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Promoting temperature control and energy conservation by smart thermal management using nanoparticle suspensions with tunable thermal conductivity

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HIGHLIGHTS

• A thermal smart material is prepared using silicone oil and graphene nanosheets suspensions.

• The variation of the thermal conductivity can be explained by the two-step model.

• A thermal smart component is designed with tunable thermal conductance.

• The thermal smart management can effectively promote temperature control and energy conservation.

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ABSTRACT

Smart thermal control technology is essential in modern technologies to manage heat transfer. However, most research has primarily been focused on the performance of thermal smart materials rather than integrating the materials into thermal smart components and devices. In this study, we proposed a kind of thermal smart system using thermal smart materials for promoting temperature control and energy conservation. Firstly, we prepared thermal smart materials using nanoparticle suspensions composed of silicone oil and graphene-based composite nanosheets. The variation of the thermal conductivity can be explained by our proposed two-step model. Then, we demonstrated a kind of thermal smart component based on thermal smart materials, whose thermal resistance can be continuously tuned by electric field. The thermal smart component has good temperature regulating ability, enabling the decrease of device temperature by 5.3 °C when the environmental temperature is 20 °C, the input heat flux is 3500 W/m², and the electric field strength is 600 V/mm. An energy conservation of 10% can be achieved by using thermal smart component. The thermal smart component can work well in practical operation conditions with complex and varying heat-flux, showing great potential in various thermal management systems for electronic devices, spacecraft systems, and power batteries.

1. Introduction

With the rapid development of science and technology, there is a growing demand for high-accuracy and energy-saving thermal management in various fields, such as electronics [1,2], spacecraft systems [3], and power batteries [4]. The thermal control system of spacecraft need to provide a constant temperature for the temperature-sensitive instruments in hostile environments of space, such as extremely temperature, drastic heat flux fluctuations and variable orbital types [5]. Therefore, the thermal control system should have the capacity to

respond in real time rapidly when the power or environmental temperature changing, to avoid sharp fluctuations in device temperature [6]. Compared with passive and active thermal control technologies, smart thermal control technologies have attracted much attention in recent years to cope with these complicated conditions [7,8].

In recent years, research on smart components has become popular [9,10]. Thermal switches [11], thermal regulators [12,13], and thermal variable resistors [14] are examples of thermal smart components with dynamic and controllable characteristics. Thermal variable resistors can continuously adjust its thermal resistance, thereby stabilizing the

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operating temperature of controlled systems, which are the development trend of thermal smart components. Thermal smart materials with tunable thermal conductivities are the foundation and core in the design principles of thermal smart components. Several thermal smart materials have been proposed in previous studies for the reversible tuning of thermal conductivities, such as nanoparticle suspensions [15,16], layered materials using intercalation [17,18], phase change materials [19], soft matter [20,21], and ferroelectric materials [22]. The most critical performance parameter of thermal smart materials is the thermal switching ratio *r*, which is the ratio of maximum and minimum thermal conductivities of materials. A good candidate for thermal smart materials is nanoparticle suspension which has a short response time, excellent reversibility, and can continuously adjust the thermal conductivities.

Nanoparticle suspensions are composed of base fluid and anisotropic nanoparticles with high thermal conductivity. The anisotropic nanoparticles tend to align in the direction of external field, contact with each other and form chains when applying external fields such as electric field [23], magnetic field [24], and shear flow [25]. These chains could form effective thermal conductive pathways, enhancing thermal conductivity parallel to external field direction. The thermal conductivity of nanoparticle suspensions exhibits anisotropy under an external field [26]. The findings on the thermal conductivity perpendicular to the external field direction are inconsistent, with some studies showing slight decreases, some indicating almost no change, and some reporting slight increases [27]. Overall, the external field has a relatively small effect on the thermal conductivity perpendicular to its direction. Therefore, we study the thermal conductivity parallel to external field direction to achieve reversible regulation. Compared with magnetic field and shear flow, electric field is easier to generate with shorter response time and lower energy consumption [28]. Electro-rheological fluids, which have tunable mechanical and rheological properties [29,30], also support the idea of choosing nanoparticle suspensions tuned by an electric field as thermal smart materials and making thermal smart components eventually.

Most research has primarily been focused on the performance of thermal smart materials, especially the thermal switching ratio of the materials under laboratory conditions, rather than integrating the materials into thermal smart components and devices. Although some developed thermal switches have been employed in solid-state refrigeration [11,31], cryogenic refrigeration [32], and thermal resonator [33], most research on thermal variable resistors is theoretical and simulation studies [14,34,35]. In this study, a kind of thermal smart material based on nanoparticle suspensions is proposed, whose thermal resistance could be tuned continuously by electric field. The nanoparticle suspensions are composed of silicone oil and graphene-based composite nanosheets, which have high thermal conductivities due to graphene or reduced-graphene oxide (rGO) core and good dielectric properties due to inorganic shell. Furthermore, a kind of thermal smart component based on the proposed thermal smart materials is proposed, whose thermal resistance can be tuned continuously by electric field. The thermal smart component can stabilize the temperature of experimental system, enabling the decrease of device temperature for 5 °C and energy conservation for 10% in varying operation conditions. The thermal smart component has potential applications in electronic devices, spacecraft and energy-saving technology [36].

2. Methods

2.1. Two-step model

A two-step model was proposed to calculate the thermal conductivity of nanoparticle suspensions in our previous research, taking into account both the effects of nanoparticle aggregation and orientation [15]. The previous paper detailed the derivation process of the two-step model, and it is found through the two-step model that better orientation, the larger aspect ratio p, and the higher volume fraction of nanoparticles could enhance the thermal conductivity parallel to the electric field direction effectively. In the first step, the thermal conductivity of nanoparticle aggregates k_{cluster} is calculated based on the Bruggeman effective medium theory [37]:

$$\phi_{\rm int} \left(\frac{k_{\rm p} - k_{\rm cluster}}{k_{\rm p} + 2k_{\rm cluster}} \right) + (1 - \phi_{\rm int}) \left(\frac{k_{\rm f} - k_{\rm cluster}}{k_{\rm f} + 2k_{\rm cluster}} \right) = 0 \tag{1}$$

where k_p , k_f are the thermal conductivity of the particles and base fluid, respectively and ϕ_{int} is the volume fraction of the solid particles in the aggregates.

Under an electric field, the nanoparticles suspended in fluid align end-to-end, forming elongated chains. Thermal conductivity of nanoparticle suspensions exhibits anisotropy. In the second step, the thermal conductivity of the system is calculated based on effective medium theory of Nan et al. [38], considering the contribution of the nanoparticle orientations. The thermal conductivity parallel to the electric field direction can be written as,

$$k_{\parallel} = k_{\rm f} + k_{\rm f} \frac{\phi_{\rm cluster} A_{33}}{1 - \phi_{\rm cluster} B_{33}} \tag{2}$$

where ϕ_{cluster} is the volume fraction of the aggregates in suspension. It is evident that increasing ϕ_{cluster} contributes to enhancing thermal conductivity parallel to the electric field direction. A_{33} and B_{33} are expressed as,

$$A_{33} = \frac{k_{\text{cluster}} - k_{\text{f}}}{k_{\text{f}} + L_{11} (k_{\text{cluster}} - k_{\text{f}})} \left[1 - \langle \cos^2 \theta \rangle \right] + \frac{k_{\text{cluster}} - k_{\text{f}}}{k_{\text{f}} + L_{33} (k_{\text{cluster}} - k_{\text{f}})} \langle \cos^2 \theta \rangle$$
(3)

$$B_{33} = L_{33}A_{33} \tag{4}$$

where $L_{\rm ii}$ is the geometrical factor depending on aspect ratio p [38,39], and $\langle cos^2\theta \rangle$ represents the orientation of nanoparticles. When the value of $\langle cos^2\theta \rangle$ is larger, it indicates better orientation of the nanoparticles. Nanoparticles are fully oriented in the direction of the electric field when $\langle cos^2\theta \rangle = 1$. The orientation of nanoparticles significantly influences the enhancement of thermal conductivity.

2.2. Preparation of materials

The nanoparticle suspensions in this study are composed of rGObased or graphene-based composite nanosheets and silicone oil. Several types of composite nanosheets are used here, including graphene nanosheets (GNS)/layered double-hydroxide (LDH), graphene oxide (GO)/polyaniline (PANI), rGO/PANI and rGO/SiO₂. The preparation of above nanosheets requires synthesization of GO colloid first.

The GO colloid was synthesized using an improved Hummers method [40,41]. 180 mL of concentrated sulfuric acid was mixed with 20 mL of phosphoric acid, followed by the slow addition of 9 g of potassium permanganate and 1.50 g of natural graphite flakes. The solution was stirred at 55 $^{\circ}$ C for 12 h and then subjected to ice bath treatment. The mixture was centrifuged, then ultrasonication and dilution were performed to obtain GO colloidal dispersion.

To make GNS/LDH composites, we mixed 2.00 g GO colloidal dispersion with 80 mL solution containing $5.12 \text{ g Mg}(NO_3)_2 \cdot 6H_2O$, $3.75 \text{ g Al}(NO_3)_3 \cdot 9H_2O$ and 3.64 g hexamethylenetetramine under stirring. The solution was ultrasonicated for 1 h, transferred into a stainless autoclave, and heated for 12 h at 140 °C. The resulting precipitate was separated, rinsed, and dried under vacuum to obtain the GNS/LDH composites.

To make GO/PANI and rGO/PANI composites, we added 2.56 g of GO colloidal dispersion and 50 mL of ethanol into 120 mL HClO₄ solution. The solution was ultrasonicated until it became transparent. 2.40 g of aniline was added to the solution at -10 °C under stirring for 30 min,

followed by the addition of 40 mL of HClO₄ solution containing 1.98 g of $(NH_4)_2SO_4$. The mixture was stirred at -10 °C for 20 h. The precipitate was then separated, rinsed, and dried under vacuum to obtain the GO/PANI composites. Finally, the GO/PANI composites were dispersed into 500 mL of water containing 1 mL of hydrazine and heated at 95 °C for 1 h to obtain rGO/PANI composites.

To make rGO/SiO₂ composites, we added 30.00 mg of GO colloidal dispersion into 100 mL of ethanol containing 1.20 g Pluronic F-127 by ultrasonic agitation for 30 min at a frequency of 40 kHz and power of 100 W. Then, 4 mL of ammonia and 8 mL of water were added to the dispersion. Next, 20 mL of ethanol containing 2 mL of tetraethyl orthosilicate was added dropwise into the GO colloid dispersion with stirring for 12 h. Finally, the precipitate was centrifugally separated, and washed with hot ethanol several times to remove Pluronic F-127 and obtain the GO/SiO₂ composite. The rGO/SiO₂ composite was prepared by reducing GO/SiO₂ in a hydrazine solution. Specifically, 0.30 g of GO/SiO₂ was dispersed into 30 mL of water containing 1.5 mL hydrazine by ultrasonic agitation. After heating for 2 h at 95 °C, a precipitate was formed. The precipitate was centrifugally separated and washed with ethanol several times to obtain the rGO/SiO₂ composites.

Finally, the required mass of composite nanosheets was weighed, placed in a vacuum drying oven, and dried at 95 °C for 48 h. The composite nanosheets were then added to silicone oil, mixed evenly, and then ultrasonically treated for 30 min to fully disperse the twodimensional composite nanosheets in the silicone oil matrix to obtain nanoparticle suspensions. The distribution of composite nanosheets in silicone oil can be altered by electric field, thereby changing the thermal conductivity of the nanoparticle suspensions. The property makes nanoparticle suspensions useful as thermal smart materials. The successful preparation of nanoparticle suspensions signifies the successful preparation of thermal smart materials. Ultrasonic treatment was performed for 15 min before each experiment to prevent the suspended nanoparticles in the dispersion from agglomerating or precipitating.

2.3. Characterization of thermal properties

The micromorphology of the prepared nanosheets was observed using scanning electron microscopy (SEM, JSM-6700F), and the microstructure evolution was observed using a light microscope (ZEISS AXIO vert.A1) and recorded using a high-speed camera (FASTCAM Mini UX 50). To measure the thermal conductivity parallel to electric field direction of nanoparticle suspensions, the laser flash method (LFA 467 HyperFlash, Netzsch) was used due to its one-dimensional and noncontact measurement. A sample holder for the liquid materials was designed specifically to apply a direct current (DC) electric field during the test. The direction of electric field was parallel to the direction of thermal diffusivity measurement. The specific heat of the suspensions was measured with differential scanning calorimetry measurements (DSC Q2000, TA Instruments), and the thermal conductivity parallel to electric field direction could be calculated from the thermal diffusivity and specific heat.

2.4. Environmental test system of thermal smart component

The experimental setup consists of heat source, system body, and heat dissipation components (including a cooling fan and the thermal smart component based on encapsulated thermal smart materials) to simulate an actual device, as shown in Fig. 1. A silica-gel film electrical heater with diameter d = 25 mm was used as surface heat source. The power of the film heater could be tuned via the DC power supply (MAISHENG, MT-1520). A 1050 aluminum alloy rod with d = 25 mmand height h = 50 mm was placed on the heater as the system body for heat transfer. The cooling fan was located above the system body and in contact with ambient air, with a rated power P = 2 W. The thermal smart component, which was composed of encapsulated thermal smart materials (rGO/SiO₂) and acrylonitrile-butadiene-styrene (ABS) container, was placed between the aluminum rod and the cooling fan. Two aluminum plates were attached to the inner surfaces of container to connect DC power supply and form uniform electric field for the inside thermal smart materials. The strength of the electric field can be adjusted to tune the thermal resistance of the thermal smart component. To minimize heat dissipation through the system surfaces, a layer of foam insulation was placed between the system and the ambient air/ baseplate. The temperature of system was quantified by thermocouples. The temperature of the thermocouple between aluminum rod and thermal smart component was taken as the device temperature T_d , while the thermocouple floating in air measured the environmental temperature T_{e} .

3. Results

3.1. Thermal properties

The thermal smart materials are composed of suspended nanoparticles with high thermal conductivity and surrounding liquid media. Comparing to spherical nanoparticles, graphene and rGO nanosheets are ideal candidates as the suspended particles due to their high thermal conductivity and large aspect ratio *p*, which are key elements to improve the performance of thermal smart materials. However, pure graphene also has high electrical conductivity, which may cause current leaching



Fig. 1. The schematic of experimental system. The system includes heat source, system body and heat dissipation components.

and power consumption. To take full advantage of the excellent anisotropic morphology and thermal conductivity of graphene, researchers have developed composite nanosheets through combining layered inorganic or organic materials as shell with graphene or rGO as supporting core by hydrothermal or polymerization method [29,42]. The formed composite nanosheets with conductive core and insulating shell thus have high anisotropy, high thermal conductivity, low electrical conductivity and good dispersibility. GNS/LDH, GO/PANI, rGO/PANI, rGO/SiO₂ are used in this study. The microstructure of samples is shown in Fig. 2. The nanosheets possess an independent sheet-like morphology without free impurity, and show tight bonding between the shell and core. The coated shell attaches to the surface of core thoroughly and uniformly, indicating the success of material manufacture.

The microstructure evolution of the suspensions under electric field is illustrated in Fig. 3, with GNS/LDH materials taken as a representative case. The nanoparticles distribute randomly in fluid without electric field as shown in Fig. 3(a). When applying electric field, the nanoparticles align in the direction of electric field, connect with each other in Fig. 3(b), and finally form chain-like structures with branches in Fig. 3 (c). When the electric field is turned off, the chains break up as shown in Fig. 3(d). The number of nanoparticles seems to decrease after the removal of the electric field because some nanoparticles aggregate resulting from van der Waals interactions. Although the structure does not completely return to its initial state after the removal of the electric field, the overall spatial and orientational distributions become random after one cycle. When the electric field is reapplied, the nanoparticles reform chain-like structures, as shown in our previous work [15]. These chain structures can form effective thermal conductive pathways, and heat can be largely transferred through the network, leading to the enhancement of thermal conductivity. The thermal conductivity of the suspensions can be tuned by switching on and off electric field accordingly.

The measured thermal conductivities of these materials without electric field are presented in Table 1, and the thermal switching ratio r with different strength of electric field is depicted in Fig. 4. These



Fig. 3. The microstructure evolution of nanoparticle suspensions under electric field. (a) random spatial and orientational distributions in the fluid (b) pack into small ordered chains (c) form long chains with small interchain bridges (d) small flocs and broken short chains appear after the removal of electric field. The scale bars are 200 μ m.



Fig. 2. The SEM image of composite nanosheets: (a) GO/PANI (b) rGO/PANI (c) rGO/SiO₂ (d) GNS/LDH. The scale bar is 1 µm.

Table 1

Thermal conductivities of thermal smart materials without electric field.

Material	GNS/LDH 4.5%	GNS/LDH 7.5%	GNS/LDH 10.5%	GO/PANI	rGO/PANI	rGO/SiO_2
$k (W \cdot m^{-1} \cdot K^{-1})$	0.129	0.138	0.145	0.141	0.156	0.170



Fig. 4. The thermal switching ratio variation of different types of nanoparticle suspensions as a function of electric field strength.

suspensions show tunable thermal properties with electric field. The thermal conductivities of the suspensions increase rapidly when applying electric field, then continue to increases with the strength of electric field gently. For the slowdown of the increase, the probable cause may be the chain-like structures become thicker and form more branch-like structures under higher strength of electric field, leading to the aspect ratio *p* reduction of chain-like structures. As a result, the heat transfer along the direction of electric field is mitigated, which is in agreement with the two-step model which indicates the increase of chain length will result in higher thermal conductivity of nanoparticle suspensions. The maximum switching ratio and curve slope are varied slightly with different kinds of materials, but they all have similar characteristics of thermal property under electric field. PANI/rGO and PANI/GO have lower thermal switching ratio at 0-300 V/mm than GNS/ LDH and SiO₂/rGO. Therefore, the thermal switching ratio of PANI/rGO and PANI/GO at higher voltages is not tested. For the same kind of suspended nanoparticles (e.g. GNS/LDH), the enhancement of thermal conductivity increases with the volume fraction of nanoparticles. The maximum thermal switching ratio occurs at approximately r = 1.45 for LDH/GNS nanoparticles with a volume fraction of 10.5% at E = 500 V/mm. The possible explanation is that higher volume fractions of nanoparticles contribute to the increase of thermal conductive pathways, leading to the enhancement of thermal conductivity as predicted by the two-step model. Comparing to GO-core nanoparticle, suspensions with rGO-core nanoparticle have better thermal switching ratio under the electric field, because rGO has higher thermal conductivity and larger aspect ratio p comparing than GO. The structure and properties of the core play a vital role in the performance of thermal smart materials, which should be taken notice in future research.

When the electric field is turned off, the thermal conductivity of the suspension reduces to the original value again, since the chain structures break up and the nanoparticle aggregates return to the uniformly distribution state in the suspension. The results of cycle test are shown in Fig. 5: the largest thermal switching ratio is about 1.53 in the first cycle, then decrease to about 1.41 and become stable. Nanoparticles do not



Fig. 5. Reversibility testing of thermal conductivity of GNS/LDH suspension under on/off cycles of DC electric field.

aggregate at the beginning, so the thermal switching ratio in the first cycle is higher. The slight decrease results from the formation of nanoparticle aggregates after switching the electric field continually. By further modifying the nanoparticles to make them more stable in suspensions, this problem can be improved. These materials have good reversibility for application in thermal smart components.

3.2. Environmental test of the thermal smart component

To demonstrate the potential of the thermal smart materials as thermal smart components in thermal control system, we design an experimental system to simulate practical devices with heat dissipation components. The schematic of the experimental system is described detailed in method section. As a part of the heat dissipation components, the thermal smart component is located between the system body and the cooling fan, including ABS container and encapsulated thermal smart materials (rGO/SiO₂ suspension). The device temperature T_d and environmental temperature T_e are monitored during the experiments by thermocouples. The thermal smart component is connected with the DC power supply to apply electric field, tune the thermal resistance of the thermal smart component and regulate the heat dissipation of the system. The thermal resistance decreases with increasing electric field strength at the same working conditions. The calculation and results of the thermal resistance are shown in the Section I (Supplementary materials). When the input heat flux q is 2100 W/m^2 and the environmental temperature T_e is 28 °C, the thermal resistance can be reduced from 11.93 K/W to 9.31 K/W through electric field regulation. The thermal smart component has response times of milliseconds.

To test the temperature regulating ability of the thermal smart component, the environmental temperature $T_{\rm e}$ is set as 20 °C, and the input heat flux q varies from 700 W/m² to 3500 W/m². The strength of electric field is adjusted during the test to change the thermal resistance of the thermal smart component with a maximum strength of 600 V/mm to avoid current leakage or short-circuits. For each test with different strength of electric field, the temperature is measured and recorded until

the system reach steady state. The variation of the device temperature T_d as a function of input heat flux q for different strengths of electric field is shown in Fig. 6, and all results are the averages of three experiments. The device temperature T_d increases with the input heat flux q. And increasing the electric field reduces the thermal resistance of the thermal smart component, effectively decreasing the device temperature. The difference of T_d between the "on" state (E = 600 V/mm) and "off" state (E = 0 V/mm) of the thermal smart component is 2.6 °C at q = 700 W/ m², 4.3 °C at $q = 1400 \text{ W/m}^2$, 4.3 °C at $q = 2100 \text{ W/m}^2$, and 5.3 °C at q= 3500 W/m². It is larger for the higher q than for lower q, which indicates that the thermal smart component can perform better in higher power dissipation and harsher environments, showing good application prospects in the cooling of high-power chips.

To further validate the performance of the thermal smart component, tests under varying environmental temperatures are also conducted. The input heat flux q is fixed at 2100 W/m^2 and the environmental temperature T_e varies from 16 °C to 28 °C. The device temperature T_d is measured as a function of T_e for different strengths of electric field and the results are shown in Fig. 7(a). The device temperature T_d increases almost linearly with the environmental temperature T_e at the same strength of electric field. The performance of the thermal smart component is not significantly affected by environmental temperature, indicating its potential in diverse industrial applications. The average temperature difference value can decrease by nearly 2.7 °C for the "on" and "off" state at $T_e = 28$ °C.

Cyclic measurements are conducted to determine the reversible cyclicity of this thermal smart component, which is important in practical conditions. In each cycle, the input heat flux and environmental temperature are fixed at $q = 2100 \text{ W/m}^2$ and $T_e = 20 \degree$ C, and the thermal smart component is switched between the "on" and "off" states. The device temperatures are measured and recorded when the device system achieve stable state at each cycle. As shown in Fig. 7(b), the difference of device temperature between the "on" state and "off" state remains stable during the cycle test, achieving a difference of about 2.0 °C at the cycle.

In addition to stabilizing device temperature, the thermal smart component as a part of the heat dissipation component in thermal control system, can also reduce the energy consumption of heat dissipation compared to devices which only use electric-driven fans for heat dissipation. To explore the energy conservation effect, we change the power of the fan P without the thermal smart component, and measured the device temperature after the system stabilized. The environmental temperature is fixed at $T_e = 20$ °C. As shown in Fig. 8(a), a nonlinear fit



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Fig. 7. (a) Device temperature variation as a function of environmental temperature with different strength of electric field. (b) Reversibility testing of thermal smart component under on/off cycles of DC electric field.

(fitting formula: $y = a \cdot b \cdot c^{x}$) is performed on the data, and the device temperature T_d will decrease nonlinearly with the increase of P for different heat flux. Without the thermal smart component, P greater than 2.18 W is required to achieve the same device temperature as when the thermal smart component is in the "on" state at P = 2 W. This demonstrates a power consumption reduction of approximately 10%, and the calculation process can be found in the Section II (Supplementary materials).

In actual working conditions, it is common for the system to experience fluctuations in heat flux and environmental temperature. Therefore, the ability of real-time response and autoregulation is critical for the thermal control system. Compared to traditional heat dissipation components, the thermal smart component can adjust its thermal resistance quickly by varying the strength of the applied electric field to affect the heat dissipation of the system, thereby helping to maintain the device temperature. To verify the performance of the variable thermal resistance under complex heat flux conditions, we conduct a periodic heat flux test, in which the generated heat flux is set at 2100 W/m^2 for 30 min and then stopped for 30 min, and so on. During the heating process, the thermal smart component is in the "on" state to increase heat dissipation efficiency. While during the non-heating process, the external electric field is removed. The results of measurements are presented in Fig. 8(b). The average device temperature with the thermal smart component in the heating process is about 2.0 °C lower than the condition without the thermal smart component, demonstrating its ability to stabilize the device temperature in varying operating conditions. The thermal smart component can effectively reduce the device temperature during cycling, illustrating the stability and repeatability of



Fig. 8. (a) Device temperature variation as a function of heat dissipation power with different heat flux in the absence of thermal variable resistor. (b) Device temperature in periodic heat flux test.

this energy-saving effect under different operating conditions.

In future studies, the proposed thermal smart component can be applied in thermal control systems considering its advantages demonstrated in this study. A possible application is an auto-regulating thermal control system which combines temperature sensors, a thermal smart component, and a control system (e.g. computer) to respond to environmental changes. The schematic in Fig. 9 illustrates its operating principle. The temperature sensor can transfer the device temperature T_d and environmental temperature T_e to computer. When T_d is higher than critical temperature T_c , the thermal smart component will be turned on and enhance the heat dissipation of the system. When T_d is lower than critical temperature T_c , the thermal smart component will be turned off. This closed-loop feedback design can be a powerful tool in various possible applications.

4. Conclusion

This paper proposes a kind of thermal smart component, which can promote temperature control and energy conservation. Firstly, we propose a kind of thermal smart material based on nanoparticle suspensions, which have continuously tunable thermal conductivities under electric field. The nanoparticle suspensions are composed of base fluid and two-dimensional composite nanosheets, which have high thermal conductivity due to GNS/rGO core and good dielectric property due to inorganic shell. Several types of composite nanosheets are fabricated, including GNS/ LDH, GO/ PANI, rGO/PANI and rGO/SiO₂. With electric field, the suspended nanoparticles align, generate chain-like structures and form effective thermal conductive pathways, leading to the enhancement of thermal conductivity. The variation of the thermal conductivity can be explained by the two-step model. The maximum thermal switching ratio is around 1.45 at E = 500 V/mm. Structural and thermal conductivity reversibility are both observed when the electric field is turned off, and the repeated on/off cycles confirm that the reversibility can be maintained.

Further, we demonstrate a kind of thermal smart component based on the proposed thermal smart materials, which thermal resistance can be tuned continuously via electric field. To demonstrate the performance of the thermal smart component, we design an experimental system to simulate practical devices. The experimental system consists of heat source, system body, and heat dissipation components which include a cooling fan and thermal smart component. The thermal smart component has good temperature regulating ability, and performs better in more challenging environments. It can enable the decrease of device temperature by 5.3 °C at $T_e = 20$ °C, q = 3500 W/m², and E = 600 V/ mm. The performance of the thermal smart component is not significantly affected by environmental temperature, and has good reversible cyclicity. An energy conservation for 10% can be achieved by using thermal smart component. This thermal smart component can work well



Fig. 9. The schematic of thermal control system with thermal smart component.

in practical operation conditions, which provides valuable insights into the design of thermal management for electronic devices, spacecraft systems, and power batteries.

Nomenclature

Abbreviations

rGO	reduced-graphene oxide
GNS	graphene nanosheets
LDH	layered double-hydroxid
GO	graphene oxide
PANI	polyaniline
DC	direct current

- ABS acrylonitrile-butadiene-styrene
- SEM scanning electron microscopy

Symbols

r	thermal switching ratio
k _{cluster}	thermal conductivity of nanoparticle aggregates [W/(mK)]
k _p	thermal conductivity of particles [W/(mK)]
$k_{ m f}$	thermal conductivity of base fluid [W/(mK)]
k_{\parallel}	thermal conductivity parallel to electric field [W/(mK)]
р	aspect ratio of nanoparticle aggregates
L_{ii}	geometrical factor
$\phi_{\rm int}$	volume fraction of the solid particles in aggregates
$\phi_{ m cluster}$	volume fraction of the aggregates in suspension
d	diameter [mm]
h	height [mm]
Р	power [W]
T _d	device temperature [°C]
T _e	environmental temperature [°C]
Ε	electric field strength [V/mm]
q	input heat flux [W/m ²]
T _c	critical temperature [°C]

CRediT authorship contribution statement

Zi-Tong Zhang: Writing – original draft, Visualization, Project administration, Investigation, Conceptualization. **Yu-Xia Dong:** Writing – original draft, Validation, Methodology, Data curation. **Bing-Yang Cao:** Writing – review & editing, Supervision, Resources, Funding acquisition.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124097.

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