate in addition to the influence of utilizing various passive heat dissipation techniques on the TEG performance are analyzed and demonstrated. The temperature of the TEG sides, power output, conversion efficiency and the response time (i.e., the time required to reach steady state operation) are accounted as a denotation to the characteristics of the TEG performance. Free convection (FC), passive water cooling (PWC) and vapor phase change cooling (VPC) are employed for heat dissipation from the TEG through the cold side. Also, the effect of utilizing finned heat sink (fins) and the effect of filling ratio (i.e., in case of utilizing PWC and VPC) on the performance of the employed heat dissipation techniques are explored. From the experimental results, it can be deduced that increasing the input heat rate and utilizing fins to aid heat dissipation have enhanced the TEG performance and provided higher power output for all other operating conditions studied. VPC aided by fins showed the best performance compared to other techniques exploited. Additionally, the results illustrated that in case of employing PWC and VPC, it is necessary to use an optimal filling ratio for the working fluid utilized in order to achieve the best performance. The experimental data obtained are compared with the data available by the TEG module manufacturer and excellent agreement is obtained.

1. Introduction

Growing demand for energy consumption in addition to rising energy prices and higher environmental awareness have become a significant problems facing the world today. These problems have given prominence to research and explore novel sources of energy and handling conventional energy in a more environmentally friendly way. Thermoelectric generators (TEGs) are among the promising clean energy resources with the cost-efficient performance, which are solid-state devices that convert thermal energy directly into electricity in an amount depending on the temperature difference across them [1]. TEGs offer various advantages over traditional electric power generators as they are robust energy converters that possess no mechanical moving components and thus are silent, lightweight, dependable, durable, compact, maintenance-free, long operating periods, uncomplicated scalability and environmentally friendly [2,3].

The direct conversion of the thermal energy into electricity is controlled by three interrelated phenomena; the Seebeck, Peltier and Thomson effects and they are as well accompanied by additional effects, including Joule heating and Fourier heat conduction [4].

The employment of TEGs has rapidly increased in recent years with applications ranging from microwatts to kilowatts. One of the most important applications for TE power generation is the recovery of waste heat from industrial processes such as combustion gases from cook stoves [5] boilers and furnaces, in addition to waste heat from cooling water of the electric furnaces, compressors and fuel cells [6]. Also, significant energy saving can be accomplished by the proper recovery of waste heat from automobiles [3,7], ships [8,9] and aircrafts [10,11]. Access to electricity is among the important challenges for developing countries and remote regions. In these situations, the employment of TEGs is considered a significant alternative to providing electricity by converting the available environmental temperature differences into electrical energy [12]. One of the promising application for TE power generation is the utilization of TEGs in the conversion of renewable energy directly into electricity especially geothermal [13] and solar energy. Besides, TEGs can be integrated with the solar photovoltaic systems [14,15] and solar heating systems [16] to constitute a hybrid system with enhanced conversion efficiency. Due to their robustness, TEGs are appropriate for specialized applications such as aerospace [17], medical [18], military and telecommunications [19]. Recently, TEGs are also employed to generate electricity by utilizing human body heat, for the aim of powering wearable electronics [20,21] and as

* Corresponding author.
E-mail address: ahmed.s.eladl@hti.edu.eg (A.S. El-Adl).

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Nomenclature

P	electric power, W
Q	heat rate, W
R	electric resistance, Ω
T	temperature, °C
V	voltage, V
ΔT	temperature difference, °C

Subscript

C	cold side
EH	electric heater
H	hot side
in	input
L	load
o	output

Abbreviation

Bi_2Te_3	bismuth telluride
FC	free convection
NI	National instruments corporation
PID	proportional-integral-derivative
PWC	passive water cooling
TE	thermoelectric
TEG	thermoelectric generator
TIM	thermal interface material
VI	virtual instruments
VPC	vapor phase cooling

Greek symbols

η	conversion efficiency, %

power sources for self-powered microsystems and electronic devices of extremely low power consumption [22]. Additionally, TEGs can also be utilized at a nuclear power plant for micro-power generation to ensure that indicators or sensors operate properly in the case of severe accidents [23].

To enhance the performance of thermoelectric (TE) power generation systems, considerable efforts are devoted to the search for new high-performance TE materials besides promoting the figure of merit of currently used materials [24–28].

In addition to exploring the properties of TE materials, optimizing the geometrical shape and design of TEG modules has been considered continuously [29–31].

Extensive research studies are also executed to analyze the characteristics and the efficiency of TE power generation systems. However, a finite number of studies are available dealing with the thermal experimental performance of TEGs. The TEG generated power against the coolant pumping power was studied by Rezania et al. [32]. The results showed that there is a specific coolant flow rate at any temperature difference that provides maximum net-power in the system. Date et al. [33] demonstrated the comparison between the thermal performances of TEGs with their cold sides were cooled down by either bare plate, 60 mm fin, 80 mm fin and 100 mm fin. From the experimental analysis, it was suggested that 100 mm fin length would be the practical boundary to the fins size, above that limit the increase in fin length was improbable to be economical. Lesage et al. [34] and Amaral et al. [35] investigated TE power enhancement of a liquid-to-liquid TEG when its flow channels were fitted with turbulating inserts. The results demonstrated that the measured power output increased with increasing the flow rates. Additionally, the inserts offered an improvement in the TE power generation. Bjørk et al. [36] characterized the capability of power production as a function of flow rate for three different thermal interface materials. The best thermal interface material was indicated to be graphite paper. The effect of metal foams utilization on the performance of TE waste heat recovery system was experimentally enquired by Wang et al. [37] The results demonstrated that filling the flow channels with metal foams could effectively increase the system performance. These mentioned studies had employed active cooling techniques for heat dissipation from the TEG cold side, however, it could be deduced that active cooling of TEGs was a problematic as mechanical devices such as pumps and fans draw a high proportion of the limited power generated. Hence, the ideal system should operate passively to avoid electricity consumption from the limited power generated by TEGs. From the studies that adopted passive cooling techniques, Nuwayhid et al. [38] developed a low-cost TEG, cooled by air free convection employing a commercially available heat sink. Also, Candadai et al. [39] investigated the performance of a solar TEG technology that used a commercial TE module cooled by natural air convection. Jaworski et al. [40] demonstrated the experimental results obtained from investigating a TEG designed for radiative heating and cooling using phase change materials. Deasy et al. [41] computationally simulated and experimentally tested a passive single phase liquid thermosyphon cooling system for use with TEGs. It can be remarked from these studies that the ideal TE system should provide effective cooling and operate passively. The last mentioned is of the most significant as it aims the deficiency of parasitic electricity consumption of the limited power generated by TEGs, alleviate start-up problems and enhances the long-term reliability. However, these investigations have not considered the performance constraint associated with the cooling technique but have focused more on constructing a working system, capable of generating power. By elucidating these constraints an in-depth understanding of how to build the most efficient passively cooled power generating system can be achieved.

From the literature, it can be concluded that enhancing the capacity of heat transfer from the cold side in a proper range with an efficient way and also maintain high and stable temperature difference across the TEG module without the need to consume additional power is a difficult task to achieve. Hence, the current study tackles this key challenge and contributes to experimentally investigate the influence of different operating conditions on the performance of a passively cooled TEG. The study focuses not only on electric power generation but also considers the optimum parameters required for the enhancement of the utilized passive cooling technique performance. The effect of varying the applied input heat rates through the hot side, in addition to the effect of utilizing different passive heat dissipation techniques on the TEG performance, are experimentally evaluated. Moreover, the optimum parameters required to achieve effective and enhanced passive cooling and consequently high performance of the TEG is explored. Also, for the first time, the influence of the filling ratio of the working fluid in case of utilizing passive water cooling (PWC) and vapor phase cooling (VPC) is experimentally investigated. In addition, the effect of integrating the finned heat sink with these techniques has been explored.

2. Experimental setup and data reduction

To investigate the influences of different operating conditions on the performance of a passively cooled TEG, experiments are conducted using an experimental setup, which is entirely designed, fabricated and constructed for this purpose. The setup is composed of six basic components, which are; thermoelectric module designed and designated for power generation, heating block with a customized electric heater as an input heat source, alienable cooling block as a heat dissipating device,

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