

Phase Changed and Thermoregulatory Yarn: A Review of Material for Next Generation Dynamic Thermal Comfort.

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ABSTRACT

Phase change materials (PCMs) are widely used in thermoregulatory yarns to provide dynamic thermal comfort in modern textiles. these materials absorb and release heat during phase changes, helping to maintain a stable temperature. When incorporated into yarns through methods such as microencapsulation or coating, PCMs enable fabrics to respond to environmental and body temperature variations. Thermoregulatory yarns improve comfort by storing excess heat in warm conditions and releasing it in cold conditions. This review highlights different PCM materials, their integration techniques, and performance in textiles. It also discusses challenges such as durability and leakage, along with future developments for advanced and sustainable thermal-regulating fabrics.

Keywords: Phase change materials; Thermoregulatory yarns; Smart textiles; Thermal energy storage; Dynamic thermal comfort; Functional fibers

INTRODUCTION

Phase change materials (PCMs) have attracted considerable attention as smart functional materials for thermoregulatory textiles due to their capability to absorb, store, and release latent heat during phase transitions. When incorporated into fibers and yarns through methods such as microencapsulation, melt spinning, or coating, PCMs enable textiles to maintain a nearly constant temperature by regulating heat exchange between the human body and the environment. This dynamic thermal regulation overcomes the limitations of conventional fabrics, which rely only on passive insulation. Recent research has focused on enhancing the thermal efficiency, stability, and durability of PCM integrated yarns, making them highly suitable for advanced applications such as smart clothing, protective wear, and performance textiles [1].



Figure 1. Research and development on phase change material integrated cloth: A review[2].

Applications of PCM-Based Thermoregulatory Yarns:

Phase change materials (PCM) integrated into thermoregulatory yarns are widely used in smart clothing to maintain a stable body temperature under changing environmental conditions. These materials absorb excess heat from the human body during high temperatures and release stored heat when the temperature drops, ensuring continuous thermal comfort and reducing thermal stress. This adaptive behavior makes them highly suitable for next generation wearable textiles [3].

Thermoregulatory yarns are extensively applied in sportswear and active wear to improve athletic performance and comfort [Figure 1]. During intense physical activity, PCM absorbs metabolic heat, preventing overheating, while during rest periods it releases heat to maintain warmth. This dynamic thermal management helps reduce fatigue and enhances endurance in athletes [4].

In protective and military textiles, PCM-based yarns act as thermal barriers against extreme environmental conditions. These materials are used in firefighter suits, military uniforms, and industrial protective clothing to delay heat transfer and maintain a stable microclimate near the skin, thus improving safety and performance in harsh conditions [5].

Medical and healthcare textiles also utilize thermoregulatory yarns to maintain optimal temperature conditions for patients. Applications include hospital bedding, patient garments, and temperature sensitive medical textiles where controlled thermal regulation is essential for patient recovery and comfort [6].

I. Types of PCMs in Thermoregulatory Yarns:

Phase change materials (PCM) used in thermoregulatory cloth are classified based on their chemical nature and structure. Each type plays a different role in controlling heat storage and release to maintain thermal comfort.

1. Organic PCM

Organic PCM such as paraffin waxes and fatty acids are commonly used in thermoregulatory cloth due to their high latent heat capacity and stable phase change behavior. They are chemically stable, non-corrosive, and safe for textile use. However, their low thermal conductivity limits fast heat transfer, which is often improved through composite or encapsulation techniques [3].

2. Inorganic PCM

Inorganic PCM mainly include salt hydrates and metallic compounds. They provide higher thermal conductivity and better heat storage efficiency compared to organic PCM. These materials are suitable for rapid thermal response applications, but issues like super cooling, phase separation, and corrosion restrict their direct use in fabrics [7].

3. Micro encapsulated PCM

Microencapsulated PCM consist of a core (PCM material) surrounded by a polymer shell. This structure prevents leakage during melting and solidification, improves durability, and allows easy integration into fibers and fabrics. It is the most widely used form of PCM in thermoregulatory cloth [4].

4. Shape-Stabilized PCM

Shape-stabilized PCM are formed by embedding PCM into a supporting matrix such as polymers or porous materials. This prevents leakage without needing a shell structure and improves mechanical strength. They are increasingly used in advanced smart textiles and functional clothing [8].

II. Working of Phase Change Materials (PCM) in Textiles:

Phase change materials (PCM) used in thermoregulatory yarn operate on the principle of latent heat storage during solid liquid phase transition. When the surrounding temperature increases, PCM absorbs heat and changes from solid to liquid, storing thermal energy without a significant rise in temperature. When the temperature decreases, the PCM solidifies and releases the stored heat back to the environment. When incorporated into textile fibers through microencapsulation, this reversible process creates a self-regulating thermal system that maintains a stable microclimate close to the human skin, improving thermal comfort in clothing applications [9].

III. Recent Development of Phase Change Material Integration into Cloth/Textiles:

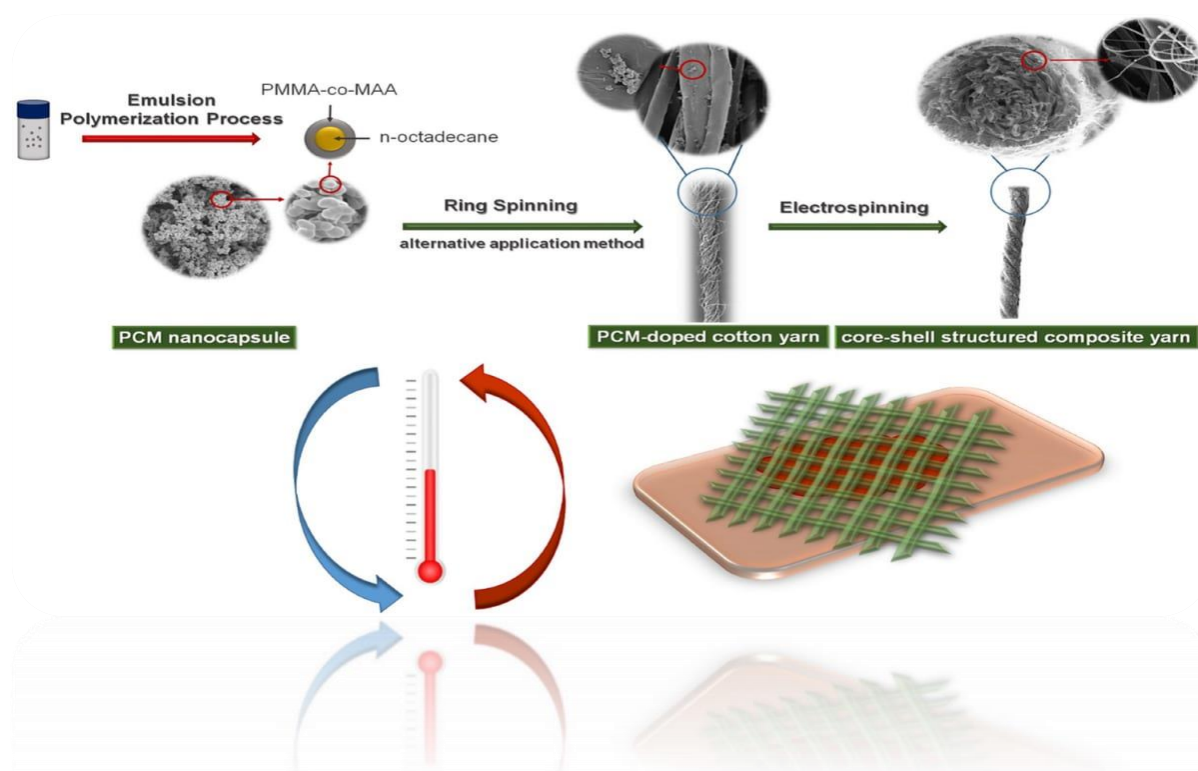


Figure 2. Development of PCM-Loaded Composite Yarns for Enhanced Thermoregulation in Medical Textiles[10].

Recent advancements in phase change materials (PCM) for thermoregulatory yarns focus on the development of microencapsulation techniques to improve durability and thermal efficiency. Microencapsulated PCM can be uniformly incorporated into fibers and yarn structures without leakage during phase transition, enhancing wash resistance and long-term performance in textile applications [Figure 2]. This innovation has significantly improved the commercial viability of PCM-based thermoregulatory fabrics [7].

Another important development is the use of Nano enhanced PCM systems, where nanoparticles are added to improve thermal conductivity and energy storage capacity. These Nano PCM composites allow faster heat absorption and release, resulting in more responsive thermoregulation. Such materials are increasingly being integrated into advanced yarn structures for high performance textiles [11].

Shape-stabilized PCM is also a key innovation in thermoregulatory yarns, where PCM is embedded within polymer matrices to prevent leakage during melting. This approach enhances structural stability and allows direct integration into fibers without the need for encapsulation, making the yarns more durable and suitable for repeated use in garments and home textiles [10].

Additionally, recent research has focused on bio based and sustainable PCM materials derived from natural sources such as fatty acids and plant-based waxes. These eco-friendly PCM systems reduce environmental impact while maintaining effective thermal regulation, aligning with the growing demand for sustainable smart textiles [12].

REVIEW OF LITERATURE

Phase change materials (PCMs) have been widely investigated for thermoregulatory textile applications due to their ability to store and release latent heat during phase transitions. Studies show that PCMs can be classified into organic, inorganic, and eutectic materials, each offering different thermal properties suitable for textile integration. Research has also emphasized encapsulation techniques such as microencapsulation and coating to improve stability and prevent leakage, enabling effective incorporation into fibers and yarns for smart textile applications. [1].

Recent literature highlights advancements in PCM integrated textiles, focusing on improving thermal performance, durability, and comfort. Modern studies report that incorporating PCMs into fibers or fabrics allows textiles to dynamically regulate temperature by absorbing excess heat and releasing it when needed, maintaining a stable microclimate around the human body. Additionally, new developments in composite PCMs and nanotechnology-based integration methods have enhanced thermal efficiency and broadened applications in smart clothing, sportswear, and protective textiles [13].

CONCLUSION

Phase change materials (PCMs) integrated into thermoregulatory yarns represent a significant advancement in the development of next-generation smart textiles aimed at achieving dynamic thermal comfort. By utilizing the latent heat storage and release mechanism, PCM based yarns can effectively regulate temperature and maintain a stable microclimate around the human body under varying environmental conditions. This functionality overcomes the limitations of conventional textiles, which rely solely on passive insulation and lack adaptive thermal control.

Extensive research has demonstrated that different types of PCMs, along with advanced incorporation techniques such as microencapsulation, melt spinning, and coating, have improved the thermal efficiency, durability, and usability of these materials in textile applications. The integration of nanotechnology and composite PCM structures has further enhanced heat storage capacity and mechanical performance, making thermoregulatory yarns suitable for a wide range of applications including sportswear, protective clothing, medical textiles, and smart garments.

Despite these advancements, several challenges remain, including long term durability, phase stability, added weight, cost effectiveness, and environmental sustainability. Future research should focus on developing ecofriendly PCMs, improving encapsulation techniques, and optimizing large scale manufacturing processes to ensure commercial viability. Overall, PCM based thermoregulatory yarns hold great potential in transforming the textile industry by enabling intelligent, responsive, and energy-efficient clothing systems for enhanced human comfort.

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