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Experimental research on thermoelectric characteristics of a thermoelectric generator with external influencing factors optimization

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ABSTRACT
The external influencing factors, the thermal interface material, load-bearing brick weight, and temperature difference, of a thermoelectric generator (TEG) device were experimentally examined. The micro heat pipe array (MHPA), as one novel thermal interface material, was investigated. The multi-variable coupling approach is used to analyze the intrinsic coupling correlation of the external influencing factors. The dimensionless synthesis economic factor index was proposed to analyze the improvement of thermoelectric characteristics, which can quickly assess the contact thermal resistance of different thermal interface materials. The results showed that the load power and load voltage generally increase with increased temperature differences. The contact thermal resistance decreases with increased load-bearing brick weight, but the decrement gradually decreases. The thermal interface material plays an important role in thermoelectric characteristics. The load-bearing brick weight performs little impact on the non-thermal interface material (NTIM) scheme. The two thermal conductive silicone grease schemes noticeably reveal better thermoelectric characteristics than those of the graphite paper schemes, although the thermal conductivity of thermal conductive silicone grease are much lower than that of graphite paper. The MHPA scheme exhibit the best thermoelectric characteristics, and its dimensionless synthesis economic factor index can be up to 371.81 %.

1. Introduction
Recently, the environmental problems and energy crisis have received widespread attention because of the acceleration of economic globalization and rapid economic development [1]. On the one hand, the reserves of coal, oil, and other nonrenewable energy can be predicted. If we do not develop new renewable energy, we will face the problem of energy shortage shortly [2,3]. Due to the excessive use of fossil fuels, the environmental and climate problems may cause a bad impact on human production and life [4]. Therefore, developing new energy and improving the utilization rate of current energy is the key to solving energy problems [5].

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1.1. Widespread application of thermoelectric generation technology

A large amount of heat is generated during the equipment operation, which causes the equipment temperature to be too high, which will affect production safety. Therefore, cooling must be used to ensure the safe operation of the equipment. In the process, a large amount of waste heat will be discharged, the energy utilization efficiency will be lowered. Without affecting the cooling effect of the equipment, the thermoelectric generation technology, as a new energy technology, can directly convert thermal energy into electrical energy. It not only improves the equipment running environment, but also enhances comprehensive energy efficiency [6]. The thermoelectric generator (TEG) draws upon the broad prospects for promotion due to its low system complexity, small size, no pollution, no vibration, the convenience of overhaul and maintenance, and so on. Consequently, it is universally concerned by many institutions and scholars [7]. In the field of waste heat recovery, Gürbüz et al. [8] performed a series of tests on a novel thermoelectric generator based on exhaust waste heat. The copper serpentine pipes and propane-fueled spark-ignition engine were designed to improve the temperature difference of thermoelectric modules. The DC electrical power rose by 11.5%–12.1% compared to the thermoelectric generator without propane at the condition of the 1500–5000 rpm of the engine. Singh et al. [9] reviewed the enhancement power output of a TEG device with low-temperature waste heat. The heat source of the Polymer Electrolyte Membrane fuel cell by means of swirl flow was analyzed. The maximum electricity power will expand from 200 mW to 3056 mW, if the swirl strength increases from non-swirl to 1.6 swirl strength. Wang et al. [10] proposed a novel thermoelectric generator integrated with heat pipes to recover high-temperature waste heat. Which can improve energy efficiency, and resolve the problem of energy supply. If the temperature of heat pipe can reach 903.15 K, the thermal conductivity will reach 100 times that of copper. To improve the energy efficiency of an integrated energy plant, Houshfar et al. [11] estimated the total product cost by adding the TEGs device in a waste-to-energy plant. The integrated energy and conventional plants are comprehensively discussed, then the lower total product cost, higher power output, and higher exergy efficiency were attained.

1.2. Thermoelectric efficiency and economic evaluation

The TEGs have received widespread attention, however, there exist deficiencies in high thermoelectric efficiency and practicality. To achieve the goal of widespread application, to find ways to improve thermoelectric efficiency, the different types of TEG systems are discussed, Musharavati et al. [12] adopted liquefied natural gas to cool the cold side of thermoelectric generators. It can strengthen power generation efficiency, and the thermal efficiency can reach 6.876% if the thermoelectric generator gets 80% output heat from the seawater. Khanmohammadi et al. [13] carried out two ocean thermal energy conversion systems, one integrated with solar energy, the other boosted with a TEG device. The exergy efficiency and output power will increase by 6.27% and 12.64 kW when the ocean thermal energy conversion system is bundled with thermoelectric modules. A thermoelectric generator using concentric filament structure was designed for low-power and high-voltage demand by Liu et al. [14], which can get excellent electrical performance with series-parallel connections in a small space and be a commendable design for aerospace fields. The available energy efficiency is improved, and the total cost is reduced. Heat pipes are integrated to improve the thermoelectric efficiency and power generation, Li et al. [15] put forward a modularised thermoelectric generator integrated with the heat pipe technology for vehicles, enhanced heat transfer performance impacted the total thermoelectric power generation with 29.8 W. Remeli et al. [16] investigated a thermoelectric generator integrated with heat pipes, the heat pipes were assisted at cold-side and hot-side of the thermoelectric modules. The thermoelectric generator can recover about 1079 W waste heat and obtain 41.6% heat transfer effectiveness.

Economic evaluation is an important indicator before the application of any energy device, the economy of traditional energy devices gradually declines with the rise in conventional energy prices. In the fields of low-grade energy and especially waste heat utilization, the TEGs have strong market economic competitiveness. Traditional energy devices are transformed by thermoelectric generation technology, which can offset the negative impact of rising energy prices. Therefore, the comprehensive utilization rate of energy will be continuously improved, and the social and economic benefits will also be steadily increased. Due to the importance of economic evaluation, Asaadi et al. [17] carried out the economic evaluation and thermodynamic performance of the TEGs with a two-stage annular. The two parameters of a height ratio and angle ratio on the economic performance of the TEGs were investigated. Results revealed that the single-stage TEG has higher economic factor than that of the two-stage one for all studied temperatures. The heat source temperature makes a significant impact on economic efficiencies. The angle ratio with one lead performs the lowest cost and the highest efficiency. Heat pipes are integrated to improve the total thermal efficiency and power generation, Li et al. [18] pointed out that economic evaluation is a significant criterion before the production of a novel TEG. The economic comparisons of two annular TEGs were conducted and discussed. A peak point of economic factors for segmented annular TEG was remarked. Li et al. [19] investigated the thermal economy evaluations of different leg shapes of a TEG. The mechanical analysis and economic evaluation were important consideration factors. Compared to the rectangular shape leg scheme, the triangular shape leg scheme could achieve more than twice the economic factor expressed in power output with the same heat flux but a less mechanically reliable design. With the steady improvement of the economic factors for the TEG, the thermal power generation technology will possess greater advantages to provide better solutions for efficiency optimization.

1.3. Effect of contact thermal resistance

The causes of contact thermal resistance for the TEGs are as follows: object surface roughness, partial contact, contact cracks, and so on. The contact thermal resistance, which is one of the important influencing factors for the thermoelectric characteristics, has a significant impact on the thermoelectric characteristics [20]. The contact thermal resistance is one of the main influencing factors on thermoelectric characteristics, which will hinder heat transfer between the heat sources and thermoelectric modules, cause the temperature of heat flow rapidly drops along the flow direction, and result in serious energy loss. The heat transfer characteristics will be weakened because the air within the crack can enhance contact thermal resistance [21].
A series of studies involving thermal contact resistance were carried out, Ga et al. [22] presented a thermal resistance model and thermoelectric conversion model of a TEG device, the models were used to solve the problem of the power supply for wireless sensor networks. The studied system can produce a maximum 0.52 V voltage and 2.24 mW power output. In order to reduce the effect of the contact thermal resistance, to promote the power output, to improve conversion efficiency, Lv et al. [23] developed a wearable thermoelectric generator and adopted the heat sink with porous sandwich substrate. Kim et al. [24] numerically evaluated the thermoelectric characteristics with neglecting Joule heating and emphasizing thermal contact resistance. Kumar et al. [25] proposed a new contact thermal resistance model to optimize the power output of a TEG device, the three-level Box-Behnken response surface method was investigated to examine the effects of contact thermal resistance. The crack between the thermoelectric module and heat source is the key influence parameters to increase thermal resistance.

The contact thermal resistance will weaken the actual temperature difference of the thermoelectric modules, and finally cause the drop of thermoelectric characteristics. The decreased contact thermal resistance can improve the thermoelectric characteristics of a TEG device, Kim et al. [26] proposed a direct contact TEG to reduce the contact thermal resistance. Astrain et al. [27] examining the contact thermal resistance of a TEG device, the results showed that for every 10% reduction in contact thermal resistance, the TEG thermoelectric characteristic will improve by 8%. Du et al. [28] discussed the effect of load pressure on a TEG device. It found that the contact thermal resistance decreases with increased load pressure, which induces an increase in the temperature difference of a TEG device. Sakamoto et al. [29] identified the thermal interface materials of a TEG device, the use of the most appropriate interface materials can reduce the contact thermal resistance and improve the thermoelectric characteristic of a TEG device. The use of thermally conductive silicone grease can eliminate the contact cracks between the heat source and thermoelectric module, which helps greatly in reducing contact thermal resistance [30,31]. Goodarzi et al. [32] analyze the effect of contact interface nanoaluminum coating on contact thermal resistance, and found a significant increase in heat transfer performance and a 38% reduction in contact thermal resistance.

1.4. Research gaps

Nowadays, thermoelectric generation technology has been widely used in all aspects of people’s life and production, there will be a broader space for development in the future [33]. How to promote the practicability of thermoelectric generation technology, discard the adverse effects of thermoelectric technology and improve thermoelectric characteristics? How to find the economical and efficient thermoelectric characteristics by analyzing the influence factors of contact thermal resistance. It is the technical guarantee for the promotion and application of thermoelectric generation technology. The effects of the thermal interface materials on the thermoelectric characteristics of a TEG device are a technical breakthrough point.

The literatures [34–38] in Table 1 are reviewed, the representative studies related to the thermal contact resistance and the innovations and research gaps are detailed discussed. Goodarzi et al. [34] found the material of aluminum nanocoating can significantly reduce the contact thermal resistance between heat source and thermoelectric module. Sakamoto et al. [35] revealed that the Whity Paint interface material can reduce the contact thermal resistance. Wang et al. [36] pointed out that the thermal contact resistance decreases with increased loading pressure. Cui et al. [37] showed that the thermal contact resistance can cause a decrease in power output. Beltrán-Pitarch et al. [38] proposed a new evaluation method of thermal contact resistance for thermoelectric generator by using three current-voltage curves. The different literatures have different research focuses, some literatures emphasized the analysis of the thermal interface material, some literatures discussed the thermal contact resistance within a moderate temperature range, some literatures showed a measurement method of thermal contact resistance, and the other literatures revealed the method to improve thermoelectric characteristics by decreasing thermal contact resistance. Due to many technical difficulties are involved and no unified method to evaluate the contact thermal resistance, no one can propose a convincing, applicable unified, and efficient testing methodology.

### Table 1

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Main contents</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goodarzi et al. [34]</td>
<td>The quantified analysis of thermal contact resistance was conducted.</td>
<td>The aluminum nanocoating can significantly reduce the thermal contact resistance.</td>
</tr>
<tr>
<td>Sakamoto et al. [35]</td>
<td>The thermal interface materials were discussed to improve the performance of a TEG.</td>
<td>Suitable thermal interface materials, such as Whity Paint, and so on, can be used to reduce the thermal contact resistance at temperature range [600K, 900K].</td>
</tr>
<tr>
<td>Wang et al. [36]</td>
<td>The effects of thermal contact resistance on thermoelectric characteristics were analyzed.</td>
<td>The thermal contact resistance decreases with increased loading pressure.</td>
</tr>
<tr>
<td>Cui et al. [37]</td>
<td>The thermoelectric characteristics of the porous TEGs were evaluated.</td>
<td>The thermal contact resistance, as an impact factor, causes a decrease in power output.</td>
</tr>
<tr>
<td>Beltrán-Pitarch et al. [38]</td>
<td>A new evaluation method of thermal contact resistance for thermoelectric generator was proposed.</td>
<td>The thermal contact resistance can be directly measured by three current-voltage curves with simple setups and no required heat flux.</td>
</tr>
</tbody>
</table>

(1) The multi-variable coupling approach is adopted to eliminate the individual performance deviations by analyzing the thermoelectric characteristics of three types of external influencing factors.

(2) The coupling relationship between the thermal interface materials and contact thermal resistance is an important discussion element based on thermoelectric characteristics.

(3) A dimensionless synthesis economic factor index is proposed to evaluate the comprehensive performances based on different thermal interface materials.

(4) Graphite paper with high thermal conductivity cannot exhibit the high thermoelectric properties of a TEG device due to the effect of the contact thermal resistance.

(5) The thermal interface material of MHPA possesses outstanding thermal conductivity and low contact thermal resistance.
technology, so the evaluation methods of existing research literatures cannot be widely promoted.

In this paper, the thermoelectric characteristics of a TEG device based on the external influencing factors with a multi-variable coupling approach were conducted. The coupling relationships within the external influencing factors, especially the thermal interface materials, including the MHPA, were discussed. The relationships between the thermal interface material, the contact thermal resistance, and the thermoelectric characteristics of a TEG device were clarified. Due to the importance of thermal interface materials, the common thermal interface materials and as a comparative MHPA with the features of inexpensive, easy to obtain, and no separate preparation required, were experimentally discussed. The load-bearing brick weight, as a cofactor, was used to instead of load pressure. The dimensionless synthesis economic factor index is proposed to fastly determine the advantages or disadvantages of the common thermal interface materials and the MHPA, as well as determine their contact thermal resistances. The innovations and research gaps are listed in Table 1, which reveal the optimizations in the analysis of the external influencing factors, and point out the important value of thermal interface materials in engineering applications.

![Fig. 1. Thermoelectric generator experiment bench.](image-url)
2. Working principle of experiment bench

2.1. Experiment bench

The experiment bench of the thermoelectric generator system is mainly composed of a TEG device, temperature control box, resistance box, flowmeter, low-temperature thermostat container, power detector, and load-bearing brick. The main components of the thermoelectric generator system are marked with a red box in the actual photo of experiment bench, as seen in Fig. 1(a). The core apparatus, a TEG device, contains heat oil box (a driving heat source), cooling heat sink, thermoelectric modules, heat collector plate, thermal interface material and load-bearing brick (which is used instead of load pressure), U-shaped heating tube, support plate, as seen in Fig. 1(b). The combined figures, the actual photos of Fig. 1(a) and (b) and sectional image of Fig. 1(c) display the detailed internal structures of a TEG device, which can facilitate the readers to understand and familiarize the location and function of each component.

The instruments and equipments used in the experimental testing process are shown in Fig. 2. The TEP1-126T200 is used for thermoelectric module, as seen in Fig. 2(a). The characteristic parameters of a thermoelectric module are as follows: the both sides of the thermoelectric modules covered with ceramic material, the geometric dimension is $40 \times 40 \times 3.3 \text{ mm}^3$, the pair of P–N junctions are 126, the optimal matching resistance is $3.3\Omega–4.3\Omega$, the operation temperature is within $[233K, 473K]$, the short-time temperature resistance is $513K$, the long-term work temperature resistance $473K$, the clearance error of surface is less than or equal to 20 $\mu m$. The temperatures of the cold and hot sides of the thermoelectric modules are measured using TT-K-36 SLE thermocouple, as seen in Fig. 2(b). The temperature measurement range is within $[233K, 533K]$, the temperature measurement error is within $[-0.15K, 0.15K]$, the temperature probe diameter is 0.127 mm. The photo of micro heat pipe arrays is seen in Fig. 2(c), the basic parameters are as follows: the material is aluminium with model 1050, the working medium is acetone, liquid filling rate is 30 %, the operating temperature $\leq 200 ^\circ C$, the number of microchannel is 35, the section size of microchannel is $2 \text{ mm} \times 2.15 \text{ mm}$, the internal pressure is 1kpa. The photo of adjustable resistance box is seen in Fig. 2(d), the power range is $[25W, 500W]$, the resistance range is $[1 \Omega, 5k\Omega]$, the operation temperature is within $[218K, 588K]$, the resistance tolerance is 10%.

2.2. Testing steps

A TEG device is composed of ten thermoelectric modules in series. With the change in temperature difference between the hot source and cooling source of thermoelectric modules (Abbreviated as temperature difference), the internal resistance of a TEG device has changed. If the internal resistance of a TEG device is the same as the load resistance, the load power of a TEG device will reach a peak point. Combined with the best matching resistance and actual testing value, the load resistance is set to 40 $\Omega$. The common thermal interface materials and the MHPA (including non-thermal interface material scheme) are prepared for comparative experiments. The specific types of the thermal interface materials are as follows: 0.1 mm thickness graphite paper (Abbreviated as GP-0.1), 0.3 mm thickness graphite paper (Abbreviated as GP-0.3), silver silicone grease with a thermal conductivity of 1.93 W m$^{-1}$K$^{-1}$ (Abbreviated as SSG), gold silicone grease with a thermal conductivity of 4.85 W m$^{-1}$K$^{-1}$ (Abbreviated as GSG), and in comparison with non-thermal interface material (Abbreviated as NTIM). The specific parameters of graphite paper are listed in Table 2.

The experimental schemes and detailed steps are as follows:

Fig. 2. Actual photos of instruments and equipments.
(1) The thermoelectric characteristics of individual thermoelectric modules must be calibrated, because the thermoelectric characteristics of individual thermoelectric module are difference. To obtain the reliable experimental data, the thermoelectric modules with the closest thermoelectric characteristics are selected.

(2) Each group of experimental testing uses an independent cooling circulation circuit. Make sure that the TEG device can obtain a excellent cooling effect, and eliminate temperature fluctuations.

(3) The power detector is used to record the thermoelectric characteristics of load voltage and load power at the condition of stable heat source temperature. The average counting function of the power detector is adopted to enhance the accuracy of data. The frequency of data collection is 5 s each time. The standard deviation method is used to ensure the reliability of collected data.

(4) Experimental programme (A): The common thermal interface materials and the MHPA are experimentally studied without load-bearing brick. The cooling circulation circuit of the low-temperature thermostat bath is enabled, and the cooling source temperature constantly maintains at 283.2 K. The heat source temperature (heat conduction oil) is adjusted within the range of 323.2 K – 423.2 K by the temperature control box. Finally, the load voltage and load power of a TEG device are recorded every 10 K.

(5) Experimental programme (B): To discuss the influence of load-bearing brick weight on load voltage and load power, the load-bearing bricks are evenly placed on the heat sink with 5 kg, 10 kg, 15 kg, and 20 kg, respectively. The NTIM scheme serves as a comparison scheme benchmark for other four thermal interface materials. The experimental processes and procedures of the common thermal interface materials and the MHPA are repeated to ensure reliability and stability of measurement.

### 2.3 Data acquisition

The heat source of a TEG device is controlled by a temperature control box, and which is consisted of eight 250 W/220 V U-shaped heating tubes. The U-shaped heating tubes in the heat oil box are arranged evenly, which are used to ensure the heat source temperature uniformity. The heat conduction oil is used as an energy-carrying working medium. The heat collector plate with perforated fin is designed to ensure uniform and stable temperature of heat conduction oil. The cooling source consists of a cooling heat sink, a DC power supply, a DC pump, as well as a low-temperature thermostat bath. The working medium within the cooling circulation system adopted glycol aqueous solution, and the working medium temperature is controlled at 283.2 K. The flow rate of cooling source fluid is kept at 240 L min⁻¹. To minimize measurement errors, ten thermoelectric modules formed a TEG device. To ensure the best cooling effect and eliminate the experimental uncertainty, the identical TEG device is used to discuss the thermoelectric characteristics. The different operating parameters are selected and the experimental steps are repeated continuously. The flow chart of the experiment.

**Table 2**

<table>
<thead>
<tr>
<th>JL-AQC-SC</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness/mm</td>
<td>0.03–3.0 mm (±0.03)</td>
</tr>
<tr>
<td>Density/g·cm⁻³</td>
<td>0.5–1.8 g/cm³ (±0.05)</td>
</tr>
<tr>
<td>Carbon content</td>
<td>95–99.9 %</td>
</tr>
<tr>
<td>Thermal conductivity/W·m⁻¹·K⁻¹</td>
<td>X.Y direction 400–600</td>
</tr>
<tr>
<td>Specific heat ratio (50 °C)/J·GK⁻¹</td>
<td>Z direction 18–20</td>
</tr>
<tr>
<td>Thermal diffusivity (25 °C)/cm·s⁻¹</td>
<td>X.Y direction 1.24</td>
</tr>
<tr>
<td>Bending test (times)/(R2/±135 °C)</td>
<td>Z direction 1.74</td>
</tr>
<tr>
<td>Electric conductivity/s·cm⁻¹</td>
<td>X.Y direction 350–400</td>
</tr>
<tr>
<td>Extensional strength/Mpa</td>
<td>Z direction 10–13</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>0.33–0.39</td>
</tr>
<tr>
<td>Resilient ratio</td>
<td>0.001–0.005</td>
</tr>
<tr>
<td>≥4.0</td>
<td>≥40 %</td>
</tr>
<tr>
<td>≥9 %</td>
<td></td>
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</tbody>
</table>

![Fig. 3. The 3D flow chart of experiment bench.](image-url)
bench for a TEG device is shown in Fig. 3.

The Keysight DAQ970A multi-channel data acquisition instrument and the TongHui high precision TH3421 multi-channel digital power meter are used to collect and process the experimental data. The functions contain real-time temperature recording, DC voltage acquisition, output power acquisition, and so on. The actual photos of the Keysight DAQ970A and TongHui TH3421 are shown in Fig. 2 (e) and (f), the detailed technical parameters of the Keysight DAQ970A and TongHui TH3421 are listed in Table 3.

2.4. Testing uncertainty

The measurement errors will reduce the reliability of testing data, so the testing uncertainty cannot be ignored. The main testing uncertainties contain measurement uncertainty and instrument acquisition uncertainty. The experimental environment uncertainty can be negligible. The temperature and humidity are strictly controlled at 298K ± 0.1K and 50 %–65 % RH, respectively. The total synthetic uncertainty $U_c$ can be expressed as Equation (1).

$$U_c = \sqrt{\left(t_p \cdot \sigma\right)^2 + \left(k_p \cdot \frac{\Delta_i}{C}\right)^2 + U_e^2}$$

(1)

Where, $t_p$ is the correction factor with the value of 1.03; $\sigma$ is the standard deviation of the arithmetic mean; $k_p$ is the credibility factor, and its value is usually 1; $C$ is the credibility coefficient with the value of 1.732051; $\Delta_i$ is the maximum allowable error of instrument acquisition; $U_e$ is the estimation error, and it can be ignored.

The final uncertainties of the measurement results of a TEG device are as follows: (1) The voltage uncertainty is within [0.52 %, 1.05 %]. (2) The temperature uncertainty is within [0.52 %, 1.05 %]. (3) The output power uncertainty is within [1.41 %, 4.13 %].

3. External influencing factors discussion

The external influencing factors of a thermoelectric generator include load-bearing brick weight, thermal interface material, and temperature difference. The multi-variable coupling approach is used to estimate the individual external influencing factor as well as internal coupling correlations with the help of the thermoelectric characteristics of load voltage and load power. The internal coupling correlations between load-bearing brick weight, thermal interface material, and temperature difference can reveal the interaction of individual external influencing factor. Especially, it can quickly determine the common thermal interface materials and the MHPA based on dimensionless synthesis economic factor index. The three different graphical representations, as seen in Fig. 4, Figs. 5 and 6, are designed to display three types of coupling relationships by analyzing the thermoelectric characteristics of the common thermal interface materials and the MHPA.

Fig. 4 exhibits the general trends of load power versus temperature difference with different load-bearing brick weights. It is clearly seen that the load power of the common thermal interface materials and the MHPA increases with an increase in load-bearing brick weight and temperature difference. The load powers using thermal conductive silicone grease materials (SSG and GSG) schemes are much higher than those of other three common thermal interface materials schemes under all load-bearing brick weights. It can be used to explain the thermal conductive silicone grease can reduce contact thermal resistance because of its outstanding thermal conductivity and almost no crack. However, the SSG and GSG schemes perform different rules, the load power of the GSG scheme is significantly higher than that of the SSG scheme at the condition of the load-bearing brick weight with a value of 0 kg. With the further increase of load-bearing brick weight, the deviations of load power between SSG and GSG schemes gradually decrease.

The load power of the MHPA is close to that of the two SSG and GSG schemes at the conditions of load-bearing brick weight with 0 kg and 5 kg. At this moment, its load power is far higher than that of other three common thermal interface materials schemes. When the toad-bearing brick weight is greater than 10 kg, the MHPA scheme reveals dominant advantage, its load power is much higher than that of the common thermal interface materials.

In Fig. 4(a), the load power of the NTIM scheme ranks fourth, and the load powers of GP-0.1 and GP-0.3 schemes rank in the last two positions. The load powers of graphite papers schemes are even lower than that of the NTIM scheme. Because the surfaces of graphite papers are not completely flat, the contact cracks between thermoelectric modules and heat sources are formed, and the air with low thermal conductivity is filled into the crack. In Fig. 4(d), the curve trends of the common thermal interface materials and the MHPA are quite distinct from each other, their distribution trends are $P_{\text{exp}}$ of MHPA > $P_{\text{exp}}$ of GSG > $P_{\text{exp}}$ of SSG > $P_{\text{exp}}$ of GP-0.1 > $P_{\text{exp}}$ of GP-0.3 > $P_{\text{exp}}$ of NTIM. With the increased load-bearing brick weight, the increment of load powers of MHPA scheme is the most obvious and its load power ranks first. In Fig. 4(e), the load power of the NTIM scheme ranks last, and the load powers of the GP-

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Technical parameters of TongHui TH342 and Keysight DAQ970A.</th>
</tr>
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<tbody>
<tr>
<td>Items</td>
<td>Keysight DAQ970A AccuracyRanges</td>
</tr>
<tr>
<td>DC Voltage</td>
<td>$\pm(0.025 + 0.006)%$</td>
</tr>
<tr>
<td></td>
<td>0.100–300/V</td>
</tr>
<tr>
<td>DC Current</td>
<td>$\pm(0.050 + 0.020)%$</td>
</tr>
<tr>
<td></td>
<td>0.001–1/A</td>
</tr>
<tr>
<td>Power</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$5 \times 10^{-5}–12 \times 10^3/W$</td>
</tr>
<tr>
<td>Temperature</td>
<td>$\pm(0.167–0.333)%$</td>
</tr>
<tr>
<td></td>
<td>$–100–1200/°C$</td>
</tr>
</tbody>
</table>
0.1 and GP-0.3 schemes rank fourth and fifth, respectively. Although the load powers of graphite papers schemes are more sensitive to load-bearing brick weight compared with the NTIM scheme, the advantage is very inconspicuous.

As shown in Fig. 5, the histograms of the load voltage versus load-bearing brick weights for the common thermal interface materials and the MHPA are exhibited. The complex coupling characteristics of temperature difference are also deeply discussed with the help of Fig. 4.

Fig. 4. Load power versus load-bearing brick weight.
the influencing parameters, 50 K, 80 K, 110 K, and 140 K. The load voltages of the MHPA scheme performs the best almost at the all conditions, as well as the increments are very obvious with the increased temperature difference and load-bearing brick weight. The load voltages of GP-0.1 and GP-0.3 schemes increase with the increase in load-bearing brick weight, but their increments gradually decrease. The load voltage of the SSG scheme is generally less than that of the GSG scheme, because the performance characteristics of the two schemes are similar, only the thermal conductivities are different. At the conditions of temperature difference 110 K and 140 K, the increments of the load voltage are remarkable, so the GP-0.1 scheme has certain superiority.  

For the NTIM scheme, the load voltages increase with the increase in load-bearing brick weight, but the increment is very limited. However, the GP-0.3 scheme performs poor thermoelectric characteristics of load voltage at the condition of low-temperature difference and low load-bearing brick weight, and the value is even smaller than that of the NTIM scheme. It can be used to explain core influencing factors of contact thermal resistance are object surface roughness, partial contact, and contact cracks, although graphite papers have a much higher thermal conductivity.  

How to intuitively distinguish the thermoelectric characteristics of the common thermal interface materials and the MHPA? How to quickly judge the thermoelectric characteristics improvement? The comprehensive performance evaluation indicators of the economic factor index (Abbreviated as dimensionless synthesis economic factor index) is proposed. The dimensionless synthesis economic factor index is designed with the help of the load power of NTIM scheme, and it is based on the load power improvement of NTIM scheme. In Fig. 6(a), the dimensionless synthesis economic factor index \((P_{\text{exp, GP-0.1}-P_{\text{exp, NTIM}}}/P_{\text{exp, NTIM}})\) exceeds zero when the load-bearing brick weight is higher than 15 kg. At this critical point, the contact thermal resistance stably reduces because of better surface contact characteristics, smaller contact cracks, and little air impact. In Fig. 6(b), for GP-0.3 scheme, the dimensionless synthesis economic factor index \((P_{\text{exp, GP-0.3}-P_{\text{exp, NTIM}}}/P_{\text{exp, NTIM}})\) is lower than zero including almost all the operating conditions of external influencing factors. If the load-bearing brick weight is greater than 20 kg, the \((P_{\text{exp, GP-0.3}-P_{\text{exp, NTIM}}}/P_{\text{exp, NTIM}})\) starts higher than zero.

![Variation of load voltage with temperature difference.](image-url)
and the improvement of thermoelectric characteristics is not significant. Which can explain the load-bearing brick weight makes little effect on thermoelectric characteristics, and performs almost the worst thermoelectric characteristics. It can be inferred that the surface roughness and contact cracks between thermoelectric modules and heat source are less affected by load-bearing brick weight. As seen in Fig. 6(c) and (d), the thermal conductive silicone grease plays a great role in effectively reducing the contact thermal resistance, because of excellent thermal conductivity, a smooth contact surface and few cracks. Their dimensionless synthesis economic factor indexes are higher than other three common thermal interface materials. The index values of \((P_{\text{exp, SSG}}-P_{\text{exp, NTIM}})/P_{\text{exp, NTIM}}\) are between 93.12 % and 274.55 %, the results of the \((P_{\text{exp, GSG}}-P_{\text{exp, NTIM}})/P_{\text{exp, NTIM}}\) increases from 190.05 % to 307.88 %. For

![Thermal Interface Materials](image-url)
MHPA scheme, in Fig. 6(e), high peak value characteristic of index for \( (P_{\text{exp, GSG}} - P_{\text{exp, MHPA}})/P_{\text{exp, MHPA}} \) is very obvious, the values indexes and their average values are significantly higher than those of SSG and GSG schemes. The maximum value of \( (P_{\text{exp, GSG}} - P_{\text{exp, MHPA}})/P_{\text{exp, MHPA}} \) can even reach 371.81 %. It is shown that the MHPA shows strong thermal conductivity and can be applied to thermoelectric generation systems.

4. Conclusions

Comprehensive investigations on thermoelectric characteristics of a TEG device based on the external influencing factors were conducted. The multi-variable coupling approach is proposed to relate the coupling relationship between thermal interface material, load-bearing brick weight, and temperature difference. The main findings are as follows:

(1) The analytical approach is used to eliminate the errors caused by the individual influencing factor, calibrate the intrinsic correlation of the common thermal interface materials and the MHPA, and strengthen the reliability of experimental data.

(2) The thermoelectric characteristics of load power and load voltage increase with the increase in load-bearing brick weight and temperature difference for all the common thermal interface materials and the MHPA.

(3) For load power and load voltage, the GSG and SSG schemes are superior to those of the other three schemes. The NTIM scheme is not the worst performing one at the conditions of low load-bearing brick weight with all temperature differences. The GP-0.3 scheme ranks last in the conditions of low-temperature difference.

(4) The thermoelectric characteristics of the NTIM scheme are almost unaffected by load-bearing brick weight and increase slowly with increasing temperature difference, but the characteristic curves are linearly distributed.

(5) Due to the load-bearing brick weight being too small, the GP-0.1 and GP-0.3 schemes will not play a strong role in reducing thermal resistance. The clearance and no flat surface of graphite papers will cause an increase in contact thermal resistance, although the thermal conductivity of graphite papers is much higher than that of the NTIM scheme.

(6) The MHPA, as a special new type of the thermal interface material, showcases an excellent thermal conductivity and their thermoelectric characteristics are far surpassing those of other common thermal interface materials.

(7) The dimensionless synthesis economic factor index of \( (P_{\text{exp, SSG}} - P_{\text{exp, NTIM}})/P_{\text{exp}}, (P_{\text{exp, GSG}} - P_{\text{exp, NTIM}})/P_{\text{exp, NTIM}} \) and \( (P_{\text{exp, MHPA}} - P_{\text{exp, NTIM}})/P_{\text{exp, NTIM}} \) can be up to 274.55 %, 307.88 % and 371.81 %, respectively. So the MHPA scheme exhibits the best thermoelectric characteristics with the least contact thermal resistance.

Contributor roles taxonomy (CRediT)

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Nomenclature

\( C \)  
Credibility coefficient

\( k_p \)  
Credibility factor

\( M_{\text{exp}} \)  
Experimental weight of load-bearing brick, kg

\( P_{\text{exp}} \)  
Experimental load power of a TEG device, W

\( P_{\text{exp}, \text{GP}-0.1} \)  
Experimental load power of graphite paper with 0.1 mm thickness, W

\( P_{\text{exp}, \text{GP}-0.3} \)  
Experimental load power of graphite paper with 0.3 mm thickness, W

\( P_{\text{exp}, \text{GS}} \)  
Experimental load power of gold silicone grease, W

\( P_{\text{exp}, \text{NTIM}} \)  
Experimental load power of non-thermal interface material, W

\( P_{\text{exp}, \text{SS}} \)  
Experimental load power of silver silicone grease, W

\( t_p \)  
Correction factor

\( U_e \)  
Estimation error

\( U_{\text{exp}} \)  
Experimental load voltage, V

\( U_x \)  
Total synthetic uncertainty

Greek symbols

\( \sigma \)  
Standard deviation of the arithmetic mean

\( \Delta_i \)  
Maximum allowable error of instrument acquisition

\( \Delta T_{\text{exp}} \)  
Experimental temperature, K

Abbreviations

3D  
Three dimension

DC  
Direct current

GP  
Graphite paper

GP-0.1  
Graphite paper with 0.1 mm thickness

GP-0.3  
Graphite paper with 0.3 mm thickness

GSG  
Gold silicone grease

MHPA  
Micro heat pipe array

NTIM  
Non-thermal interface material

SSG  
Silver silicone grease

TEG  
Thermoelectric generator

Subscript

exp  
Experiment

References


