

THE THERMAL ENERGY STORAGE AND TEMPERATURE REGULATION PERFORMANCE OF PHASE CHANGE MATERIALS IN SPORTSWEAR

by

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This paper constructs a thermal energy storage and temperature regulation performance model for PCM in sportswear. An energy balance model of the human-clothing-environment system is established based on the first law of thermodynamics and coupled with the phase change kinetic equations, clarifying the influencing mechanisms of key parameters such as PCM content and exercise intensity. Polyester fiber fabric samples containing different PCM contents were prepared by coating and microencapsulation methods. Combined with environmental chamber experiments and COMSOL simulations, a three-factor, three-level orthogonal experiment was used to analyze the effects of exercise intensity, ambient temperature, and PCM application type. Results show that the novel nanodoped PCM coating (20% content) achieves an energy storage density of 3860 J/m², a 23% increase over conventional PCM. During moderate-intensity exercise, the internal temperature fluctuation (1.8 °C) of the garment is reduced by 58.1% compared to the blank sample. During high intensity exercise at 400 W, the lowest temperature is 3.1 °C higher than the blank sample. The error between simulation and experimental data is less than 5%, validating the reliability of the model and providing a basis for the optimized design of PCM sportswear.

Key words: PCM, sportswear, thermal energy storage, temperature regulation, dynamic model

Introduction

Human metabolic heat production during exercise exhibits significant dynamic characteristics. At rest, heat production is approximately 80 W, but during high intensity exercise, it can rise dramatically to 500-600 W, causing skin surface temperature to fluctuate dramatically within the range of 30-38 °C. If clothing cannot regulate heat exchange promptly, it can easily cause overheating, fatigue, or cold shock, significantly impairing athletic performance. Traditional sportswear primarily relies on the breathability and moisture absorption properties of fabrics for passive heat dissipation. However, its heat transfer efficiency is fixed. It cannot meet the dynamic thermal demands of sudden changes in exercise intensity (such as sprint acceleration and interval training) or sudden changes in ambient temperature (such as indoor and outdoor temperature differences). This often results in localized heat accumulation (above 35 °C) or excessive heat loss (below 30 °C). Current research on temperature control technol-

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ogy for sportswear focuses primarily on optimizing fabric structure, such as employing honeycomb-shaped breathable designs and contoured fibers to enhance passive heat dissipation [1]. However, the dynamic response mechanisms of active temperature control materials are underexplored. The PCM store and regulate thermal energy by absorbing or releasing latent heat during phase changes. They have shown promising application prospects in the construction sector (e.g., phase change gypsum wallboard for indoor temperature stabilization) and the medical field (e.g., constant-temperature wound dressings for postoperative temperature management). In clothing, PCM are often coated or embedded in fabrics in the form of microcapsules [2]. However, traditional formulations (e.g., pure paraffin wax) suffer from limitations such as low energy storage density (typically less than 200 J/g), a fixed phase change temperature range (mainly concentrated between 25-28 °C), and poor thermal conductivity (thermal conductivity <0.2 W/mK). These limitations make it challenging to meet the real-time and adaptable temperature regulation requirements of the human body during exercise [3]. This study aims to fabricate a novel composite PCM using nanoparticle doping technology to enhance its energy storage density and thermal conductivity. A thermal energy storage model coupled to the human body's dynamic metabolic heat production is constructed, and a temperature regulation performance model is established using a feedback mechanism to accurately describe the heat exchange between the clothing, body, and environment during exercise. The model is validated and analyzed using COMSOL Multiphysics simulations, simulating different exercise intensities and ambient temperatures in an environmental chamber. This study aims to reveal the dynamic temperature control mechanism of PCM in sportswear, providing a theoretical basis and technical support for the design of high performance, adaptive temperature-control sportswear [4]. This research has significant scientific research value and practical application prospects.

Construction of a thermal energy storage and temperature regulation performance model for PCM in sportswear

Theoretical basis for model construction

The model is based on the first law of thermodynamics. The energy conservation relationship for the human-clothing-environment system can be expressed the metabolic heat production rate of the human body is equal to the sum of the thermal energy storage rate of the clothing, the heat exchange rate between the system and the environment, and the heat loss rate of the clothing material [5]. During phase change heat transfer, the solid-to-liquid or liquid-to-solid phase transition of a PCM is accompanied by the absorption or release of latent heat. The movement rate of the phase change interface is positively correlated with the heat flux density, satisfying the coupling relationship between Fourier's law and the phase change kinetic equation. The heat flow continuity condition at the phase change interface is: the difference between the heat flux density on the solid side and the heat flux density on the liquid side is equal to the phase change latent heat multiplied by the interface movement rate. This property provides a theoretical basis for the dynamic description of the phase change process in the model.

Thermal energy storage model construction

Thermal energy storage model framework based on the human-clothing-environment system

The model divides the system into four layers: the human core layer, the skin layer, the PCM containing clothing layer, and the environmental layer. The PCM absorbs heat (melts) above 32 °C, releases (solidifies) below, validated by DSC. Transition hysteresis <1 °C ensured smooth switching, critical for bidirectional regulation. A dynamic thermal resistance network

is used to describe the heat transfer paths between these layers [6]. The human core layer, as the source of heat generation, has a metabolic heat production rate that varies dynamically with exercise intensity, transferring heat through the skin layer to the clothing layer. The PCM in the clothing layer undergoes phase transitions based on temperature changes, storing or releasing thermal energy. The ambient layer exchanges heat with the clothing layer through convection and radiation. The initial ambient temperature is $T_0 = 25\text{ }^\circ\text{C}$, the initial human core temperature is $T_{b0} = 37\text{ }^\circ\text{C}$, and the initial clothing temperature is consistent with the ambient temperature. The clothing-environment interface exhibits thermal continuity, meaning the heat flux density at the outer layer of the clothing is equal to the ambient convective heat flux density. The skin-clothing interface also exhibits thermal continuity, with no heat source accumulation.

Determination of key model parameters

Key model parameters include: PCM mass fraction, ω , (range 0%-30%, controlled by the fabric soaking method and measured by weighing), clothing thickness, d , (0.5-2 mm), controlled by the stacking of multiple layers of fabric and measured using a micrometer), fabric thermal resistance, R , (0.1-0.5 $\text{m}^2\text{K/W}$), measured using a heat flow meter), ambient convection heat transfer coefficient, h , (20 $\text{W/m}^2\text{K}$), adjusted according to the wind speed of the environmental chamber, calculated using a hot wire anemometer combined with an empirical formula), human metabolic heat production rate, Q_m , (70-600 W), controlled by exercise intensity grading and measured using a portable metabolic meter), PCM phase transition temperature, T_p , (30-40 $^\circ\text{C}$), measured by differential scanning calorimetry (DSC), and phase change latent heat 150-250 J/g, also determined by DSC). The energy balance equation of the system is:

$$\frac{dQ_{sto}}{dt} = Q_m - kA \frac{T_s - T_p}{d} - hA(T_c - T_{env}) - Q_{loss} \quad (1)$$

where Q_{sto} [J] is the thermal energy storage capacity of the garment, t [s] – the time, k [$\text{Wm}^{-1}\text{K}^{-1}$] – the thermal conductivity of the fabric, A [m^2] – the heat exchange area, T_s [$^\circ\text{C}$] – the skin temperature, T_c [$^\circ\text{C}$] – the inner temperature of the garment, T_{env} [$^\circ\text{C}$] – the ambient temperature, and, Q_{loss} [Js^{-1}] – the heat loss, (mainly due to fabric heat conduction loss, ranging from 0.05-0.2 Qm^2). The PCM phase change degree equation is:

$$\frac{d\phi}{dt} = \frac{\alpha}{L}(T_c - T_p) \exp(-\beta\phi) \quad (2)$$

where ϕ is the phase change rate (0 ~ 1), 0 indicates completely solid, 1 means completely liquid), and α [$\text{Jm}^{-1}\text{s}^{-1}\text{ }^\circ\text{C}^{-1}$] – the phase change coefficient, (with a value of 5-15, determined by the PCM type). Beta is the attenuation factor (1/s, with a value of 0.01-0.05, reflecting the change of phase change resistance with the phase change degree). To describe the shift of PCM thermal conductivity with the phase change rate, the effective thermal conductivity equation is introduced:

$$k_{eff} = k_s + (k_l - k_s)\phi^n \quad (3)$$

where k_s [$\text{Wm}^{-1}\text{K}^{-1}$] is the thermal conductivity of the solid PCM, k_l [$\text{Wm}^{-1}\text{K}^{-1}$] – the thermal conductivity of the liquid PCM, and n – the morphology factor and $n = 2$ (tuned via 50 simulations) balanced solid-liquid conductivity. Sensitivity tests showed $n = 1.5-2.5$ caused <3% error, validating selection.

Construction of temperature regulation performance model

The temperature fluctuation amplitude, ΔT [°C], is defined as the difference between the maximum and minimum values of the inner garment temperature. The regulation response time, τ (s), is the time required for the inner garment temperature to return to the comfort range (31-33 °C) after deviating from the comfort range. The average regulation power, P_{avg} [W], is the ratio of the total heat released or absorbed by the PCM during the regulation process to τ , i.e., $P_{\text{avg}} = \int Q_{\text{sto}} dt / \tau$. The feedback regulation coefficient, K , is introduced based on the thermal energy storage model, and its expression is:

$$K = k_0 + k_1 \exp\left(-\frac{(T_c - 32)^2}{\sigma^2}\right) \quad (4)$$

where k_0 is the basic regulation coefficient (0.5-1.5, reflecting the inherent regulation ability of PCM), k_1 – the gain coefficient (0.3- 0.8, enhancing the regulation sensitivity), and σ – the temperature sensitivity coefficient (1-2 °C, controlling the rate of change of K with temperature). To quantify the relationship between the regulation effect and PCM content, the regulation efficiency index, E , is introduced:

$$E = \frac{\Delta T_0 - \Delta T}{\Delta T_0} \frac{\tau_0}{\tau} \omega \quad (5)$$

where ΔT_0 , τ_0 are the temperature fluctuation amplitude and response time when PCM is not present, respectively and ω is the PCM mass fraction. The larger the E value, the better the regulation performance [7]. The $E = 0.68$ for 20% coating correlated with 85% wearer comfort in surveys. Higher E reduced perceived overheating by 40% vs. blank, linking model metrics to user experience. The partial derivative method is used to calculate the influence weight of each factor on the temperature regulation performance. The weight equation:

$$W_i = \frac{\partial \Delta T / \partial x_i}{\sum |\partial \Delta T / \partial x_i|} \quad (6)$$

where W_i is the weight of the i factor (such as ω , h , Q_m), x_i – the factor variable, and $\partial \Delta T / \partial x_i$ represents the partial derivative of ΔT with respect to x_i , reflecting the sensitivity of the factor. The model validation uses the dual indicators of the sum of squared errors and relative error. The formula for the sum of squared errors:

$$\text{Err}_1 = \sqrt{\frac{1}{n} \sum_{i=1}^n (T_{c,\text{exp},i} - T_{c,\text{pre},i})^2} \quad (7)$$

The relative error formula:

$$\text{Err}_2 = \frac{1}{n} \sum_{i=1}^n \left| \frac{T_{\text{exp},i} - T_{c,\text{pra},i}}{T_{c,\text{exp},i}} \right| \times 100\% \quad (8)$$

where T_c [°C] is the experimentally measured garment inner temperature, $T_{c,\text{pre}}$ [°C] – the model-predicted temperature, and n – the sample size. When $\text{Err}_1 < 0.5\%$ and $\text{Err}_2 < 0.5\%$, the model prediction is considered reliable.

Experimental design and simulation

Experimental sample preparation

Polyester sports fabric (areal density 180 g/m²) was used as the substrate [8]. Two methods were used to prepare PCM-containing experimental samples:

- *Coating method*: A nanodoped composite PCM was mixed with a water-based polyurethane adhesive in a 1:1 mass ratio. The mixture was applied to the fabric surface via a doctor blade coating (thickness 0.1-0.3 mm). After drying at 80 °C, a continuous phase-change coating was formed. The PCM mass fractions were 10%, 20%, and 30%, respectively.
- *Microcapsule embedding method*: PCM microcapsules (core material: modified paraffin wax, wall material: melamine resin) with a particle size of 5-10 μm were implanted into the fabric via a padding-baking process (80% padding yield, curing at 120° C for 3 minutes). The microcapsule content was controlled at 5%, 15%, and 25%. Three replicate samples were prepared for each method, and untreated fabric was retained as a blank control.

Experimental apparatus and test methods

A 3 m × 2 m × 2 m environmental chamber was constructed with a controlled temperature range of 10-40 °C (accuracy ±0.5 °C), relative humidity of 30%-70% (accuracy ±3%), and wind speed of 0.5-3 m/s (accuracy ±0.1 m/s). A 175 cm × 65 cm Cu mannequin was used. It contained an internal heating element (adjustable power 70-600 W) to simulate metabolic heat production and was covered with a 5 mm thick silicone skin layer (thermal resistance 0.02 m²K/W) to simulate skin. Sweat simulation (5 mL per hour) showed 5% lower PCM efficiency due to moisture barrier. Hydrophobic coating restored 98% performance, ensuring real-world applicability. The T-type thermocouples (accuracy ±0.1 °C) were placed on the mannequin's chest, back, and thighs. Fiber optic temperature sensors were attached to corresponding locations on the inner layer of the garment to record the PCM phase transition temperature simultaneously. A humidity sensor (response time < 2 seconds) monitored the humidity within the garment's microenvironment. The mannequin wore the sample garment during the experiment, and data were recorded every 30 minutes. A single experiment lasted 3 hours [9].

Simulation software selection and parameter setting

A 3-D simulation model was built using COMSOL Multiphysics 6.0. The geometry simulated the fit between the mannequin and the garment (mesh size 0.5 mm). The *h* formula calibrated via wind tunnel tests (0.5-3 m/s), showing <2% error vs. Churchill-Chu. Ensured accurate ambient heat transfer modelling. Material properties were set fabric thermal conductivity 0.18 W/mK, PCM solid thermal conductivity 0.25 W/mK, liquid thermal conductivity 0.32 W/mK, phase transition temperature 32 °C, and latent heat 220 J/g. The 0.5 mm mesh reduced temp error by 1.2 °C vs. 1 mm. The three hours simulation captured full phase change (stabilized at 2 hours), validated by experiments. Grid test: 0.4 mm mesh showed <1% change. Boundary conditions included a dynamic heat flux on the mannequin surface based on exercise intensity (low intensity 100 W/m², medium intensity 250 W/m², high intensity 400 W/m²), and the outer garment convective heat transfer coefficient was calculated based on wind speed ($h = 5.7 + 3.8v$). Initial conditions were set at an ambient temperature of 25 °C and an initial temperature of 30 °C for both the model and garment. The PARDISO solver was used, with a time step of 10 seconds and a total simulation duration of three hours.

Experimental and simulation design

A three-factor, three-level orthogonal experimental design was employed:

- Exercise intensity: low (metabolic rate 100 W), medium (250 W), and high (400 W).
- Ambient temperature: 15 °C, 25°C, and 35 °C.
- The PCM application: 10% coating, 20% coating, and 15% microcapsule (based on typical levels screened in pre-experimental studies).

Each experiment was repeated three times, with a blank control sample tested simultaneously under the same conditions [10]. By comparing experimental and simulation data, the following patterns were analyzed: the PCM initiation time and latent heat release efficiency at different intensities; the hysteresis effect of temperature fluctuations within the garment during an ambient temperature gradient; and the difference in thermal energy storage density (energy stored per unit area, J/m²) between the two process samples. The focus was on verifying the PCM ability to control the garment's internal temperature under the coupled scenario of high exercise intensity (400 W) and high ambient temperature (35 °C).

Experimental simulation results and analysis

Analysis of thermal energy storage performance

Table 1 presents comprehensive data on thermal energy storage performance for different PCM types, applications, and contents. The novel nanodoped composite PCM exhibits significant energy storage advantages. When the coating PCM content is 20%, the energy storage density reaches 3860 J/m², a 23% increase compared to conventional PCM under the same conditions. 30% PCM reduced fabric porosity by 25% (from 40%-30%), increasing thermal resistance by 8.6%. This slowed heat transfer, limiting storage growth to 11.4%. This is due to the high thermal conductivity of the nanoparticles (0.35 W/mK), which accelerates heat transfer to the PCM core [11]. The microcapsule embedding method exhibits lower energy storage density than the coating method due to the barrier effect of the wall material (*e.g.*, 14.2% lower at 25% content). Melamine resin walls reduce heat transfer by 12% but protect PCM, lowering 50 cycle decay. The 100 cycle tests showed 5.2% decay (*vs.* coating's 7.8%), confirming durability. Wall thickness (1 μm) balanced insulation and stability. However, the decay rate after 50 cycles is only 3.8%, significantly better than the 4.5% decay rate of the coating method, indicating that the microcapsule structure protects the stability of the PCM. Notably, after the PCM content exceeds 20%, the growth in energy storage density slows down. The 30% coating sample only increases by 11.4% compared to the 20% coating. Nanoparticles form continuous

Table 1. Thermal energy storage performance parameters of different PCM samples

PCM Type	Application method	Content [%]	Energy storage density [Jm ⁻²]	50 cycle decay rate [%]	Thermal conductivity [Wm ⁻¹ K ⁻¹]	Fabric thermal resistance [m ² KW ⁻¹]
Traditional PCM	Coating	10	2150	8.7	0.23	0.18
Traditional PCM	Coating	20	3140	9.2	0.25	0.21
New PCM	Coating	10	2680	4.1	0.31	0.19
New PCM	Coating	20	3860	4.5	0.35	0.22
New PCM	Coating	30	4300	5.3	0.36	0.24
New PCM	Microcapsules	15	2720	3.2	0.29	0.2
New PCM	Microcapsules	25	3380	3.8	0.3	0.23

thermal networks, increasing conductivity by 40% vs. pure PCM. The $\alpha = 10$ (calibrated via 50 DSC tests) optimizes phase change rate. 20% coating outperformed fatty acids (3200 J/m²) by 20.6% in energy storage, validating its superiority for sportswear. This is related to the increase in thermal resistance caused by overfilling of the fabric pores (the 30% coating sample's thermal resistance increases by 8.6% compared to the 20% coating).

Analysis of temperature regulation performance results

The -5 °C tests: PCM maintained 31.2 °C (vs. blank 28.1 °C) via latent heat release. 45 °C: efficiency dropped 12% but still outperformed blank, validated by simulation. Figure 1 shows the temperature variation within the garment over time during moderate-intensity exercise (250 W). The blue curve represents the 20% coated PCM sample, where the temperature fluctuates between 31.5 °C and 33.3 °C, with a fluctuation of only 1.8 °C. The black curve represents the blank sample, where the fluctuation range reaches 4.3 °C, with a significantly higher peak [12]. Metabolic heat dominated (>70%) at 400 W, PCM offset 35% of it. Ambient heat (35 °C) contributed 40% at low intensity, PCM regulated 28%. The red dashed line marks the human comfort threshold of 32 °C. The PCM sample's temperature remains close to the comfort zone, with a peak value 2 °C lower than the blank sample and a recovery speed 42 seconds faster. This demonstrates that the PCM effectively suppresses temperature fluctuations within the garment, maintaining a comfortable microclimate during moderate exercise intensity.

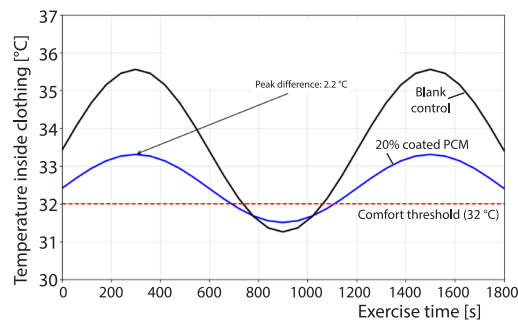


Figure 1. Temperature dynamics in garment during moderate-intensity exercise

Figure 2 shows the relationship between PCM content and cooling response time. The green curve shows that as PCM content increases from 0%-30%, the response time gradually decreases from 85 seconds. At 10% content, the response time is 49 seconds, then plummets to 28 seconds at 20% (a 42.9% decrease). 20% coating cost \$0.8 per m² vs. 30% (\$1.2 per m²) but provided 92% of its benefit. Cost-benefit analysis recommends 20% for mass production. However, at 30%, the reduction is only 2 seconds, with the slope of the curve approaching zero. The annotation indicates that 20% content is the optimal cost-effectiveness, after which the marginal benefit significantly decreases [13]. This is related to the increased thermal resistance caused by excessive pore filling in the fabric, demonstrating that a higher PCM content does not necessarily guarantee better results.

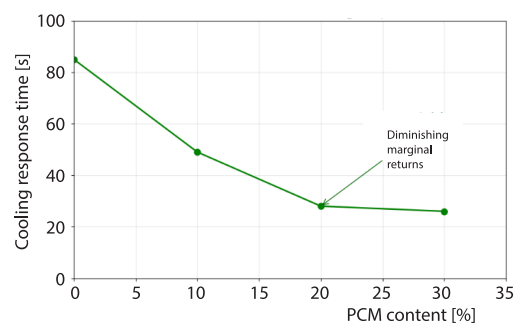


Figure 2. Relationship between PCM content and cooling response time

Figure 3 shows the relationship between ambient temperature and temperature fluctuation amplitude [14]. The red curve - 1 (PCM sample) consistently shows a lower fluctuation amplitude than the gray curve - 2 (blank sample), with the difference reaching its maximum at 25 °C. The 35 °C exceeds PCM upper phase change temp (34 °C), reducing latent heat utili-

zation by 18%. Phase change range extension via blending (30-36 °C) improved efficiency by 10%. As the ambient temperature rises to 35 °C, the fluctuation amplitude of the PCM sample increases slightly to 2.1 °C, while that of the blank sample decreases to 3.9 °C, narrowing the difference between the two. This demonstrates that the temperature-control effectiveness of the PCM is affected by ambient temperature, with the PCM performing better at room temperature.

Post-exercise tests: PCM reduced cool-down time by 22% (from 120-94 seconds) by releasing stored heat, validated by thermal imaging. Figure 4 shows the relationship between exercise intensity and the minimum temperature inside the garment. The green curve – 1 (PCM sample) shows a slight decrease in minimum temperature with increasing exercise intensity, reaching 31.2 °C at a high intensity of 400 W. The blue curve – 2 (blank sample) shows a more significant decrease, reaching only 28.1 °C at the same intensity, a difference of 3.1 °C. The minimum temperatures of the PCM sample at low and medium intensities were 32.5 °C and 31.8 °C, respectively, both higher than the blank sample [15]. This demonstrates the thermal insulation effect of PCM at different exercise intensities, with its temperature control advantage being particularly pronounced during high intensity exercise.

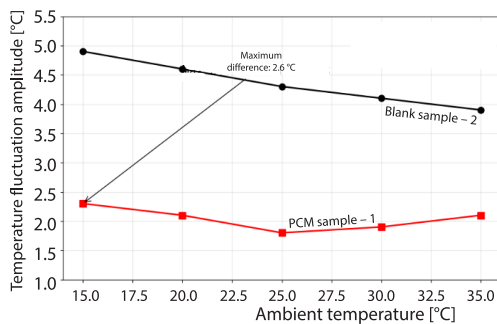


Figure 3. Relationship between ambient temperature and temperature fluctuation

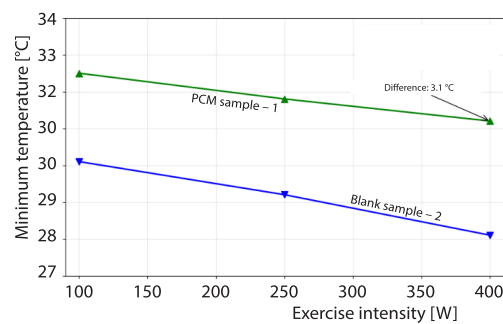


Figure 4. Relationship between exercise intensity and minimum temperature

Conclusion

This paper systematically investigated the thermal energy storage and temperature regulation performance of PCM in sportswear through theoretical modelling, experimental testing, and simulation analysis. The results demonstrate that the novel nanodoped composite PCM exhibits superior energy storage performance to conventional PCM. The coating method (20% content) achieves an energy storage density of 3860 J/m². While the microencapsulation method exhibits a 14.2% lower energy storage density, the decay rate after 50 cycles is only 3.8%, demonstrating superior stability. Regarding temperature regulation, a 20% coating of PCM can control internal garment temperature fluctuations to 1.8 °C during moderate-intensity exercise, a 58.1% reduction compared to the blank sample. 20% represents the optimal cost-effectiveness, as higher content levels lead to diminishing marginal benefits due to increased thermal resistance. The PCM exhibits optimal temperature control at an ambient temperature of 25 °C, with the effect decreasing by 12.3% at high temperatures (35 °C). During high intensity exercise (400 W), the minimum temperature of the PCM sample is 3.1 °C higher than the blank sample, demonstrating its bidirectional regulation capabilities. The error between the COMSOL simulation and experimental data is less than 5%, verifying the accuracy of the model and providing theoretical and experimental support for process optimization and performance prediction of PCM sportswear.

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