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Opinion Article

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Opinions on phase change materials for personal thermal management

Abstract

As the demand for comfort rises, phase change materials (PCMs) offer a transformative solution for personal thermal management by dynamically regulating body temperature through heat absorption and release. Organic PCMs are particularly noted for providing extended thermal comfort in various environments and activities within wearable technology. However, challenges such as low thermal conductivity and leakage during phase transitions hinder their effectiveness. While recent advancements in encapsulation and composites have made progress, developing flexible, high-performance PCMs remains essential. Flexible phase change materials (FPCMs) enhance impact resistance, heat transfer, and comfort. Continued innovations may lead to durable, responsive PCMs that revolutionizing personal thermal management and broadening applications in health, sports, and daily life.

Keywords: phase change materials, phase change fibers, thermophysical properties, thermal comfort, personal thermal management

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Introduction

With the advancement of humanity and technology, there is an increasing emphasis on thermal and physiological comfort, as the human core temperature needs to be maintained within an appropriate range for optimal performance.[1] Conventional thermal management methods, such as passive insulation or simple cooling solutions, often fail to effectively adapt to varying environmental conditions and human activity levels.[2] To overcome these limitations, phase change materials (PCMs) have been introduced into personal thermal management. As an important thermal management medium, PCMs offer a new approach to temperature regulation by absorbing and releasing heat during phase transitions, thus providing dynamic thermal adjustment.[3] The thermal storage capacity of PCM is significantly higher than that of traditional materials, allowing for prolonged stable temperature maintenance.[4] This characteristic is particularly beneficial in wearable technologies where comfort and performance are crucial. Researchers are increasingly exploring the application of organic PCMs, such as paraffin, fatty acids, and polyethylene glycol, in smart textiles and clothing to enhance thermal comfort.[5] A key advantage of PCMs is their ability to operate over a wide temperature range, making them suitable for various climate conditions and activity levels. By integrating PCMs with clothing or bedding, excess heat can be absorbed during physical activity and warmer environments, while heat can be released in cooler settings, effectively regulating body temperature and improving thermal comfort.[6]

This opinion includes the study of PCMs and their applications in the field of personal thermal management.

Advantages and challenges of PCMs

PCMs are essential components in thermal management due to their unique heat storage and release properties, which allow them to regulate body temperature in various environments and ensure comfort. During the phase change process, PCMs can absorb and release significant amounts of heat, maintaining a stable temperature range for a certain period, making them highly suitable for smart textiles and wearable devices (Figure 1).

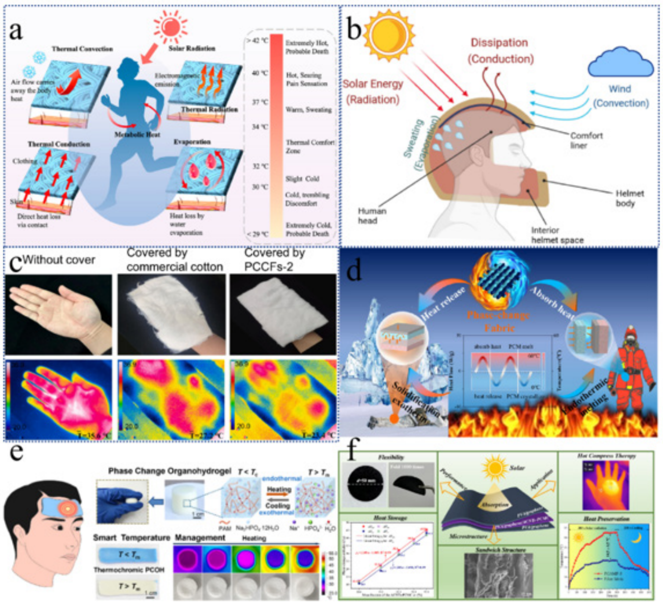

Figure 1 a) Heat transfer pathway between the human body and outer environment as well as adverse physiological responses to variations in core body temperature.[1] b) The components and heat transfer modes of helmet.[7] c) Optical and infrared images of the human palm before and after covering the commercial cotton and PCCFs-2.[8] d) Excellent temperature control effect of PCFS in different temperature atmospheres.[9] e) Phase-change mechanism and antileakage performance of the PCOH.[10] f) The flexibility, structure and solar-to-heat performance of PGAMF.[11]

However, one of the main challenges associated with PCMs is their relatively low thermal conductivity, which limits the rate of heat transfer. This issue can hinder the responsiveness of PCMs in dynamically changing temperature environments. Additionally, to prevent leakage during phase transitions, proper encapsulation of the materials is crucial, presenting another design and manufacturing challenge. Therefore, optimizing the performance and stability of

PCMs is a current research focus, aimed at maximizing their potential in human thermal management applications.

Shape-stable PCMs for personal thermal management

The development of shape-stable PCMs effectively addresses low thermal conductivity and leakage issues faced by conventional PCMs in personal thermal management.[12] By integrating high thermal conductivity fillers, these materials enhance heat transfer, ensuring efficient temperature regulation in rapidly changing environments.[13] Moreover, encapsulation technology prevents leakage during phase changes, improving the stability and durability of the composites while maintaining comfort. Omara et al.[7] embedded PCMs in helmets, allowing the materials to absorb and store heat generated by the wearer's head, thus promoting internal cooling of the helmet. The added nanoparticles further enhance the cooling effect. Xu et al.[8] developed a three-dimensional textile with phase change cotton-like fibers (PCCFs) using direct electrospinning combined with polyethylene glycol. This textile exhibits a fluffy, porous structure, high compressibility, and excellent thermal insulation properties, demonstrating strong elasticity and comfort, making it a promising alternative for thermal insulation in personal temperature regulation.

Flexible PCMs for personal thermal management

However, shape-stable PCMs often exhibit inherent rigidity, making them brittle and resulting in low mechanical strength, which limits their suitability for practical thermal management applications.[14] In contrast, flexible phase change materials (FPCMs) have recently garnered significant attention.[15] By combining phase change functionality with flexibility, FPCMs offer advantages such as easy assembly, strong impact resistance, and low interfacial thermal resistance.[16] This makes FPCMs a promising solution to address the rigidity challenges associated with conventional PCMs.[14] Xiao et al.[9] produced a scalable sheath-core phase change fiber (PCF) with polyurethane and PCM through coaxial wet spinning. The PCF exhibited high encapsulation efficiency (77.77%), significant thermal storage (157.98 J/g), and good mechanical strength. The PCF cotton fabric demonstrated effective thermal insulation with a distinct temperature plateau and heat release. Yin et al.[10] synthesized a phase change organohydrogel (PCOH) using a photoinitiated one-step in situ polymerization method, combining phase change hydrated salts with polyacrylamide. The PCOH showcased a uniform structure, high energy efficiency, stability, and flexibility, enhancing the adaptability of wearable temperature management devices. Zhao et al.[11] prepared a flexible polyvinyl alcohol/grapheme/aminated multi-walled carbon nanotubes modified phase-change microcapsules composite film (PGAMF) using a simple tape-casting method, achieving an enthalpy of 45.5 J/g and a photothermal efficiency of 88.8%. Under low solar radiation, it raised the fabric temperature by 14.5°C, making it ideal in cold environments.

Prospects

The integration of PCMs in personal thermal management systems offers significant advantages for temperature regulation and comfort. The unique thermal properties of PCMs allow for efficient heat absorption and release, which can greatly enhance thermal comfort in wearable applications. However, several challenges related to the performance and stability of PCMs must be addressed. The following issues require further study:

1) The cycling stability and long-term durability of PCMs are critical for personal thermal management, which requires stable performance over frequent phase changes. Many PCMs can experience phase point drift, latent heat degradation, or structural deterioration after repeated cycles, affecting their long-term effectiveness and increasing maintenance costs.
2) The thermal response speed of PCMs is crucial for personal thermal management, especially in rapidly changing environments. FPCMs often need to maintain flexibility, which can limit the use of thermal conductive fillers and result in lower thermal conductivity. This limitation can slow down heat transfer rates, affecting response times and hindering effective temperature regulation, especially in dynamic environments.
3) The compatibility of PCMs with fabrics is another important consideration. The interaction between PCMs and textile materials is critical for successfully integrating them into wearable technology. Further research is needed to assess the compatibility of different PCMs with various types of fabrics, ensuring that they retain their thermal performance without adversely affecting the mechanical properties of the textiles.

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Conflicts of 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.

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