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Performance Analysis of Thermoelectric Modules Using Polyhedron Elements

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Our previous work showed that the utilization of polyhedron elements has better advantages than the parallelogram elements in the thermoelectric (TE) generation. Especially a high efficiency of converting heat into electricity can be achieved at an optimal shape. This study proposed new TE module configurations consisting of polyhedron elements, and examined the TE performance of them by conducting the finite-element analysis. The simulation results show that the performance of TE module in the case of symmetrically arranging the polyhedron elements is slightly higher than that of arranging elements in parallel because of the more homogeneous heat flux and current density. The heat transfer and electric resistance, respectively, depend on the module configuration and element shape, and affect the TE performance simultaneously. TE performance increases significantly when the internal resistance becomes smaller and the heat diffuses slower.
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1. Introduction

Heat can be directly converted into electricity by a TE generation system, which is based on the Seebeck effect at a junction of two different materials. This method can use inexhaustible resources and low-grade energy, such as renewable solar heat and unrecovered waste-heat, and has merits of noiseless and pollution-free operations.[1)] It works even in the places isolated from the electric power supply. The chemical reactions or mechanical moving parts are no longer needed. However, the low efficiency of converting heat into electricity is still an indisputable disadvantage.[2)] The performance of TE generator depends on its geometric configurations as well as materials properties. Many studies focused on the improvement of the inherent properties of thermoelectric materials. The performance index, figure-of-merit, has been updating,[3,4)] while it is only achieved after optimizing at a narrow temperature range. Other approaches for maximizing efficiency are the optimal design of the TE generator because the heat harvesting and output power maximization can be significantly enhanced by optimizing the configurations and geometries of TE panels, modules and elements.[5,6)] Our previous work reported that the performance of TE module can be enhanced by changing the shape of element from parallelogram into polyhedron.[7)] The parts of TE element at edges are removed mechanically from the parallelogram shape, as shown in Fig. 1. The simulation results indicated that the utilization of polyhedron element gives many advantages. The output power, voltage and current in the modules consisting of polyhedron elements are higher than those before cutting. Especially higher conversion efficiency was expected by the optimal shape. Here we further explore the effect of module configuration on TE performance on the basis of this polyhedron shape and thus provide the fundamental perception on module design. The numerical simulations are conducted in an ideal case that the electric and heat loss at the junction parts as well as the convection and radiation heat exchange inside TE module are neglected. The predictions by this work are valid when these assumptions are accepted.

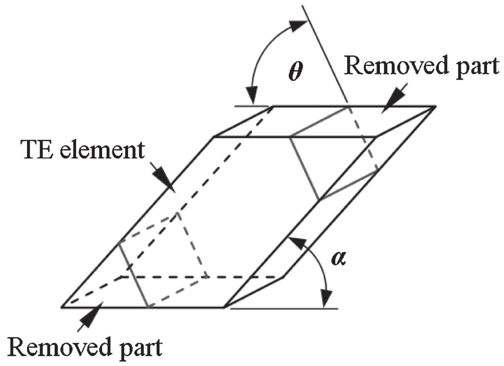

Fig. 1 Schematic representation of a polyhedron element.

This study examined TE module performance in the cases of arranging the polyhedron elements in parallel and symmetrical, as shown in Fig. 2(a) and (b). In addition, two new module configurations are studied by removing the low current density regions from the n-type elements, and by arranging p- and n-type elements in parallel, as shown in Fig. 2(c) and (d). The vacated spaces are replaced by the insulator as shown in Fig. 2(c), or simply on the empty as shown Fig. 2(d). The vacant space does not convey the electric charge, and it may contribute to saving the heat and materials. The new configurations are inspired from the previous prediction that the area in TE element with low current density should be removed.[7)]

2. Modeling

2.1 Basic conditions

Here all polyhedron elements are set as the same volume. The structural differences for all designs are listed in Table 1. The cutting angle of $\theta = 67.5°$ ensures that the cross-section of removed part in Fig. 1 is an isosceles triangle with apex angle of 45°. The previous report demonstrated that utility of this polyhedron geometry can improve TE performance

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Table 1 Designs for TE modules using polyhedron elements.

Designs	Tilting angle	Cutting angle (p/n)	Module configuration	Filler materials
	α (degree)	θ (degree)		
Case-1	45	67.5/67.5	Parallel	Electrode
Case-2	45	67.5/67.5	Symmetrical	Electrode
Case-3	45	67.5/90	Parallel	Insulator
Case-4	45	67.5/90	Parallel	—

Table 2 Thermal and electric properties of materials.[7)]

		Seebeck coefficient ($\mu V \cdot K^{-1}$)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Electric resistivity ($\mu\Omega \cdot m$)	Figure-of-Merit (−)
Bi_2Te_3	(p-type)	190	2.06	5.5	0.90
Bi_2Te_3	(n-type)	−210	2.02	10.0	0.92
Cu	(electrode)	1.83	398	0.0155	
Al_2O_3	(insulator)		36	0	

significantly compared with the other volume-equal polyhedron-shape elements.[7)] The properties of the materials used are listed in Table 2.

Finite-element analysis is conducted on the modules consisting of 18 pairs of p-n elements in series to examine three-dimensional TE effects. For simplicity, the following assumptions are made in formulating the entity models: (1) the entire TE system is adiabatic to the outside, (2) the perfect tight bonding exists among all parts, and (3) the properties of the materials are temperature independent and isotropic to shed light on the fundamental macroscopic TE phenomena. The macroscopic heat balance in the TE module can be expressed by eq. (1) and eq. (2). The theoretical output power P is deduced as eq. (3).

$$Q_1 = Q_c + Q_{P1} - \frac{1}{2} Q_J \tag{1}$$

$$Q_c + Q_{P2} + \frac{1}{2} Q_J = Q_2 \tag{2}$$

$$P = Q_{P1} - Q_{P2} - Q_J \tag{3}$$

where, Q_1 and Q_2 are the heat conducted through the insulators and Q_{P1} and Q_{P2} are the Peltier heat at hot and cold junctions, respectively, which depend on the temperature and current. Q_J is Joule heat following the Joule law, Q_c is the total heat conducted through all the TE elements, and P is the output power of TE module. Here the outer surfaces of insulator plates are set as hot and cold surfaces of TE module, as shown in Fig. 2(a). The temperature of the cold surface, T_2, was fixed at 300 K to represent an ambient temperature, while the temperature of the hot surface, T_1, was selected as 400 K and 500 K to generate a suitable temperature difference, $\Delta T = T_1 - T_2$.

2.2 Constitutive equation

The internal heat transfer and electric charge transportation are analyzed based on the thermal diffusion and charge transportation equations in addition to the TE phenomena. The differential equations for the heat conduction at each finite-element volume are solved on the basis of energy conservation. The details of analytical method were reported in the previous work.[7)] The finite-element models of TE modules are meshed using three-dimensional equilateral hexahedron makes finite-element volume have same edge length 0.05 mm. The use of this volume size ensured that a convergence can be achieved as quickly as possible in less than 5000 iterations on each complex calculation for the entire TE process. The differential equations are solved numerically with the finite-volume method using the commercial software, FLUENT. By referring to the reported codes,[8)] the contribution of the TE phenomenon was evaluated by our custom-written C program,[9)] and then combined with the conventional functions of FLUENT.

3. Results and Discussion

3.1 Performance comparison

The voltage U and current I increase almost linearly with the temperature difference between hot and cold sources because the electromotive force of TE module is the sum of multiplication of relative Seebeck coefficient S and ΔT. The output power P generated by TE module is generally proportional to the square of ΔT. The conversion efficiency η is defined as the ratio of output power P to input heat Q_1 absorbed at hot surface. The higher temperature difference ΔT leads to the higher performance. The performance of TE modules at $T_1 = 500$ K and 400 K are shown in Fig. 3, where ΔT are 200 K and 100 K, respectively. The performance changes are small for Case-1 and Case-2 where the p- and n-type elements have the cutting angle of 67.5° and connected in parallel and symmetrical, respectively. All of the voltage, current and output power of module using Case-2 (in symmetrical) are slightly higher than those using Case-1 (in parallel). Inversely, the input heat of module using Case-2 is lower than that using Case-1, thus making efficiency of converting heat into electricity ($\eta = P/Q_1$) higher at Case-2.

Although the low current density regions are removed from the n-type elements for the purpose of saving the heat and materials, as shown in Fig. 2(c) and (d), the module performance is not enhanced. The performance of Case-3 and Case-4 significantly decreased compared to those of Case-1 and Case-2. This is mainly because the internal electric resistances of TE modules using Case-3 and Case-4 increased as a result of changing the geometric aspect ratio of polyhedron elements, resulting in reduction of voltage, current and output power in a closed electric circuit. The configurations disparity leads to the distinctly different performance for TE modules using Case-3 and Case-4, even if they have the same internal electric resistance. Interestingly, Case-3 has the highest input heat Q_1 in all four designs. It is because a part of heat transfers through the filler material (insulator) of which is contacted directly with the n-type elements. The insulator has low thermal conductivity so that the thermal energy slowly diffuses and the heat is absorbed sufficiently from the hot source surface. In Case-4, heat only passes through the truncated electrode plates that are sandwiched between the insulator plates and TE elements. The module is indeed missing the physical parts that contribute to heat transfer. This suppression of thermal diffusion is the lowest input heat among four cases.

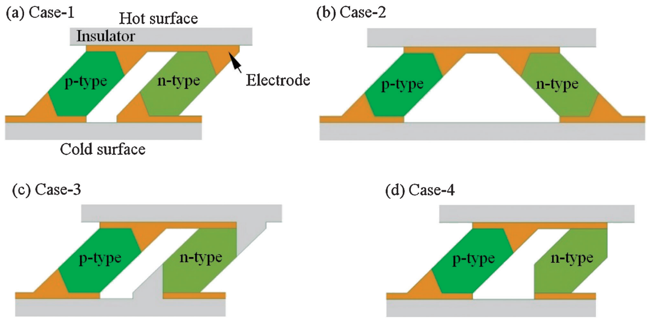

Fig. 2 TE module configurations.

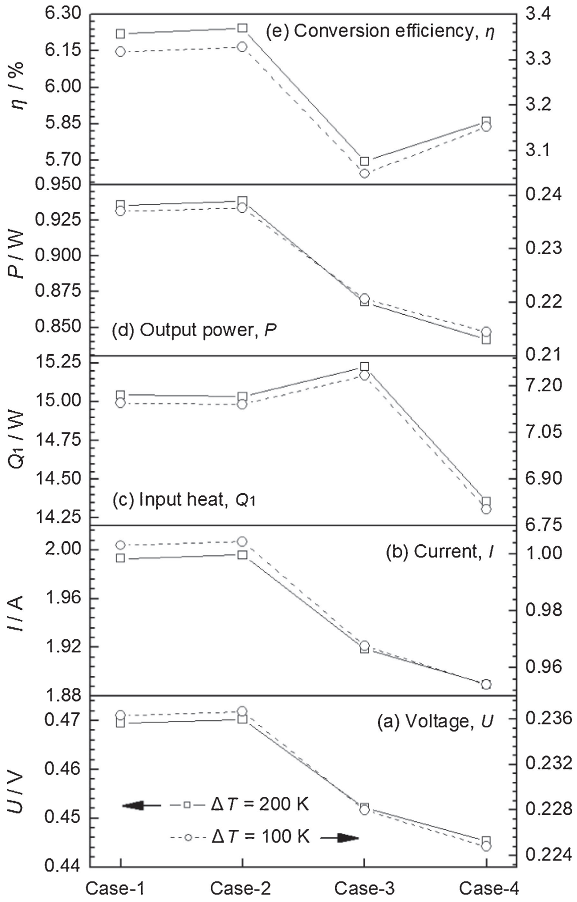

Fig. 3 Performance comparisons of TE modules.

In short summary, the module configuration largely determines the heat transfer, and thus affects the TE behavior. Therefore the detailed analysis on heat flux is effective to enhance TE performance.

3.2 Features inside modules

The previous results indicated that the temperature distribution strictly depends on the materials properties and exhibits a hierarchical trend at the entire module.[10)] However, the distributions of heat flux and current density are significantly affected by the module configurations. The heat fluxes of all the cases are shown in Fig. 4. Their common feature is that the heat flux value is distinguished by the thermal conductivities of materials. The low and high thermal conductivities lead to low and high heat flux on the TE elements and the electrode plates, respectively. The heat flux is not hierarchically distributed throughout TE module.

The previous work reported that the heat preferentially transferred through a geometry-dependent fast route, i.e. the shortest path.[7)] Here the length of this fast route is changed with the module configuration. The thermal diffusion in module is therefore largely affected by the length of the path and thus influencing TE performance. For example, the heat preferentially transfers through two paths, which are indicated by two arrows in Case-1 and Case-2, as shown in Fig. 4(a) and (b), respectively. The high-flux regions are clearly formed at both terminals of these paths. Although the fast routes in Case-1 and Case-2 have the same length, the performance of Case-2 is slightly better than that of Case-1, as shown in Fig. 3. It is because the difference between maximum and minimum heat fluxes is narrowed from 15.6–1120 kW·m^{-2} (Case-1) to 52.8–1030 kW·m^{-2} (Case-2). This

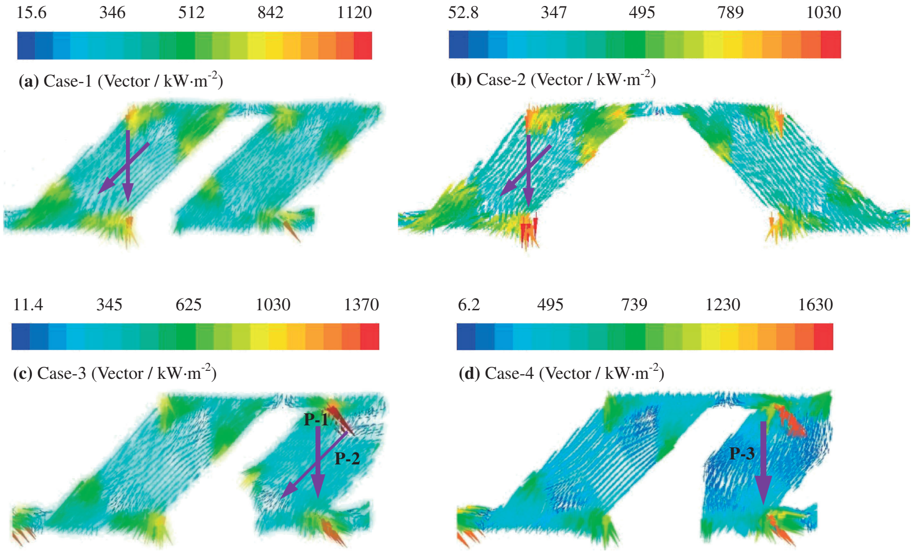

Fig. 4 Heat fluxed inside TE modules.

means that the heat diffuses more homogeneously in the symmetrical design of Case-2. On the other hand, only one shortest path exists at n-type elements in both Case-3 and Case-4, as seen in Fig. 4(c) and (d). The difference between two cases is that n-type element in Case-3 has two paths of different length, shorter one of P-1 and longer one of P-2, and receives a portion of heat transferring from the insulator through the direct bonding with TE elements. This channel forms a secondary heat-transfer path, which is delineated by a long-thin arrow (P-2) in Fig. 4(c). However, the heat in Case-4 only passes through the truncated electrode plate that is sandwiched between the insulator plate and n-type element. The heat is mainly transferred through a single path, as depicted by a long-thick arrow (P-3) in Fig. 4(d). The differences between the maximum and the minimum heat fluxes are significantly expanded for Case-3 and Case-4. Especially the maximum heat flux increased to 1630 $\mathrm{kW \cdot m^{-2}}$ in Case-4 and the heat rapidly transferred through fast route in n-type elements and so the module performance is depressed.

4. Conclusions

This paper clarified that the module configuration determines the TE performance largely by affecting the heat diffusivity. TE performance in the case of polyhedron elements symmetrically arranged (Case-2) is slightly higher than that of elements arranged in parallel (Case-1). This showed that the more homogeneous heat flux throughout TE module is essential, although the internal electric resistance is same in both cases. TE performances of Case-3 and Case-4 are significantly reduced in comparison with those of Case-1 and Case-2 because the electric resistance becomes higher in Case-3 and Case-4. The heat flux increased locally at the edges of TE elements in Case-4 and the heat is rapidly transferred through a single path. This uniform heat flow causes the lowest performance. The performance of Case-3 is slightly better than that of Case-4 because the heat received through a secondary heat-transfer path allows the heat transfer more homogeneously.

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REFERENCES

1) L. E. Bell: Science **321** (2008) 1457–1461.
2) G. J. Snyder and E. S. Toberer: Nat. Mater. **7** (2008) 105–114.
3) K. Biswas, J. He, I. D. Blum, C. Wu, T. P. Hogan, D. N. Seidman, V. P. Dravid and M. G. Kanatzidis: Nature **489** (2012) 414–418.
4) K. Koumoto, R. Funahashi, E. Guilmeau, Y. Miyazaki, A. Weidenkaff, Y. Wang and C. Wan: J. Am. Ceram. Soc. **96** (2013) 1–23.
5) R. O. Suzuki, Y. Sasaki, T. Fujisaka and M. Chen: J. Electron. Mater. **41** (2012) 1766–1770.
6) A. Rezania and L. A. Rosendahl: J. Electron. Mater. **41** (2012) 1343–1347.
7) X. Meng and R. O. Suzuki: J. Electron. Mater. **44** (2015) 1469–1476.
8) M. Chen, L. A. Rosendahl and T. Condra: Int. J. Heat Mass Transf. **54** (2011) 345–355.
9) X. Meng, T. Fujisaka and R. O. Suzuki: J. Electron. Mater. **43** (2014) 1509–1520.
10) X. Meng, T. Fujisaka, K. O. Ito and R. O. Suzuki: Mater. Trans. **55** (2014) 1219–1225.