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# EXPERIMENTAL EXPLORATION FOR OPTIMAL OPERATION CONDITIONS OF THERMOELECTRIC MODULES

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## ABSTRACT

Thermoelectric generators (TEGs) have been considered as a promising technology for waste heat recovery owing to energy depletion and environmental pollution. Properties of a thermoelectric module (TEM) affect the TEG system performance essentially. This research investigated the optimal operation conditions of a TEM under steady state by experiments to achieve superior performance. The impacts of clamping force and interface material thickness on the characteristics of a TEM with given heat and cold source temperature are analyzed in detail. Results indicate that increased pressing force diminishes the contact thermal resistance and enhances the heat conduction. The maximum stress that a module can withstand should also be taken into account. In addition, graphite layers material replaces the air gaps between interfaces on account of its compressibility, which conduce to higher thermal conductivity. However, the thermal resistance of graphite material increases with excessive thickness as well. From the analysis above, it can be concluded that the optimal operation conditions of the TEM in this test are the clamping force from 2.5 kN to 3.7 kN and the graphitic layers thickness of 0.8 mm.

**Keywords:** thermoelectric module, experimental test, optimal operation conditions, output power

## NONMENCLATURE

| *Abbreviations* | |
|---|---|
| TEG | Thermoelectric generator |
| TEM | Thermoelectric module |
| ZT | Figure of merit |

| *Symbols* | |
|---|---|
| P | Output power |
| R | Resistance |
| T | Temperature |
| U | Output voltage |

## 1. INTRODUCTION

Energy dilemma and environmental pollution problems have been increasingly serious with the rapid development of modern industry. Relative research indicates that only one-third of the energy generated by fossil fuels can be utilized effectively [1]. As a result, multiform techniques for waste heat recovery are supposed to improve energy efficiency and reduce emissions. Thermoelectric generators (TEGs) are considered as one of the promising methods that convert waste heat into usable power directly [2, 3].

The performance of TEGs primarily depends on thermoelectric materials and numerous researches concentrate on improving the figure of merit (ZT) [4]. For example, fullerene [5] and half-Heusler [6] thermoelectric materials were proved to be more efficient in power generation. Zhou et al. [7] summarized the recent development of new thermoelectric materials and various methods of improving the power factor. Valuable suggestions on material improvement and extensive application outlook of devices were also provided. In addition, optimization of other components in TEG systems has been of significant importance to take full advantage of each thermoelectric module (TEM). Deasy et al. [8] proposed a new cooling system using passive liquid thermosyphon for a TEG without any electrical input. Results showed that the system was long term reliable and the cold end temperature could maintain at around 70℃, which provided desired cooling effect. He et al. [9] analyzed the optimal dimensions of heat exchanger in a TEG system under all kinds of operating conditions. The concluded fitting correlations could provide guidance for achieving highest net power. However, none of them considered the optimal working conditions of a TEM.

A module performance test system was constructed to investigate the optimal operation conditions of a TEM when installed in a TEG system. The effects of clamping force and thermal interface material thickness were analyzed to evaluate the characteristics of a TEM. The results contribute to higher power output in real application of TEMs.

## 2. DESCRIPTION OF EXPERIMENTAL DESIGN

The schematic of the TEM performance test system is given in Fig 1. The main components are heating unit, cooling unit and electrical parameters measurement unit. Two variables that affect the performance of TEMs considered in this study are clamping force and graphitic layers thickness. The data acquisition was completed under steady state condition.

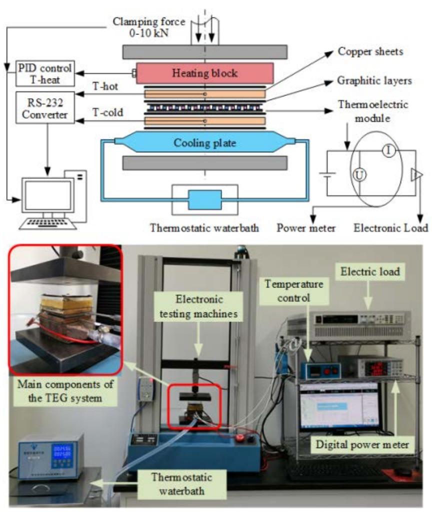

Fig 1 Schematic of TEM test system

The heat source adopts cast copper electric heating block with a temperature control system. A constant heating surface temperature can be maintained by PID automatic adjusting, while the other side is covered by thermal insulation material. The cooling plate designed in the experiment provides uniform temperature distribution for the cold side of TEM. The coolant temperature is controlled by a thermostatic waterbath from 283 K to 378 K. KTGM161-18 thermoelectric module with dimensions of 51.5 mm × 55 mm made in KELK Ltd. is used for experimental test. IT8813 electric load represent the resistance in the circuit and the output parameters are measured by PA310 digital power meter. The hot and cold side temperature of TEM is acquired by PT100 platinum resistor, which is calibrated by the thermostatic waterbath, as shown in Fig 2. It is indicated that the measurement results agree fairly well and the relative error is under 4%.

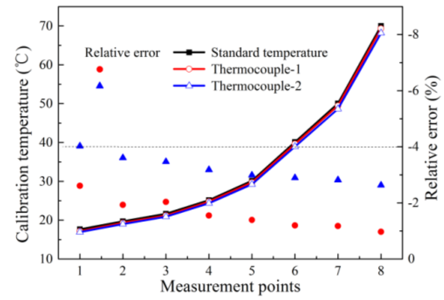

Fig 2 Calibration of platinum resistor

One of the factors that affect the performance of TEM is clamping force, which ranges from 0 to 10 kN provided by electronic testing machines. The function of graphitic layers is to reduce the contact thermal resistance between interfaces owing to the high thermal conductivity and compressibility. Therefore, the thickness of thermal interface material is the other factor considered in this work.

## 3. RESULTS AND DISCUSSION

In this research, the temperature of hot side and coolant is set at 373 K and 298 K, respectively. The impacts of clamping force and graphitic layers thickness on the properties of a module are discussed. Then the optimal operation conditions for a TEM are concluded based on the experiments results.

### *3.1 Effects of clamping force*

In this section, the graphitic layers thickness is set at 0.5 mm and the clamping force varies from 0.01 kN to 4.9 kN. The output voltage and output power under each resistance are recorded after all parameters remaining unchanged.

Fig 3 depicts the output voltage and output power under several clamping forces. The output voltage changes almost linearly with current and the slope stands for the internal resistance of TEM, which slightly decreased with lower current. The variation of output power with low resistance accords with the Ohm theorem. Nevertheless, the output power descends much slower when it is higher than 2.5 Ω on account of the decline of internal resistance. It is indicated that the change of load resistance affects the internal resistance of a TEM. Besides, both parameters improve distinctly with higher clamping force due to the enhancement of thermal conduction. The increasing pressing force reduces the contact thermal resistance to a large extent to achieve more efficient heat transfer. However, two parameters almost reach maximums when the force is 1.9 kN and the effect of heat conduction enhancement weakens after that. This can be explained that the thermal conductivity cannot be increased without limit.

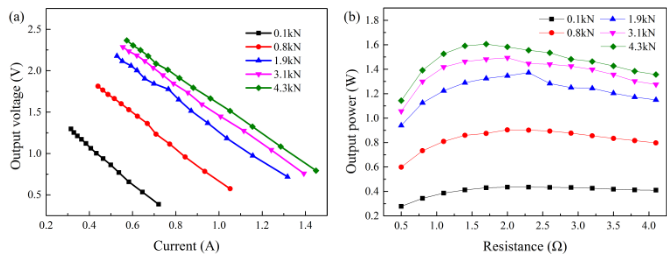

Fig 3 Output voltage and output power with clamping force

The cold side temperature measured at each steady state condition is displayed in Fig 4. It is slightly higher than the coolant temperature owing to the limited cooling capacity with constant flow of 16 L/min. In addition, the cold side temperature decreases around 4 K with larger clamping force. The reason is that the coolant dissipates heat more effectively from the heat source with better thermal conductivity. Therefore, increasing force contributes to higher temperature difference of a TEM as well as the output performance. It is worth noting that the cold side temperature drops about 1.5 K by adjusting the load resistance from 0.5 Ω to 4.1 Ω on average under each clamping force. The current declines with rising resistance, leading to less joule heat generated in the TEM. It is conductive to reduce the cold side temperature and improve the performance of TEM.

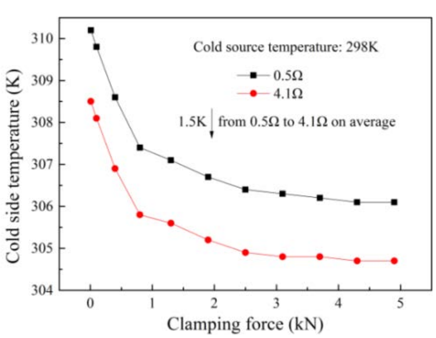

Fig 4 Effects of clamping force on cold side temperature

Fig 5 illustrates the open circuit voltage and maximum output power obtained by linear fitting and quadratic function fitting from Fig 3, respectively. It is indicated that the increasing clamping force has significant influence on the performance of thermoelectric module. The maximum output power improves from 0.28 W to 1.64 W and the open circuit voltage increase by 1.9 V with the pressing force changing from 0.01 kN to 4.9 kN. Nevertheless, the power output increments are 1.15 W and 0.21 W with the force range of 0.01 to 2.5 kN and 2.5 to 4.9 kN, respectively. Similar results apply to the open circuit voltage as well, which means the impacts of clamping force on the performance of a TEM diminish a lot. Although the clamping force contributes to fixing the module position, excessive mechanical stress not only adds difficulty to the assembly of TEG system, but also results in structural damage of a TEM. Consequently, the determination of clamping force for a certain TEM needs to take these factors into account.

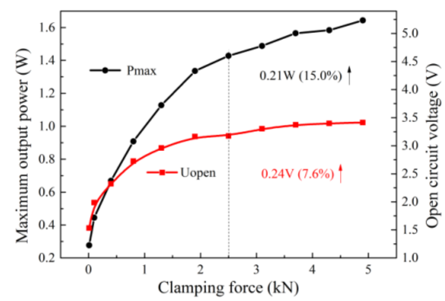

Fig 5 Maximum output power and open circuit voltage with clamping force

Based on the analysis above, clamping force on the module indeed intensifies the thermal conductivity of the TEG system as well as the performance of TEM. The optimal range of clamping force for a TEM is supposed to be from 2.5 kN to 3.7 kN in consideration of its pluses and minuses.

### *3.2 Effects of graphitic layers thickness*

In this part, the constant clamping force of 3.1 kN is selected according to the conclusions before. Thermal interface materials between interfaces are regarded as the main method of improving the heat transfer efficiency. As a result, the thickness of graphitic layers from 0 mm (without graphite) to 1.2 mm is considered to analyze the optimal characteristics of a TEM.

The maximum output power and open circuit voltage are measured with different graphite thickness, as shown in Fig 6. The graphite material has significant effect even if it is only 0.05 mm with a power increment by 45.8% compared to the direct contact structure. The peak values of 1.54 W and 3.43 V are achieved at 0.8 mm. The reason is that the compressible material with higher thermal conductivity replaces the air gaps between interfaces under appropriate clamping force. At the same time, the thermal resistance of graphitic layers increases when the thickness is larger than 0.8

mm, resulting in lower temperature difference and the performance degradation of TEM. As a consequence, the best properties of a module can be realized with moderate graphite thickness under given pressing force. In addition, the interface materials also avert the TEM from unsmooth surface contact and reduce the damage of module.

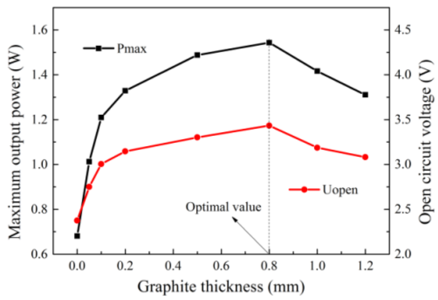


Fig 6 Maximum output power and open circuit voltage with graphite thickness

Fig 7 depicts the impacts of clamping force and graphite thickness on the internal resistance of a TEM, which declines a lot by increasing both variables. On the one hand, clamping force reduces the contact thermal resistance. On the other hand, different graphite thickness also alters the internal temperature distribution. The resistance changes due to the temperature dependent electrical conductivity. The decrease of internal resistance is another factor that conduces to higher power output.

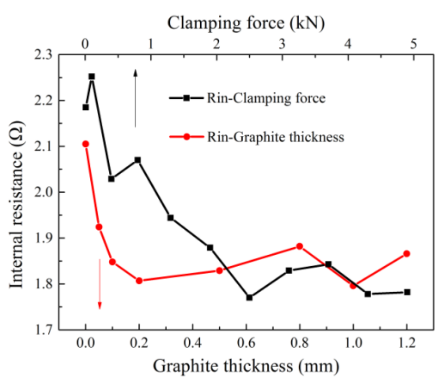


Fig 7 Effects of clamping force and graphite thickness on internal resistance

It can be concluded that TEMs with appropriate graphite thickness performs better under specific force and the optimal value in this work is 0.8 mm.

## 4. CONCLUSIONS

In this research, a module test system is developed to explore the optimal working conditions of TEMs. The impacts of clamping force and graphitic layers thickness on the characteristics of TEMs are analyzed. Main conclusions are given as follows:

- Clamping force enhances the thermal conductivity of the TEG system effectively and the optimal working condition of a TEM is from 2.5 kN to 3.7 kN.
- Interface material like graphite reduces the thermal resistance between each component of the TEG system. The optimal thickness is 0.8 mm to achieve better performance under the force of 3.1 kN.


## ACKNOWLEDGEMENT

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## REFERENCE


[1] Fitriani, Ovik R, Long BD, Barma MC, Riaz M, Sabri M et al. A review on nanostructures of high-temperature thermoelectric materials for waste heat recovery. Renewable and Sustainable Energy Reviews 2016;64:635–59.

[2] Cui YJ, Wang BL, Wang KF, Zheng L. Power output evaluation of a porous annular thermoelectric generator for waste heat harvesting. International Journal of Heat and Mass Transfer 2019;137:979–89.

[3] Fernández-Yañez P, Armas O, Capetillo A, Martínez-Martínez S. Thermal analysis of a thermoelectric generator for light-duty diesel engines. Applied Energy 2018;226:690–702.

[4] Asaadi S, Khalilarya S, Jafarmadar S. A thermodynamic and exergoeconomic numerical study of two-stage annular thermoelectric generator. Applied Thermal Engineering 2019;156:371–81.

[5] Rincón-García L, Ismael Ali K., Evangeli Charalambos, Grace Iain, Rubio-Bollinger Gabino, Porfyrakis Kyriakos et al. Molecular design and control of fullerene-based bi-thermoelectric materials. Nature Materials 2016;15(3):289.

[6] Zeier WG, Schmitt J, Hautier G, Aydemir U, Gibbs ZM, Felser C et al. Engineering half-Heusler thermoelectric materials using Zintl chemistry. Nat Rev Mater 2016;1(6):5135.

[7] Zhou X, Yan Y, Lu X, Zhu H, Han X, Chen G et al. Routes for high-performance thermoelectric materials. Materials Today 2018;21(9):974–88.

[8] Deasy MJ, Baudin N, O'Shaughnessy SM, Robinson AJ. Simulation-driven design of a passive liquid cooling system for a thermoelectric generator. Applied Energy 2017;205:499–510.

[9] He W, Guo R, Takasu H, Kato Y, Wang S. Performance optimization of common plate-type thermoelectric generator in vehicle exhaust power generation systems. Energy 2019;175:1153–63.