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Research Paper

Helical configuration for thermoelectric generation

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HIGHLIGHTS

- Confirm the performance advantage of the helical TE module.
- Clarify the effect of geometric parameters on the TE performance of helical module.
- Define the unit performance to reflect the performance of entire TE module.
- Propose a design orientation to optimize the helical TE module.

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ABSTRACT

Performance of thermoelectric (TE) generator (TEG) depends on its physical structure in addition to the properties of TE materials. This study numerically simulated the characteristic performances of a three-dimensional (3-D) helical TE module using finite-volume method, and compared them with those of a conventional straight module. The effect of geometric parameters of helical TE module on the characteristic performances was analyzed, and an optimal helical design was proposed to obtain higher performance. The simulation results show that the helical module can harvest more heat than the straight module, and thus generate higher output power because the conversion efficiencies of two modules are approximately equal. The increase in pitch of the helical module has a positive influence on the characteristic performances, including more heat harvesting and output power, as well as higher conversion efficiency. However, the radial expansion of helical module brings an opposite effect on the unit performances, which is defined by dividing the characteristic performances by the number of *p*–*n* pairs, and unit input heat, unit output power, and unit heating area of helical module are decreased with module diameter. Higher performance can be generated by the use of helical module with longer pitch and shorter diameter.

1. Introduction

Inexhaustible resources and low-grade energies, such as renewable solar heat and unrecovered industrial heat, can be directly converted into electricity by using a thermoelectric (TE) generator (TEG), which is based on the Seebeck effect at a junction of two different materials, and chemical reactions or mechanical moving parts are no longer needed [1,2]. The conversion efficiency of this method depends on the inherent properties of TE materials and TEG designs. Many previous studies focused on the improvements of the electrical conductivity, the thermal resistance and the Seebeck coefficient in order to fabricate the efficient TE materials with high figure of merit. High performance of TE materials with hierarchical architectures can be largely enhanced by the maximum reduction in lattice thermal conductivity [3], and appropriate supplement of dopant in TE materials can significantly promote the value of figure of merit [4]; meanwhile, some metal oxides have been developed as candidate TE materials for cascade-type modules that are usable in air atmosphere [5]. On the other hand, the optimization of the geometric configurations and dimensions is critical for obtaining the maximum performance of a TEG [6]. Basic cognitions for optimizing a TEG have been proposed, including performance criteria of meeting thermal demand and maximizing coefficient of performance, as well as manufacturing criteria of minimizing material volume and minimizing number of *p*-*n* junctions [7]. The maximum power generation and maximum cost-performance of a TE module can be achieved using an optimal footprint ratio of p-type and n-type TE elements due to difference in electrical resistance and heat conductivity [8]. A novel linear-shaped TEG has a better performance than that of traditional π-shaped TEG because its unique structure makes *p*-type and *n*-type elements be optimized independently, so that they generate the maximum power and maximum efficiency at different length ratios of TE elements [9]. A mathematical model was proposed to develop an integrated design method and

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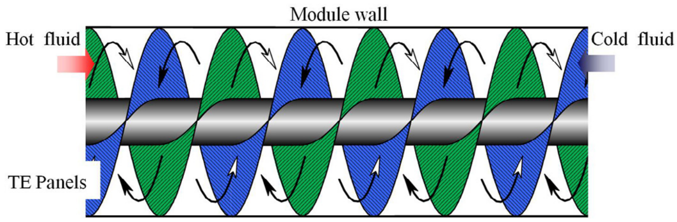

Fig. 1. Schematic of a helical TE module.

identify the impact factors of TEG performance, and then the optimal design for improving the performance of TE ventilator was confirmed in order to conduct a series of experiments to test ventilator's performance under different weather conditions [10]. The mechanical performance of TEG was also considered for running safety, especially under large operating temperature difference [11]. The optimal design can be more effective in promoting the weight-loss of TEGs, the saving of constituent materials and the utilization of heat energy. Rezania and Rosendahl [12] indicated that poor design and load matching have been limiting factors in achieving high performance, and the temperature difference is affected remarkably by the thermal conductivity and the thickness of the ceramic substrate on the hot side of TEG. Meng and Suzuki [13] studied TE elements in the shape of a polyhedron that is obtained by mechanically truncating the edge of a parallelogram element in order to further enhance TE performance and reduce materials usage. Moreover, some feasible TE devices consisting of multiple modules were designed for the large-scale power generation of TEGs. For example, TE modules of cylindrical multi-tubes [14], roll-cake tubes and double cylinders [15] can effectively provide a larger temperature difference ΔT through multiple heat exchange between the thermal fluids of hot and cold sources. Higher ΔT helps to improve TE performance because the electromotive force of a TEG is the sum of the products of ΔT and relative Seebeck coefficient S of TE elements for all serial connections. Further, a three-dimensional (3-D) helical design using two counter-flowing thermal fluids was proposed to form a homogeneous ΔT for the entire TE module by passing the heat from hot fluid to counter-flowing cold fluid through the TE panel, as shown in Fig. 1. This design also favors to compact the TE module by bending the constituent parts, and to minimize the flow pressure loss and the fluid inner friction in the seamless path.

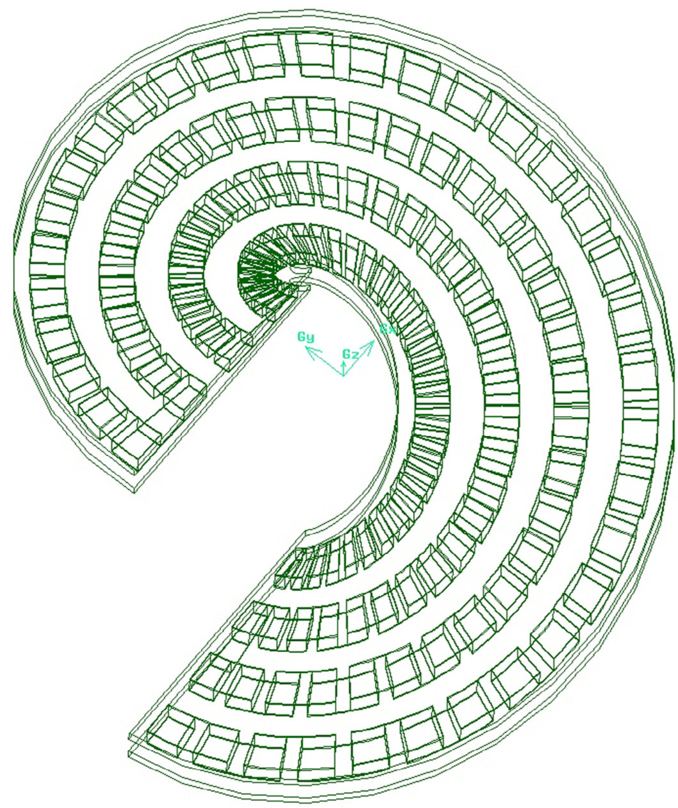

Fig. 2. A single cycle of TE panel in helical TEG.

The previous work [16] investigated the basic TE phenomena of tilted elements and clarified the effect of the bending of TE elements on the distributions of the electric current density, the temperature and the heat flux, and then indicated that the current preferentially flows along a main path, which is chosen spontaneously based on the specific configuration, dimensions and connection of TE junctions. TE performance of a helical module was also roughly compared with a straight module in which all the constituent parts have equivalent geometry. This study conducted ideal model simulations in terms of constant materials properties and continued to

Table 1
Geometric dimensions of TE modules.

Modules	p–n pairs	Diameters outer/inner (mm)	Elements edge length (mm)	Electrodes thickness (mm)	Insulators thickness (mm)
Helical	18	19.2/17.2	1.0	0.1	0.5
Straight	18	–	1.0	0.1	0.5

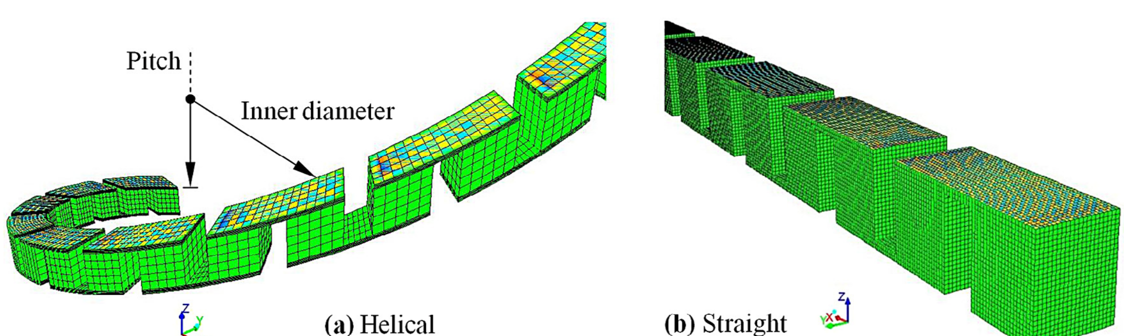

Fig. 3. Meshed models of TE modules.