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Research Article

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Thermal Regulation of LED Chip Using PEG/CF Composite: A Hands-On Experiment For Undergraduates

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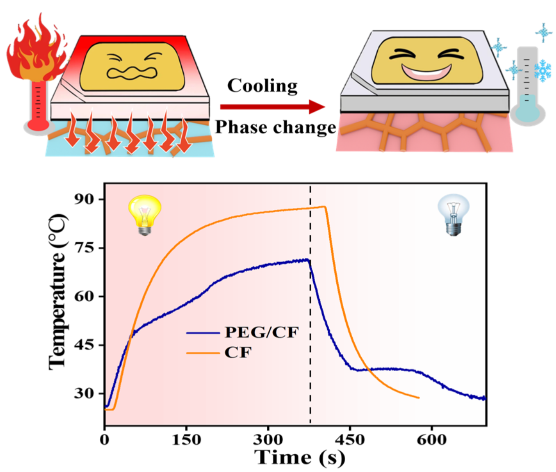
Abstract

A comprehensive laboratory experiment comprising the preparation of polyethylene glycol/copper foam (PEG/CF) composite, phase change properties test and thermal regulation evaluation of LED chip was designed for the undergraduate students. In this experiment, students can not only master material preparation, DSC testing, device assembling and performance evaluation, but also gain the capability of literature searching, data analysis and result discussion, thus to uncover the relationship between phase change properties and temperature regulation performance. From the perspective of higher education, this experiment could facilitate undergraduates to have a basic understanding of scientific research, strengthen their professional knowledge as well as cultivate their capability to consult literature, design experiment, analyze data and solve problems. Moreover, the experiment can arouse students to realize the importance of electronic device's temperature control and the crucial role of PCM composite in thermal regulation.

Graphical Abstract



Keywords: Undergraduate, Hands-On Experiment, Pcm Composite, Phase Change Properties, Thermal Regulation Performance

1. Introduction

Increasing power density of portable electronic devices may result in overheating, short circuit and even fire, all of which can seriously hinder the performance enhancement of electronics [1, 2]. Recent thermal regulation methods used in industry are mainly utilizing air, water, and electricity for active cooling, which are effective but consuming energy and physical space [3-5]. Comparing to active thermal regulation, passive one that absorbs excess heat from electronics for cooling is highly attractive. Specifically, phase change materials (PCMs) are widely applied in the passive thermal regulation due to fixed phase change temperature and large latent heat [6-8]. Among them, organic PCMs such as paraffine, fatty acid, polyols are frequently utilized because of their highly thermal stability. Moreover, organic PCM like polyethylene glycol (PEG) can have the phase change temperature been adjusted by changing chain length, thus showing potentials in different thermal regulation applications9,10. Nevertheless, pristine PCM cannot be applied in thermal regulation directly due to low thermal conductivity and leakage from solid-liquid transition [11-13]. Therefore, it's urgent to construct highly efficient PCM composite for thermal regulation of electronics.

Abundant methods have been proposed to improve thermal regulation performance of PCM composite, which can be classified into two main categories as microencapsulation and porous skeleton absorption [14]. Organic PCMs like paraffin and fatty acid can be encapsulated by polymers like polystyrene and polymethyl methacrylate via in-situ polymerization to prevent leakage completely [15,16]. However, thermal conductivity of the microcapsule is still low and the synthesis process is too complex to be scaled up for industrialization. Liquid PCMs can also be stably absorbed and stored in porous skeletons by capillary force, such as metal foams, carbon aerogel and porous silica [17-19]. The three-dimensional network skeletons based on highly conductive material can be efficient for heat conduction, thus to transfer heat from electronics to PCM composite quickly. Among them, easily fabricated organic PCM/copper foam composite was demonstrated to be promising for electronics cooling as enhancing thermal conductivity by 300% [20].

From the perspective of the undergraduate's professional education, it's meaningful to integrate frontier science with fundamental knowledge in class teaching to achieve research-motivated education. Faraudo et al. presented a low-cost temperature control from 160 K to ambient temperature using liquid nitrogen evaporation in undergraduate laboratory courses [21]. Amelia et al. introduced differential scanning calorimetry in a general chemistry laboratory course to determine thermal properties of organic hydrocarbons [22]. As a result, fundamental knowledge combining with frontier science and industrial application favored undergraduates a comprehensive and deep understanding of class teaching [23,24]. To be specific, for undergraduate students majoring in chemistry related disciplines, design experiment to explore the relationship between fundamental chemistry, material property, device engineering, and performance evaluation is crucial to the understanding of professional knowledge [25,26]. So, if we can guide undergraduate students to design an experiment focusing on PCM composite preparation, phase change property test, device engineering, thermal regulation performance evaluation, as well as data analysis and result discussion, it would be more educational meaningful than theoretical teaching and pure scientific research.

Herein, with conventional equipment and instruments in a comprehensive laboratory, an experiment focusing on PEG2000/copper foam (PEG/CF) composite preparation, phase change properties test and thermal regulation performance evaluation of LED chip was designed. Schematic illustration of the thermal regulation process is shown in Figure 1. Thermal energy generated by the working LED transfers from chip to the tightly attached PCM composite, which will absorb and store the excess heat by changing from solid to liquid. As a result, LED chip is cooled to restrain overheating successfully. It should be noted that heat transfer can be facilitated by the highly conductive three-dimensional network copper skeleton. Meanwhile, liquid PCM can be stored stably in the porous copper via capillary force. By integrating the fundamental knowledge of phase transition and temperature control with device engineering, this experiment design is suitable for undergraduate students majoring in physical chemistry and the related engineering disciplines, such as chemical engineering. Moreover, this experimental design also provides students with a basic recognition of scientific research and cultivates their capability of literatures search, experiment design, data analysis, as well as result discussion and problems solving.

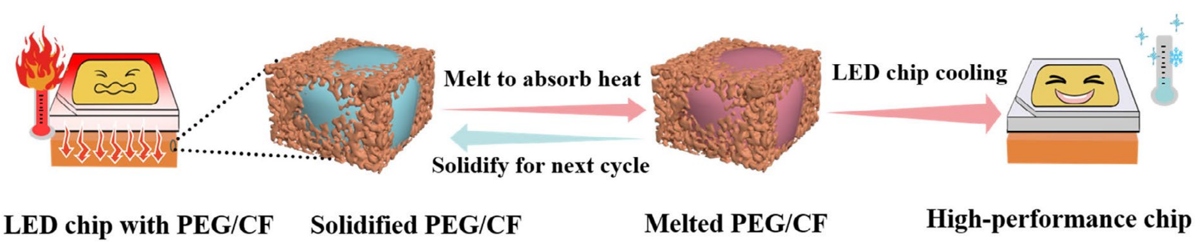


Figure 1: Scheme illustration of PEG/CF based thermal regulation process

2. Experiment

2.1. Prelab Assignment

A prelab assignment containing thermal regulation of chips, phase change properties, and working mechanism of differential scanning calorimeter were described detailly in supporting information. Students were encouraged to search literatures to obtain a deep and comprehensive understanding of the experiment background.

2.2. Materials And Instrumentation

PEG2000 (98%, Sinopharm Chemical Reagent Co., Ltd., China), copper foam (1.6 mm thickness, DoDoChem Co., Ltd., China), and LED chip (20 W, Jingyuan Co., Ltd., China) are all used directly without further treatment.

All required equipment including balance (BSA224S, Saratorius), vacuum oven (DZF-6020, Yixi Co., Ltd., China) and differential scanning calorimeter (DSC, Hitachi DSC6220) have already existed in the comprehensive lab. Measuring tools like K-type thermal couple, thermal meter and digital multimeter are also present in the lab with no requirement to purchase new.

3. Procedures

3.1. PEG/CF Composite Preparation

The students were divided into groups to prepare PCM composite. The whole process was explained detailly and exhibited in Figure 2 below. Firstly, copper foam (CF) was cut to fit the size of LED chip. Then, it was covered with PEG2000 powders and placed in a vacuum oven, which was maintained at 60°C and 0.07 MPa for 20 minutes. Next, the vacuum was closed and air was pushed in, the state of which was maintained for another 20 minutes. Finally, the PEG/CF was placed on filter paper and heated to remove the surface attached PEG, which was melted and absorbed by filter paper to obtain shape-stable PEG/CF. By following the above procedures, students can obtain PEG/CF composite, which is different from pristine CF as the present of waxy PEG (Figure 3A). Meanwhile, question 1 and 2 in supporting information were posted to help student strengthen the understanding of PEG/CF composite preparation.

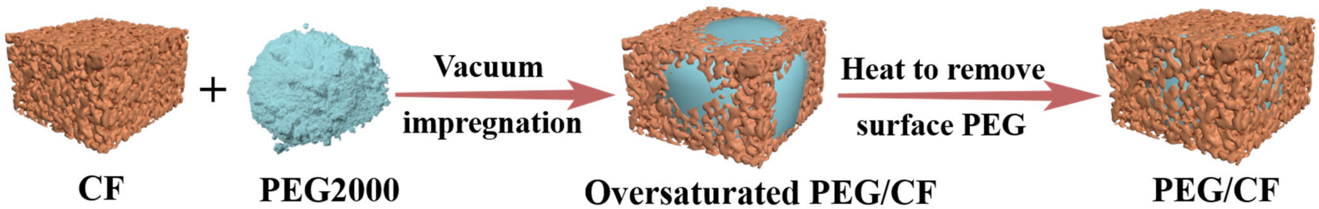


Figure 2: ZScheme illustration of the PEG/CF composite preparation process

3.2. Phase Change Property Test

Students were required to master DSC operation, and understand how to figure out phase change properties from the DSC melting curve. To be specific, 10-20 mg sample was weighted and placed into the aluminum pan for DSC testing. The test was conducted in Ar atmosphere with a heating rate of 5°C/min. The raw data were processed in data analysis software Originlab, to acquire critical phase change parameters such as start/peak/end temperatures, latent heat, thermal conductivity or resistance. Question 3 in supporting information was posted to inspire student to think the relationship between phase change properties of PEG/CF.

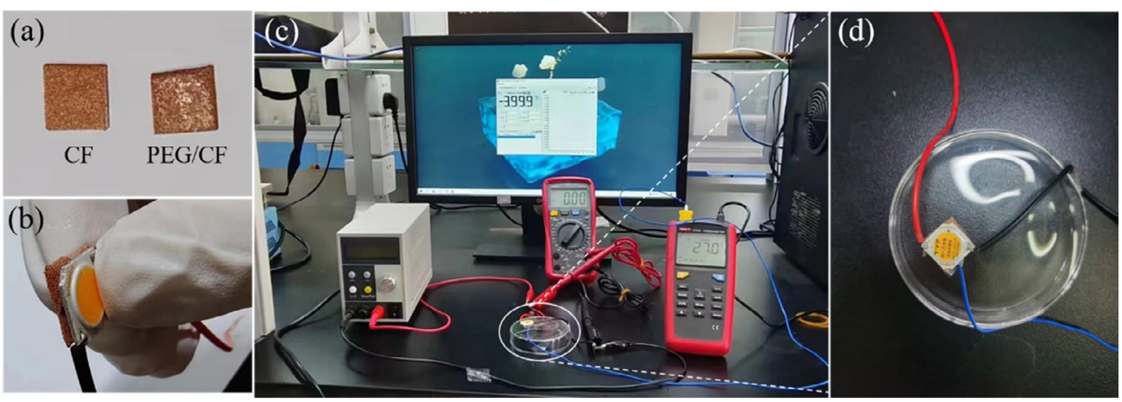


Figure 3: PEG/CF composite and copper foam (A), PEG/CF composite sticked to LED chip (B), thermal regulation performance evaluation system (C), zoom-in image of connected LED chip (D).

4. Results And Discussion

Phase change properties that are crucial to the thermal regulation performance were tested by using a DSC, the working mechanism of which was described detailly in supporting information. Based on the DSC curves in Figure 4, melting point temperatures, thermal conductivities and latent heats of the PEG/CF composite and pristine PEG were analyzed. Phase change is a process as melting of pristine PEG starts from 50°C and ends at 65°C, while peak temperature at 60°C is the point possessing the fastest melt velocity. Interestingly, the PEG/CF composite that possesses higher thermal conductivity starts to melt several degrees later than the pristine PEG, which may stem from the difference in PEG status (contacts directly with DSC pan or caged by Cu foam). As pristine PCM usually has low heat transfer velocity, PCM composite is designed to enhance thermal conductivity. The slope of DSC curve can be related to the total thermal resistance, which is negatively correlative with heat transfer velocity in PCM composite [27].

$$Slope = \frac{d\Delta P}{dT} = \frac{2}{R} \quad (1)$$

Where ΔP, T, and R are the calibrated differential power, the sample temperature, and the total thermal resistance. The total resistance R containing three parts as the thermal resistance between sample and sample pan (R_1), the thermal contact resistance between heating source and sample pan (R_2), and the thermal resistance of sample (R_s), which depends on sample's geometric dimension and thermal conductivity as following.

$$\frac{1}{slope} = \frac{1}{2}(R_1 + R_2 + \frac{h_S}{A_S k_S}) \quad (2)$$

where h_s, A_s, and k_s are the height, surface area and conductivity of sample. As the sample and reference were shaped into the same geometric dimension, the slope ratio can be related to thermal conductivity directly. As being calculated, slope values of the PEG/CF and PEG curves' right part of are 10.4 and 7.3, demonstrating the copper foam can effectively facilitate heat transfer. The superior heat transfer velocity of PEG/CF can be attributed to copper material with a thermal conductivity up to 500 W/m·K, as well as the three-dimensional network skeleton that provides more heat transfer pathways. Finally, melting enthalpy is crucial for the PCM composite's cooling function, which determines the amount of PCM composite used and the time for maintaining the constant temperature process. The melting enthalpy can be calculated from the peak area of DSC curves as following:

$$Enthalpy = \frac{S}{m*r} \quad (3)$$

Where *S, m*, and *r* are the peak area, sample mass and heating rate, respectively. Pristine PEG2000 has a high latent heat up to 190 J/g. Although involving of Cu foam reduces the latent heat to 115 J/g, the value is still higher than most literatures reported ones [13-15].

Above all, a lot of valuable information can be acquired from the DSC curve and students should learn to figure out the critical phase change properties. Moreover, the instructor should guide students to correlate the phase transition properties with cooling function. Specifically, the phase change process can be described using the start/peak/end temperatures, and the shift of the phase change point can be ascribed to the change of thermal property. Next, thermal conductivity determining the heat remove velocity from electronic device to PCM composite is critical for avoiding heat accumulation. Although the value cannot be read out from the DSC curve directly, the slope of which can provide a qualitative description of thermal conductivity. Finally, melting enthalpy determines the amount of PCM composite used and time for constant temperature process lasted during cooling, which can be calculated from the peak area.

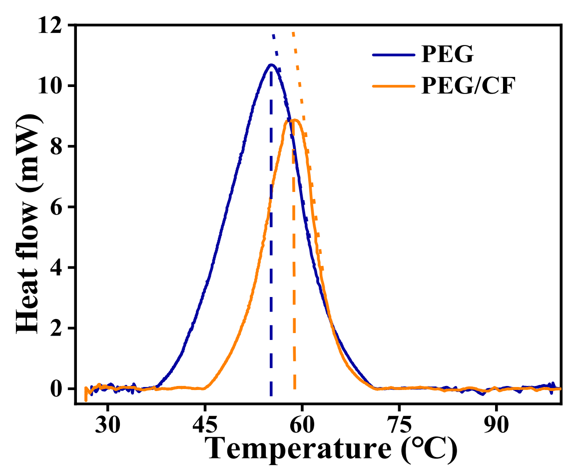


Figure 4: DSC melting curves of PEG/CF composite and pristine PEG.

Phase change properties were then associated with the thermal regulation performance of LED chip. As the limited working condition for LED chip is 9-10 V and 300 mA, voltage and current were turned to 8 V and 300 mA to study the cooling function of PEG/CF composite. While temperature of the CF based chip continued raising until 90°C, temperature increase velocity of the PEG/CF based chip slowed down at 60°C as melting to store heat temporarily (Figure 5). As a result, peak temperature of the CF based chip is 16°C higher than that of the PEG/CF based one. When the LEDs were turned off, temperatures of both dropped dramatically at the beginning. When it reached at 40°C, temperature dropping velocity of the PEG/CF based chip slowed down due to PEG solidification. Therefore, the PEG/CF composite can be used effectively and cyclically for LED chip cooling. In this part, students should learn how to evaluate the thermal regulation performance of PEG/CF for the normally working LED chip from the temperature-time curve.

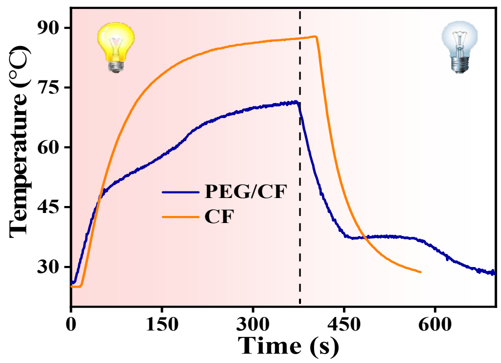


Figure 5: Temperature-time curves for the PEG/CF and CF based LED chips working under 8 V voltage and 300 mA current.

To integrate the thermal regulation performance with phase change properties, calculation was done based on the above results. Assume the LED chip worked under 6 V voltage and 100 mA current, and 50% of the energy input was conversed to heat, the heat generation power thus was calculated to be 0.3 W. On the other hand, 5 grams PEG/CF composite with a melt enthalpy of 115 J/g was utilized to cool LED chip. Thus, the composite can restrain chip temperature below 60°C for 30 minutes theoretically by absorbing the excess heat by PEG melting. If we want to prolong the time for temperature control, it's useful to enhance the amount or latent heat of PCM composite. Instructor should associate the temperature regulation performance of PEG/CF with the phase change properties, to clarify the mechanism of PEG/CF based temperature control.

When LED chip works within the permitted voltage and current, the outputting power can maintain stable. However, if the voltage or current is beyond the permitted value, the chip will be overheated to decrease LED working power as the reduction of electron transfer velocity, fluorescence quantum efficiency and electrical capacity [28-29]. Therefore, voltage and current of the LED chip were turned to 11 V and 300 mA to study the influence of overheating on chip's performance. Both temperatures of the CF and PEG/CF based LEDs raised rapidly above 100°C due to the overheating of LED chips (Figure 6a). Nevertheless, PEG melting could exert a cooling function since PEG/CF based LED is 13°C lower than the CF based one.

Meanwhile, output powers of the LED chips were tested to study the PEG/CF composite's influence on chip performance. The LED's voltage was measured by using a digital multimeter, combing with constant current to calculate the output power by using the following simple equation:

$$P = U * I \quad (4)$$

The overaged voltage generated unstable output power, which declined continuously as temperature raising (Figure 6b). When the temperature of PEG/CF based chip was 13°C lower than that of the CF based one, the corresponded output power can be 5% higher, demonstrating that the LED's performance can be enhanced via the cooling function. In this section, students were encouraged to adjust the current and voltage to obtain the law regarding the influence of PEG/CF on LED chip performance. Then, the instructor should guide students to link the phase change properties, temperature regulation performance and LED chip working performance together, to uncover the fundamental relationship between them.

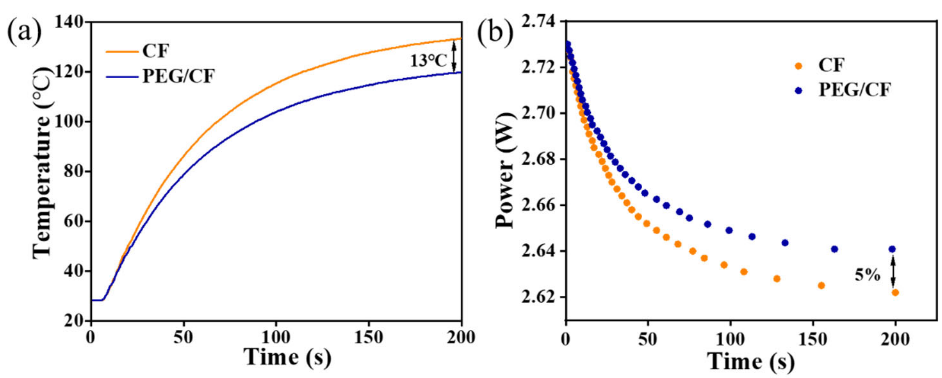


Figure 6: Temperature-time curves (a) and output power-time curves (b) of the PEG/CF and CF based LED chips under 11 V voltage and 300 mA current.

5. Educational Aspects

Preparation of PEG/CF composite, phase change properties test and thermal regulation performance evaluation of LED chip can all be conducted in a comprehensive laboratory with conventional equipment and instruments. Generally speaking, this experiment will provide undergraduate students with a basic understanding of scientific research, strengthen their professional knowledge and cultivate their capability to consult literature, design experiment, analyze data and solve problems. To be details, several educational aims can be achieved by this experimental design. (1) By following the designed hands-on experiment, students can master the PEG/CF composite preparation, DSC testing and performance evaluation device assembling. (2) By analyzing the DSC curves, students can figure out critical properties of PEG/CF composite (phase change points, latent heat, and thermal conductivity) from the DSC melting curve. Through analyzing these properties detailly, students can further correlate the phase change properties with the cooling function. (3) The temperature-time and power-time curves of LED under various working conditions can be obtained for thermal regulation and LED work performance evaluation, respectively. Thus, students can uncover the relationship between phase change properties, thermal regulation, and LED chip working performance. (4) The questions in supporting information inspire students to think deeply and comprehensively with the assistance of literatures. Thus, students can be familiar with literatures searching in this process.

6. Conclusions

A comprehensive experiment including PEG/CF composite preparation, phase change properties test and thermal regulation performance evaluation was designed for undergraduate students. Through this hand-on experiment, students can master the material preparation, DSC testing, device assembling and performance evaluation, as well as gain the capability of literature searching, data analysis and result discussion. Meanwhile, by studying the relationship between phase change properties and thermal regulation performance, students can clarify the temperature control mechanism of PEG/CF composite. Moreover, the students could strengthen their professional knowledge and fundamental experiment skills, grasp a basic understanding of scientific research, and understand the significance of thermal regulation to electronics device.

Supporting Information

Prelab assignment, the time required for the experiment, discussion section, and question sets and answers.

Acknowledgments

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