Research on heat dissipation optimization of power module and application of thermoelectric cooler

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Abstract

The power module in electric vehicles is a core component of the vehicle's power system, primarily responsible for the conversion and distribution of electrical energy. It plays a critically important role in controlling the motor to achieve vehicle propulsion, significantly impacting the overall performance of electric vehicles. As power module technology continues to evolve and upgrade, trends such as high-frequency operation, miniaturization, high power consumption, and high integration have emerged as the main directions of development. With the increasing integration of automotive power modules and the rising heat generated by power chips, the thermal management of power modules faces increasingly severe challenges. Thermoelectric coolers, with their advantages of compact size, simple structure, high reliability, and rapid cooling capabilities, have attracted widespread attention. Through this experimental research, the feasibility and effectiveness of thermoelectric cooling technology in controlling the temperature and heat dissipation of power modules have been successfully validated.

Keywords: Power module, Thermoelectric Cooler, Thermal management.

1 Background

As a very important high-power device in the field of electric vehicles[1], power modules are widely used in various power electronics fields, such as electric locomotives, industrial control, renewable energy systems, household appliances, battery charging, motor drive and other fields[2], In recent years, with the rapid advancement of the electronics industry and semiconductor technology, the high-frequency, miniaturization, high power consumption, and high integration characteristics of power modules have become the main trends in their development. During actual operation, a portion of the electrical energy in power devices is converted into heat. The prolonged exposure of chips to high temperatures can affect the processing of electrical signals and the reliability of the devices. The accumulation of excessive heat not only significantly reduces the performance of electronic components but also severely impacts their lifespan. In severe cases, it can even lead to explosions, posing a threat to personal and property safety. Therefore, there is an increasingly urgent need for efficient thermal management of power devices. The methods for temperature control are mostly water cooling and air cooling. With the continuous development of semiconductor technology, semiconductor cooling technology, as an emerging temperature regulation method[3], is gradually gaining more attention and favor[4-5].

2 Working Principle of Thermoelectric Coolers

The working principle of TEC(Thermoelectric Cooler): According to the Peltier effect, when current is applied to a circuit composed of different conductors, in addition to generating irreversible Joule heat, heat absorption or release occurs at the contact points of the conductors depending on the direction of the current. Modern TEC utilize this effect, using appropriately doped thermoelectric semiconductor materials to form "N-type" and "P-type" materials with different electronic properties. N-type materials gain extra electrons through doping, while P-type materials form holes due to a lack of electrons. These extra electrons and holes act as carriers for heat transfer. Most thermoelectric cooling devices consist of an equal number of N-type and P-type elements, with one pair of N-type and P-type elements forming a basic thermoelectric unit. As shown in Figure 1, when current is applied, the TEC can move heat according to the direction of the current. This design can absorb or release heat depending on where the current flows[6].

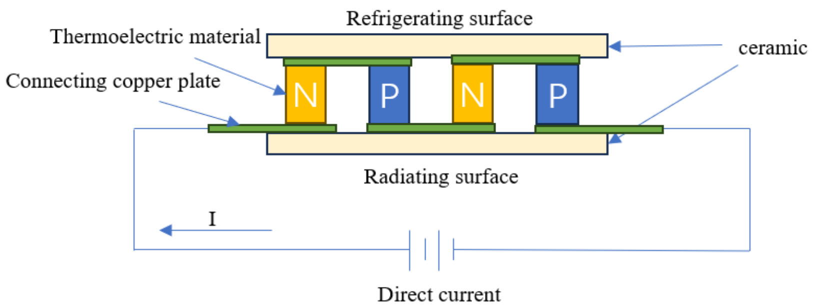


Figure1: Schematic of TEC

The heat absorption and release at the hot and cold ends of the TEC are determined by equations (1) and (2), where Q_c and Q_h represent the heat absorption at the cold end and the heat release at the hot end of the TEC, respectively. S_{np} is the Seebeck coefficient of the thermoelectric material, T_h and T_c are the temperatures at the hot and cold ends of the TEC, I is the applied current, R is the TEC resistance, and K is the total thermal conductivity of the TEC.

$$Q_c = S_{np} T_c I - \frac{1}{2} I^2 R - K\left(T_h - T_c\right) \tag{1}$$

$$Q_h = S_{np} T_c I + \frac{1}{2} I^2 R - K\left(T_h - T_c\right) \tag{2}$$

The coefficient of performance (COP) of the TEC:

$$COP = \frac{Q_c}{P} \tag{3}$$

P is the electrical power consumed during the cooling process of the TEC, calculated as shown in equation (4).

$$P = S_{np} I \left(T_h - T_c\right) + I^2 R \tag{4}$$

3 Layout Optimization and Thermal Simulation

3.1 Power Module Chip Layout Optimization

Automatic layout optimization is based on natural random selection and genetic mechanisms in nature, involving encoding transformation, initial population generation, fitness evaluation, and DNA operations (selection, crossover, mutation) to obtain the optimal solution[7]. The figure 2 shows an algorithm flow for chip layout optimization. The total length of the minimum spanning tree is used as the fitness, and the quality of the chip layout is evaluated by calculating the total length of the minimum spanning tree. The longer the total length, the higher the fitness, indicating greater distances between chips. The elite selection strategy is adopted to retain the maximum fitness, ensuring that the characteristics of these excellent individuals are not lost. Single-point crossover and random mutation are performed on non-optimal individuals.

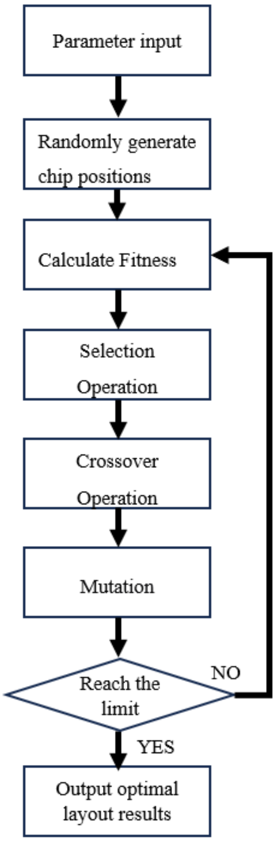


Figure2: Flowchart of Automatic Chip Layout Optimization

Table 1 shows the parameter settings for the chip layout optimization algorithm. The number of chips is 8, the chip size is 5.2 mm * 5.7 mm, and the layout is on a 40 mm * 40 mm DBC upper copper sheet. The population size is set to 200, the number of generations is 2000, and the mutation rate is 0.2. After setting these parameters, the algorithm was run multiple times to ensure the stability and reliability of the results.

Table 1: Parameters of Chip Layout Optimization Algorithm

Item	Value(mm)
Number of chips	8
Chip length	5.2
Chip width	5.7
Copper sheet size	40*40
Mutation rate	0.2

3.2 Analysis of Automatic Chip Layout Optimization Results

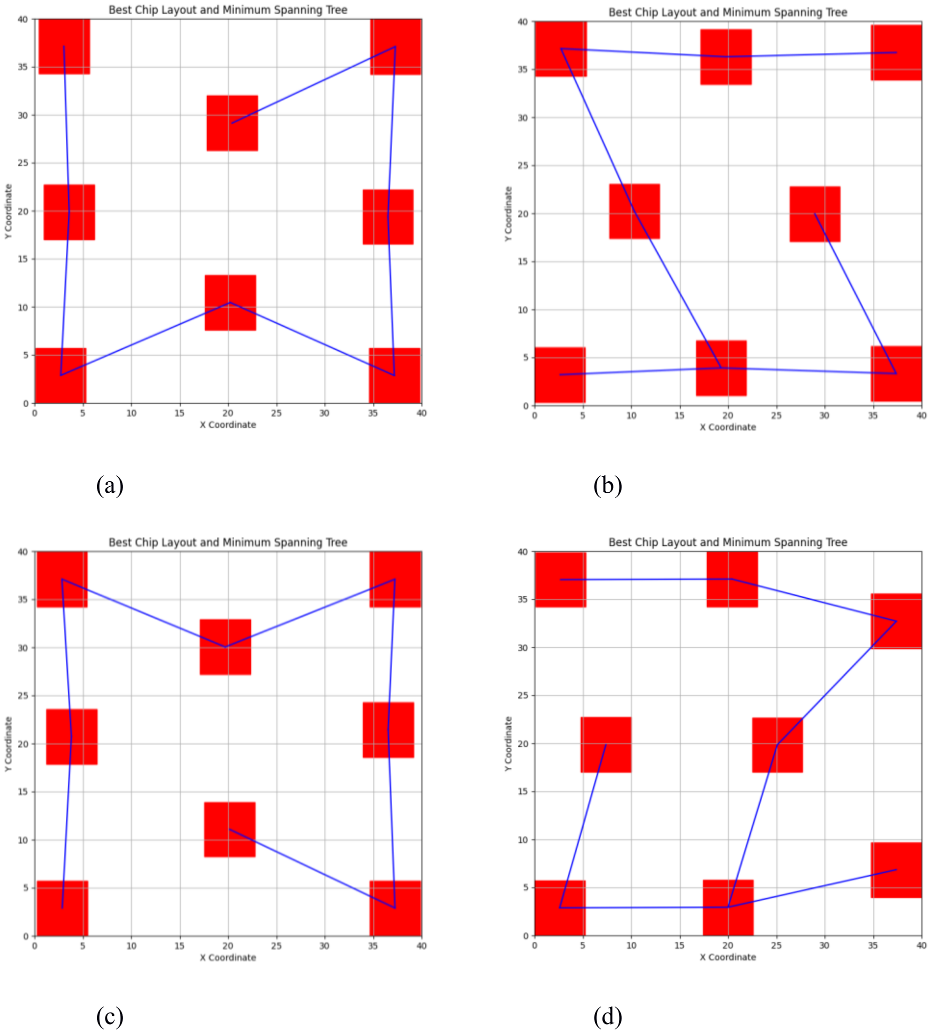


Figure3: Diagram of Automatic Chip Layout Optimization and Minimum Spanning Tree

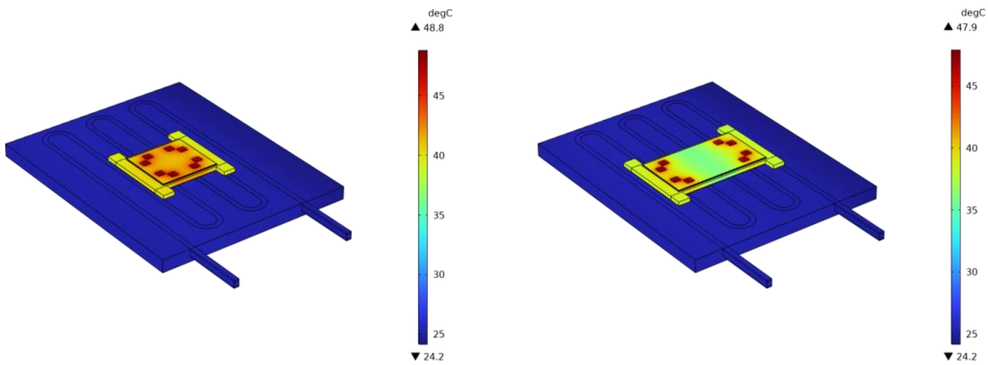
Figure 3 shows the diagram of automatic chip layout optimization and the minimum spanning tree, with their respective fitness values shown in Table 2.

Table 2: Fitness of Different Chip Layout Schemes

Chip Layout Design	Fitness
a	124.908
b	125.271
c	124.636
d	123.570

In this section, we use a genetic algorithm to optimize the chip layout of electric vehicle power modules, aiming to achieve better heat dissipation and higher energy efficiency. The results show that automatic chip layout optimization can effectively search the solution space and find high-fitness chip layout schemes. In multiple runs, the algorithm consistently converged to the optimal or near-optimal solution, proving its effectiveness in solving chip layout problems and providing an effective optimization method for power module chip layouts. Future work can study parameter adjustments of the algorithm, its combination with other optimization algorithms, and its application in different types of power modules to achieve broader engineering applications and further performance improvements.

3.3 Thermal Simulation Analysis



(a) Short module (b) Long module

Figure4: Thermal Distribution Simulation Diagram of Power Module without TEC

To verify the thermal management performance of the experimental test module, we conducted a thermal simulation analysis using CFD Multiphysics software. During the simulation, we ensured that the parameters of each object in the simulation model were consistent with those of the actual module to improve the accuracy and reliability of the simulation results. Through CFD thermal simulation analysis, we obtained the temperature distribution diagrams of two experimental test modules, as shown in Figure 4. The chip heat generation power corresponds to the actual chip input current of 100 A(118W), and the water flow temperature is 25 ℃. The simulation results are consistent with the actual results, verifying the effectiveness of the simulation model. The causes of errors include but are not limited to fluctuations in water temperature and changes in water flow velocity.

4 Application of Thermoelectric Coolers in Power Modules

In the application of electric vehicle power modules, the efficiency and reliability of the cooling system are key factors in ensuring the stable operation of the module. As the core component of the electric vehicle power system, the development trends of high frequency, miniaturization, and high integration of power modules place higher demands on cooling technology. TEC, with their unique performance, have become an ideal choice for power module cooling. TEC coolers adopt a sheet-like structure that can closely fit the surface of the power module, occupying minimal space and perfectly adapting to the miniaturization needs of power modules. At the same time, TEC have no rotating or sliding parts, operate without vibration or noise, and avoid mechanical wear, significantly improving the reliability and lifespan of the cooling system.

4.1 TEC Integrated Cooling Power Module

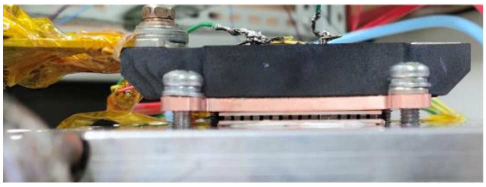


Figure5: Integrated Power Module

Theoretically, it is entirely feasible to use the cooling effect of semiconductor coolers to enhance the heat dissipation performance of power modules. Applying this theory to practice, the main structure of the processed TEC integrated cooling power module includes SiC chips, chip solder layers, DBC substrates, copper layers, solder layers, TEC, substrate solder layers, Pin-fin heat sinks, and water channels. The physical diagram of the TEC integrated power module is shown in Figure 5, and the cross-sectional diagram is shown in Figure 6.

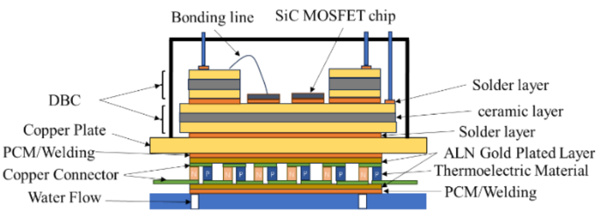


Figure6: Cross-Sectional Diagram of Integrated Power Module

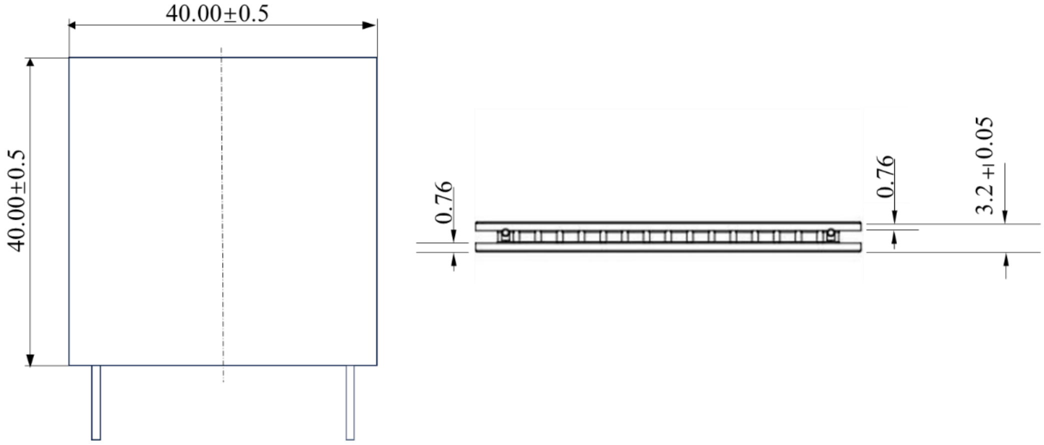


Figure7: TEC Dimensions

As shown in Figure 7, the TEC used in this experiment has a length and width of 40.00± 0.5 mm, an aluminum nitride height of 0.76 mm, and a TEC height of 3.2± 0.05 mm. The parameters of the TEC used in the experiment are shown in the table 3.

Table 3: TEC Parameters

Item	Value	Conditions
$I_{\max}$	12 A	$Q_c = 0, \Delta T = \Delta T_{\max}, T_h = 27℃$
$V_{\max}$	15.5 V	$Q_c = 0, I = I_{\max}, T_h = 27℃$
D_{Tmax}	69 ℃	$Q_c = 0, I = I_{\max}, T_h = 27℃$
Q_{cmax}	115 W	$I = I_{\max}, \Delta T = 0, T_h = 27℃$
T_{hmax}	200 ℃	Maximum Processing Temperature

4.2 Experimental TEC Model

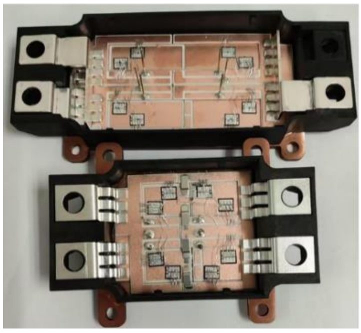


Figure8: Two Types of Power Modules Used in the Experiment

The power modules mainly used in this experiment are shown in Figure 8, and a power module cooling and temperature control test platform was built as shown in Figure 9.

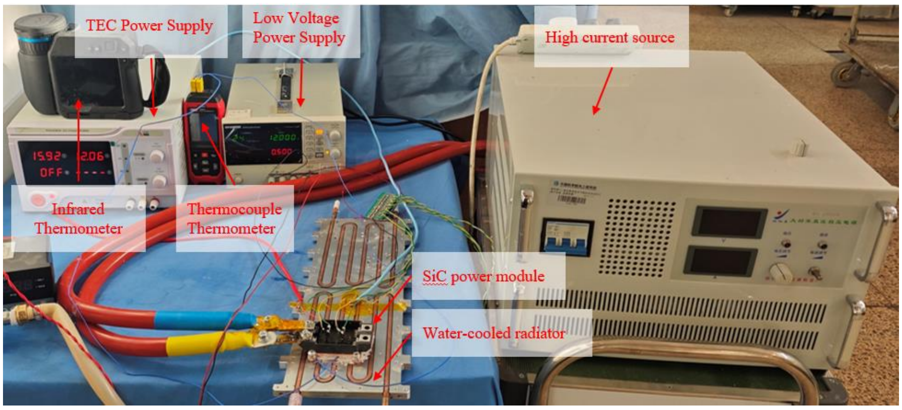


Figure9: Power Module Cooling and Temperature Control Test Platform

The experiment mainly compared the power module under two conditions: with TEC and without TEC, to discuss whether the use of TEC is more conducive to module cooling. In the case of TEC, two methods of connecting the cold end of TEC are further compared: welding and using phase change materials, and whether welding TEC is more effective for module cooling is discussed. The main objective of the experiment was to enhance the cooling effect of the power module. The phase-change material used in this experiment was the Honeywell PTM950 phase-change material.

5 Experimental Data and Result Analysis

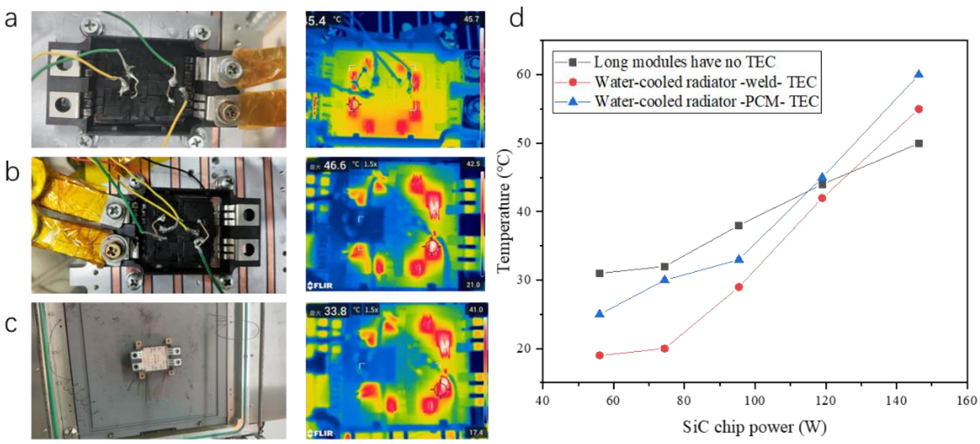


Figure10: Analysis of Thermal Imaging and Temperature Characteristics of SiC Short Power Modules

Figure10 illustrates three different processing methods: (a) without TEC, (b) with phase change sheet and TEC, and (c) with welding and TEC. The results from the infrared thermal imaging camera show the temperature variation of the chip under a power input of 119W. Figure d presents the test data comparison under three different heat dissipation structures. The hot end of TEC is uniformly cooled using phase change material attached to a water-cooled plate for heat dissipation. Based on this, the study leads to the following conclusions:

- Effectiveness of TEC: The experimental results indicate that TEC plays a significant role in temperature management. Short modules with TEC (whether with phase change sheet or welded) outperform those without TEC in temperature control within a certain current range. This demonstrates that TEC can effectively enhance the heat dissipation of short modules.
- Impact of Installation Method: Among the two installation methods of TEC, the short module with welded TEC exhibits the best temperature control performance. The welding method may provide better thermal conductivity, resulting in faster temperature changes. Although the TEC with phase change sheet is also effective, its performance is slightly inferior to the welded TEC, possibly due to the slightly lower thermal conductivity of the phase change sheet.
- Current Limitation Zone Impact: Within the range where the current is below the cooling power, TEC can exert its cooling effect and reduce the operating temperature of the module. However, when the current exceeds a certain range, the cooling effect of TEC is not only insufficient to effectively control the module temperature but may also increase the module temperature. The intersection point when using the phase change sheet is between 90A-100A, but after welding, the intersection point moves to between 100A-110A, enhancing the heat dissipation effect.

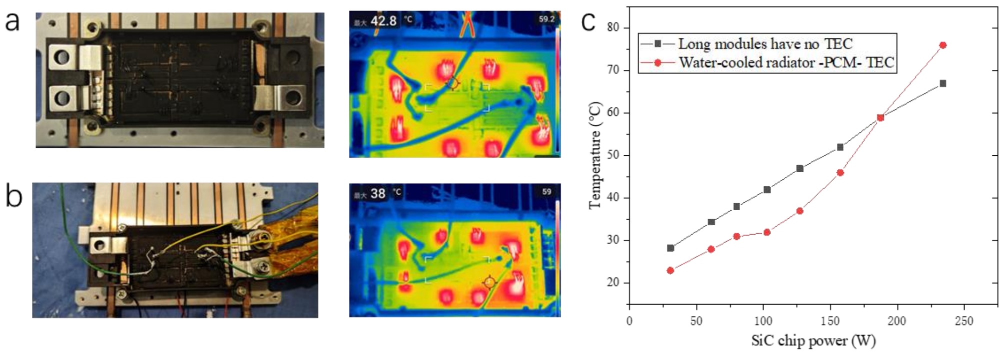


Figure11: Analysis of Thermal Imaging and Temperature Characteristics of SiC Long Power Modules

Figure 11 displays the comparison of temperature changes and results under two different conditions for long modules: In the figure, a represents the situation without TEC, while b represents the scenario with phase change material attached to TEC. The results from the thermal imager show the temperature distribution when 187.2W was applied to the chip. Additionally, c presents the comparison of test data under two different heat dissipation structures. This study, by comparing the temperature variations of long modules under both with and without TEC conditions, led to the following conclusions:

- Effectiveness of TEC: The use of TEC, especially TEC with a phase change sheet, can significantly improve the heat dissipation efficiency of long modules. Under high current load, the heat dissipation effect of TEC is more pronounced, effectively reducing the operating temperature of the module, thereby potentially extending the module's service life.
- Current Limitation Zone Impact: Within the range where the current is below the cooling power, TEC can exert its cooling effect and reduce the operating temperature of the module. However, when the current exceeds 120A (module heating power is 187.2W), the cooling effect of TEC is not only insufficient to effectively control the module temperature but may also increase the module temperature.

6 Conclusion

This study provides a new engineering application scheme for the module temperature control, and provides a reference for the optimization design and application of TEC. By selecting the right TEC installation, the heat dissipation effect of the module can be significantly improved to meet the needs of specific applications, confirming the effectiveness of TEC in the heat dissipation of electric vehicle power modules, in addition, automatic layout optimization can further enhance the heat dissipation effect of the module, and future work will focus on optimizing the TEC materials and design. And explore the combination of TEC with other heat dissipation technologies to further improve the thermal management efficiency of electric vehicle modules.

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