Experimental Study on the Effect of Phase Change Material Melting Point on TG/PCM Thermal Control Properties

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Abstract. Three composite phase change materials (PCM) with peak melting points of 42°C, 50°C and 58°C were prepared using different mass fractions of stearic acid (SA) and lauric acid (LA). A thermal control model structure of thermoelectric generation/PCM (TG/PCM) was designed using PCM, and analyzed for its internal thermal conversion, transmission and storage mechanisms. In addition, TG/PCM experimental prototypes with PCM melting points at 42°C, 50°C and 58°C were designed and tested for their temperature control properties and output power. The results showed that under PCM melting points of 42°C, 50°C and 58°C, temperature difference between the cold and hot end of the TG/PCM prototype thermoelectric battery was maintained above 8°C for 70 minutes, 45 minutes and 27 minutes, respectively. The total energy of system output power above 6mW was 73.9J, 52.4J and 18.9J.

1. Introduction
Since the discovery of Seebeck effect by Seebeck in the early nineteenth century, thermoelectric conversion materials gain continuous development and thermoelectric generation technology has been widely applied abroad (in US, former Soviet Union) by the 1960s. The research results are widely used in the fields of satellite power supply, lighthouses and navigation signs, but thermoelectric generation has low efficiency, generally 5%~7% [1-3]. At present, as the energy crisis continues to intensify, thermoelectric generation has been widely studied as a new technology for renewable energy applications, and its application have been continuously expanded in fields like solar energy, marine energy and industrial & domestic waste heat utilization [4-7]. The research mainly focuses on improving conversion efficiency of thermoelectric batteries and expanding applications. Where, the research on improving the conversion efficiency of thermoelectric batteries mainly focuses on new thermoelectric materials and thermoelectric figure of merit (ZT) value improvement. For example: Ping et al. utilized ion beam sputtering Bi/Te and Sb/Te binary composite targets to directly prepare n-type Bi₂Te₃ thermoelectric thin films and p-type Sb₂Te₃ thermoelectric film, achieving an output voltage of 15.26mV in the prepared thin-film thermoelectric unit cell [8]. Jianyun et al. prepared nanostructured materials of Bi₂Te₃-Sb₂Te₃ and GeTe₄Sb₂Te₂ with ZT values exceeding 1.5 by doping nano-powder [9]. With carbon nanotube (CNT) as the electrode material and glycerol sodium chloride solution or glycerol water sodium chloride solution as the electrolyte solution, Haoyu et al. prepared thermoelectric battery [10]. In terms of application extension, studies are focused on key application technologies such as thermoelectric battery maximum power point tracking (MPPT) and cold end thermal control. For example: Fuyu et al. studied the proposed MPPT algorithm through experiments and simulation analysis. The experimental data had an error of less than 7%, with a
tracking time of less than 2ms [11]. Yongsheng et al. designed a thermoelectric generation system based on the temperature difference between soil and air to power a forest wireless sensor [12]. In addition, the use of phase change materials in controlling cold end temperature of thermoelectric batteries has also been theoretically and experimentally studied. The results show that phase change materials play an obvious role in thermal control of thermoelectric generation systems and demonstrate great application potential [13, 14]. However, application of phase change materials in thermal control of thermoelectric generation systems is still in its infancy. The mechanism behind and experiment on the effects of PCM thermophysical properties and structures on thermal control properties demand further study. Based on the basic structure of PCM thermoelectric generation (TG/PCM) system, this paper carries out experimental research on the effect of PCM material melting point on TG thermal control properties and output power to provide an experimental basis for optimization design of TG/PCM system.

2. Basic principle of thermoelectric generation
Thermoelectric generation is to directly convert thermal energy into electrical energy based on Seebeck effect, which has the characteristics of small size, no noise and high reliability. Structural representation of thermoelectric generation is shown in Figures 1 and 2.

![Diagram of thermoelectric effect](image1)

**Figure 1.** Diagram of thermoelectric effect

In Figures 1 and 2, when two metal conductors (or semiconductors) A and B with different free electron densities (or carrier densities) in a temperature difference environment are in contact with each other, if the two terminals 1 and 2 are maintained at different temperature $T_1$ and $T_2$, a temperature difference $\Delta T$ will be generated. Then, a potential difference will appear between the open-circuit positions x and y of the conductor A. The value is:

$$V_{xy} = \alpha_{ab} (T_1 - T_2)$$  \hspace{1cm} (1)

Where, $\alpha_{ab}$ is the Seebeck coefficient, whose unit is V/K. The value and sign of Seebeck coefficient depends on thermoelectricity of conductors a and b, which has nothing to do with the magnitude and direction of the temperature difference gradient.

The voltage $V_0$ actually output by the thermoelectric battery to the load $R_L$ is also related to internal resistance $R_0$ of the thermoelectric battery, which can be expressed as:

$$V_0 = \alpha_{NP} (T_1 - T_2) \frac{R_L}{R_L + R}$$  \hspace{1cm} (2)

The output current can be expressed as:

$$I_0 = \frac{\alpha_{NP} (T_1 - T_2)}{R_L + R}$$  \hspace{1cm} (3)

The output power of the thermoelectric generation system can be expressed as:

$$P_0 = \frac{\alpha_{NP}^2 (T_1 - T_2)^2 R_L}{(R_L + R)^2}$$  \hspace{1cm} (4)

It can be seen from the formulas (1)-(4) that the key to improving the output power of
thermoelectric generation is to maintain a sufficiently big temperature difference between the hot and cold ends.

3. TG/PCM structure design and thermal control principle
Thermoelectric battery is usually composed of multiple thermoelectric generation units in series or in parallel. For example, the thermoelectric battery consisting of 127 pairs of thermoelectric generation units has a size of length 30mm×width 30mm. Each power generation unit has a size of 2mm×2mm and a height of 5mm, as shown in Figure 3.

![Figure 3. Outline structure of thermoelectric battery](image)

Based on characteristics of the phase change material, that is, the temperature remains unchanged during heat absorption in phase change process, thermally controlled thermoelectric generation system (TG/PCM) is designed for the phase change material. The structure diagram is shown in Figure 4. In Figure 4, TG/PCM is mainly composed of a thermoelectric battery and a phase change material thermal control unit. Where, the thermoelectric battery is composed of cold and hot-end ceramic chips, N-type, P-type semiconductor materials, and conductive copper sheets; the thermal control unit is mainly composed of phase change materials, packaged aluminum boxes. In addition, a thermally conductive silica gel is coated between the thermoelectric battery and the phase change material thermal control unit to reduce the contact thermal resistance between the cold end of thermoelectric battery and the thermal control unit.

4. Prototype design and test analysis

4.1. Design of TG/PCM experimental prototype
In the prototype design, the phase change material was a binary mixed material of lauric acid (LA) + stearic acid (SA), and three phase change materials with peak melting points at 50℃, 42℃, 58℃ were prepared at SA mass fractions of 10%, 35% and 80%, respectively. The DSC curves are shown in Figure 5. The phase change material was packaged in the aluminum box with length, width and height of 21cm×7cm×5cm. The aluminum box has reserved loading and unloading port and temperature testing port for the phase change material. The thermoelectric battery adopts 10 pieces in series, each piece composed of 127 pairs of PN-junction thermoelectric arms. 1mm thick thermally conductive silicone is coated between the thermoelectric battery and the PCM aluminum box.

![Figure 5. DSC diagram of the phase change material](image)
4.2. Testing and analysis

In the laboratory, the heating table temperature was set at 65°C to respectively conduct experimental tests on thermal control thermoelectric generation system without phase change (10 pieces in series) and TG/PCM prototypes with melting points at 42°C, 50°C, 58°C. The test contents include cold end temperature of the thermoelectric battery, phase change material temperature, system output voltage and current. The test schematic diagram is shown in Figure 6, and the prototype test photo is shown in Figure 7.

![Figure 6. Prototype test diagram](image)

![Figure 7. Prototype test photo](image)

The test system consists of multiple data acquisition cards, temperature transmitters, computers, heating table. Measurement of the cold end temperature of the thermoelectric battery, phase change material temperature, system output voltage and current was completed, with the test results shown in Figures 8, 9, 10, and 11. Where, Figure 8 shows the hot and cold ends temperature and output power characteristics of thermal control thermoelectric battery with no phase change material. Figure 9,10,11 shows hot, cold end and PCM temperature and output power characteristics of TG/PCM prototype with a melting point of 42°C, 50°C and 58°C.

![Figure 8. Temperature and output power characteristics of TG](image)

![Figure 9. Temperature and output power characteristics of TG/PCM (42°C)](image)
Figure 10. Temperature and output power characteristics of TG/PCM (50°C)

(a) Temperature characteristics  (b) Output power

Figure 11. Temperature and output power characteristics of TG/PCM (58°C)

(a) Temperature characteristics  (b) Output power

5. Conclusion

Based on PCM characteristics of unchanged temperature despite heat absorption during melting, three experimental prototypes of TG/PCM thermoelectric generation system were designed, and temperature and output power characteristics of each part were tested. The results show that the PCM thermal control unit plays an important role in stabilizing the temperature difference between the hot and cold ends of TG. At the same time, the melting point of PCM directly affects the temperature difference characteristics of TG cold and hot end. The lower the melting point of PCM, the better the temperature difference characteristics. In addition, the output power of TG / PCM system is greatly affected by the
melting point of PCM. When PCM melting point of 42°C, 50°C and 58°C, TG/PCM test system total output energy of 73.9J, 52.4J and 18.9J, respectively to output power greater than 6mW. The research results provide theoretical and experimental basis for TG/PCM design.

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References
[1] Zhao J Y, Zhu D S, Zhou Z G, Wang C H and Chen H 2010 Research progress and current status of thermoelectric generation technology Chinese Journal of Power Sources 03 310-13
[2] Zhu D S, Wu H X, Qi X L and Zhou Z G 2012 Research progress in solar thermoelectric generation technology Chinese Journal of Power Sources 03 431-34
[3] Yan W, Qiu G Y and Yuan X F 2016 Application and research overview of semiconductor thermoelectric generation technology Chinese Journal of Power Sources 08 1737-40
[4] Ma Z Z, Yan X P, Meng Y B, Wang X L and Yang J W 2019 Research on Automobile Exhaust Energy Recovery Based on Thermoelectric generation Chinese Journal of Power Sources 03 310-13
[5] Wang L S, Liang Q Y, Li L, Ding X Z and Tang L J 2015 Performance Analysis and Test on Concentration Solar Thermoelectric Generation Device Transactions of the Chinese Society of Agricultural Engineering 24 64-71
[6] Chen H P, Wang Z P, Shi Z Y and Wu S L 2012 Experimental study of thermoelectric generation from thermal power plant exhaust Power System Engineering 02 19-21
[7] Feng G and Zhong S 2011 Research Status and Prospect of Ocean Thermoelectric generation Journal of Northeast Electric Power University 02 72-77
[8] Fan P, Cai Z K, Zheng Z H, Zhang D P, Cai X M and Chen T B 2011 Fabrication and Characterization of Bi-Sb-Te Based Thin Film Thermoelectric Generator Prepared by Ion Beam Sputtering Acta Physica Sinica 09 746-51
[9] Zhao X B, YANG S H, Cao Y Q, Mi J L, Zhang Q and Zhu T J 2009 Synthesis of nanocomposites with improved thermoelectric properties Journal of Electronic Materials 38(7) 1017-24
[10] Sun H Y, Pu J H and Tang G H 2016 High Performance Thermoelectric Battery Based on Nano Organic Liquids Acta Physico-Chimica Sinica 10 2555-62
[11] Wu F Y, Hu S H, Ma X R, Wang Y Q and Zhou D L 2019 Based on MPPT temperature difference power generation experiment and simulation research Journal of Electron Devices 04 843-49
[12] Huang Y S, Xu D C, Li W B and Zhang B W 2018 Forest soil thermoelectric generation based on Seebeck effect Journal of Forest and Environment 38(1) 84-90
[13] Maciej J, Marta B and Marceli C 2016 Experimental investigation of thermoelectric generator (TEG) with PCM module Applied Thermal Engineering 96 527-33
[14] Tang H and Ren B G 2014 Simulation of A Phase Change Heat Storage Thermoelectric Generator Chinese Journal of Power Sources 09 1670-74