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Multi-objective thermal analysis of a thermoelectric device: Influence of geometric features on device characteristics

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ABSTRACT

Proper assessment of geometric features of a thermoelectric generator is important to design devices with improved performance features such as high efficiency and output power. In the present study, three the-state-of-the-art multi-objective evolutionary algorithms, namely, NSGA-II (Non-dominated Sorting Genetic Algorithm-II), GDE3 (Generalized Differential Evolution generation 3), and SMPSO (Speed-constrained Multi-objective Particle Swarm Optimization) are used to optimize the geometric features of a thermoelectric generator for improved efficiency and output power while incorporating different operating conditions. The parameters assessing geometric features of the device include shape factor and pin length size while operating parameters include temperature ratio and external load parameter. Thermal analysis incorporating geometric features and operating parameters of the device is introduced prior to the optimization study. The findings are validated against the results reported in the open literature. It is found that shape factor and pin length size have significant effect on the device performance. Increasing shape factor ($S \leq 0.5$) first increases thermal efficiency to reach its maximum (~17%), and furthermore, an increase in shape factor ($S \geq 0.5$) lowers thermal efficiency significantly (~8%). Device output power behaves similar to that of efficiency for small increment in shape factor, provided that further increase in shape factor does not influence output power of the device. A unique design configuration is present for a fixed operating condition of a thermoelectric generator; in which case, thermal efficiency and output power of the device attain high values.

1. Introduction

Increasing demand for electrical energy consumption led to the development of efficient energy conversion devices, which use clean energy resources. Sustainable development of energy efficient devices requires extensive research into design and operation of the electrical energy generation devices through integration of renewable energy technologies. Thermoelectric power generator is one of these devices, which involves efficient electrical energy generation from waste heat. Although efficiency of traditional thermal to electric generators is several times higher than the efficiency of a thermoelectric system for large electrical power generation applications, the traditional systems are expensive, due to large scale energy requirements, and they operate at high temperatures. On the other hand, for applications requiring less than 100 W, thermoelectric generators become less costly and have several advantages over the traditional thermal to electric generators [1]. The recent developments in thermoelectric materials extend the thermodynamics analysis to cover high temperature ranges. This is vital since the efficiency of a thermoelectric converter depends heavily on the temperature differences. In addition, efficiency of thermoelectric devices can also be enhanced through modifying device geometric configurations [2–4]. Consequently, investigation into influence of geometric configuration of thermoelectric generator on device performance including efficiency and power becomes essential.

Considerable research studies have been carried out to examine thermoelectric device performance for various applications. Exergy analysis and performance assessment of thermoelectric generator were carried out by Wang et al. [5]. Their findings revealed that both the maximum energy efficiency and exergy efficiency increased with increasing hot-reservoir temperature for the case where the Seebeck coefficient and thermal conductivity was temperature-dependent. Performance of a solar heat pipe

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thermoelectric generator unit was carried out by He et al. [6]. They presented the influence of basic parameters on device performance. These parameters included solar irradiation, cooling water temperature, thermo-element length and cross-section area, and a number of thermo-elements. Efficiency improvement of thermoelectric generators was investigated by Patyk [7]. He demonstrated that, under various operating conditions, thermoelectric generators in power units could save waste energy and reduce the environmental burden due to their eco-efficient characteristics. Parametric and exergetic analysis of waste heat recovery system based on thermoelectric generator was carried out by Shu et al. [8]. They suggested that combined thermoelectric and an organic cycle system was suitable for waste heat recovery from engines. In this case, thermoelectric generation could extend the temperature range of a heat source and thereby improve the fuel economy of engines.

Thermoelectric energy conversion incorporating linear and nonlinear temperature dependence of material properties was examined by Wee et al. [9]. They indicated that inclusion of the Thomson effect was essential to assess the qualitative behavior of thermoelectric energy conversion system. Influences of effective temperature differences and electrical parameters on performance of thermoelectric generators were studied by Kim [10]. He showed that approximately 25% of the maximum output power was lost because of the parasitic thermal resistance of the thermoelectric module. Efficiency analysis of thermoelectric combined energy systems was carried out by Chen et al. [11]. They indicated that the overall conversion efficiency of the thermal system could be improved significantly through integration of thermoelectric devices.

With regard to multi-objective optimization, a few notable recent studies have been carried out to investigate the performance of thermoelectric devices under various operating conditions and device configurations. Rao and Patel [12] successfully utilized a modified TLBO (Teaching-Learning based multi-objective optimization) algorithm to maximize the cooling capacity and the coefficient of performance of TEC (thermoelectric cooler). In this study they have considered two different configurations of TECs, electrically separated and electrically connected in series as well as the contact and spreading resistance of the TEC. On the other hand Belanger and Gosselin [13] developed a simulation model of a heat exchanger with thermoelectric generators in its walls to optimize the total volume, total number of thermoelectric modules, output power, and pumping power. Their results showed that the number of sub-channels in the heat exchanger has a more significant impact on the overall performance than the fin geometry. Moreover, the net output power is largely dependent on the number of thermoelectric modules but not on the heat exchanger volume. NSGA-II was widely used in optimization of thermal systems for improved performances [14–23]. Optimization of thermodynamic system incorporating an ammonia-water power cycle was carried out by Wang et al. [14]. They demonstrated that the optimization provided the useful information to maximize the exergy efficiency and minimize the total heat transfer capability and turbine size parameter under the given waste heat conditions. The Pareto optimal solutions for an Organic Rankine Cycle for diesel engine waste heat recovery system were introduced by Hajabdollahi et al. [15] using the NSGA-II algorithm. They indicated that the algorithm used maximized the thermal efficiency and minimized the total annual cost simultaneously. Design and optimization of a tubular recuperative heat exchanger used in a regenerative gas turbine cycle were carried out by Sayyaadi et al. [16]. They showed that the multi-objective optimization scenario incorporating the NSGA-II algorithm could be considered as a generalized optimization approach in which balances between economical viewpoints of both heat exchanger manufacturer and end user of recuperater could be achieved. Systematic analysis of the heat exchanger arrangement problem using multi-objective genetic optimization was presented by Daroczy et al. [17]. In the analysis, they considered the conditions, which were particularly suited for low-power applications, as found in a growing number of practical systems in an effort toward increasing energy efficiency.

Recently, Ibrahim et al. [18] have used the NSGA-II and GDE3 algorithms to investigate the optimal PV (photovoltaic) farm design yielding the maximum field incident energy collected while minimizing the deployment cost of PVs in the Toronto area, Canada. They were able to find a diverse set of optimal PV farm design solutions which would not be possible to achieve similar result using single objective algorithms.

With regard to energy planning, Silva et al. [35] have utilized three recent PSO (Particle Swarm Optimization) based multi-objective optimizers, MOPSO-CDR, MOPSO-DFR, and SMPSO to investigate the optimal operational planning involving hydrothermal systems composed of eight Brazilian hydroelectric plants. The optimization problem involved minimizing the total cost of thermal power while maximizing the total stored energy in all reservoirs. They have shown that it is possible to approach the planning of hydrothermal systems as a multi-objective problem.

The performance characteristics of thermoelectric devices, mainly, depend on the design parameters and operating conditions. The design configuration can be improved through the enhancement of the average Figure of Merit ($ZT_{average}$) and re-sizing of the thermoelectric active elements such as thermoelectric pins [2]. Enhancement of the averaged Figure of Merit requires improvement in the pin materials, such as Bi_2Te_3 and Skutterudites [24]. Since the improvement of the device active material involves material science research, this is not considered in the present study. However, the influence of geometric configurations on thermal performance of thermoelectric devices was investigated previously [2–4], where the main focus was the assessment of device performance as a result of a single parametric variation. Therefore, the geometric parameters maximizing device performance are considered in the present study in line with the previous findings [2–4]. However, optimization study for device performance considering all geometric configurations under various operating conditions was not thoroughly investigated. Moreover, the two objectives, namely, the maximization of power and efficiency are conflicting objectives. To fill out this gap, the present study uses three state-of-the-art multi-objective evolutionary algorithms, namely, NSGA-II, GDE3, and SMPSO to optimize the efficiency and the output power of a thermoelectric device. The optimization of thermoelectric device performance due to different device geometric configurations and operating conditions are presented, yielding an analysis of optimum device geometric configurations for high thermal efficiency and output power.

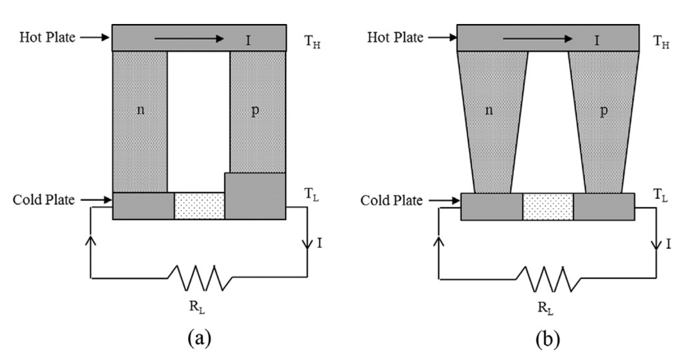

Fig. 1. A schematic view of thermoelectric generator for different geometric configurations: a) size of pin legs is different and b) shape factor is different.