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Abstract

Efficient thermal regulation is critical in healthcare environments and medical cold chain logistics, where temperature-sensitive operations directly affect patient safety and pharmaceutical efficacy. Phase Change Materials (PCMs) have emerged as advanced thermal energy storage solutions capable of maintaining strict temperature thresholds through latent heat absorption and release. This chapter explores the integration of PCMs into hospital infrastructure and medical cold chain systems, focusing on their thermal performance, encapsulation strategies, and compatibility with healthcare-specific materials. The analysis extends to the thermophysical behavior of PCMs, including supercooling, nucleation, and response to rapid thermal fluctuations common in intensive care and emergency settings. Special attention is given to the selection criteria guided by ASHRAE, WHO, and ISO standards, ensuring compliance with global healthcare regulations. Advancements in PCM technologies are also examined, including their coupling with Internet of Things (IoT) frameworks and Wireless Sensor Networks (WSNs), enabling real-time monitoring and adaptive thermal control. The integration of smart PCM systems facilitates predictive energy management, enhances the resilience of temperature-critical environments, and supports the decarbonization of healthcare facilities. Emerging encapsulation methods and nano-composite formulations further enhance PCM stability and conductivity, promoting reliable long-term deployment, lifecycle considerations such as durability, recyclability, and cost-effectiveness are addressed to align with healthcare sustainability goals. This chapter provides a comprehensive assessment of PCM-enabled thermal solutions, highlighting their transformative potential in achieving operational efficiency, energy resilience, and regulatory compliance in clinical and pharmaceutical applications.

Keywords: Phase Change Materials, Thermal Energy Storage, Cold Chain Logistics, Smart Hospitals, IoT Integration, Healthcare Sustainability

Introduction

Healthcare facilities demand strict and continuous thermal regulation to support patient care, equipment functionality, and the safe storage of temperature-sensitive medical products [1]. From surgical suites and intensive care units to pharmaceutical warehouses and mobile vaccine transport

systems, precise temperature control is indispensable [2]. Conventional HVAC and refrigeration systems often struggle to cope with fluctuating loads, high energy demands, and emergency scenarios [3]. These challenges are particularly evident in areas with unstable power supplies, extreme climates, or limited infrastructure [4]. In response, the adoption of Phase Change Materials (PCMs) has gained momentum as a passive yet efficient method of thermal energy storage. PCMs regulate temperature by absorbing and releasing latent heat during phase transitions, thereby maintaining stable conditions without continuous mechanical intervention [5].

The incorporation of PCMs into hospital walls, ceilings, cold rooms, or packaging units introduces a buffer mechanism that smooths out thermal spikes and dips [6]. This capability is particularly valuable in critical zones where even minor deviations in temperature can compromise patient outcomes or degrade medical supplies [7]. In emergency departments or operating rooms, sudden changes in occupancy, lighting, or equipment use can result in unexpected heat loads [8]. Similarly, cold chain systems that transport vaccines or blood products face unpredictable ambient conditions that can exceed or drop below recommended storage ranges [9]. PCMs address these vulnerabilities by acting as thermal shock absorbers, ensuring environmental consistency during peak loads or power disruptions [10].