Advancements in Phase Change Materials: A Path to Sustainable Energy Solutions in China

Kaiyan Zhang *

School of New energy materials and devices, Soochow University University, Suzhou, China

* Corresponding Author Email: 2124402026@stu.suda.edu.cn

Abstract. With the rapid development of China, the country's demand for energy has significantly increased. According to the "World Energy Outlook 2020," China's annual average growth rate of primary energy consumption is 1.9%, and it is predicted that China's energy consumption will account for over 20% of global energy consumption by 2050. In the energy budget, 90% is allocated to thermal energy conversion, transmission, and storage. Facing an impending energy crisis, enhancing energy production while minimizing energy loss has become a matter of widespread concern. Phase Change Materials (PCMs), also called phase change energy storage materials, have garnered attention as a novel energy-efficient and environmentally friendly material. PCMs refer to substances that undergo a change in state and provide latent heat without changing their temperature. Phase change thermal storage materials utilize phase transitions during heat exchange processes to store energy by means of these phase changes. Compared to chemical energy storage materials, PCMs offer high thermal efficiency and energy storage density, maintain constant temperature, and are more easily controllable. They hold great potential as a promising material in the field of thermal energy storage and have been widely applied in areas such as solar energy, lithium batteries, building insulation, and medical applications. This article offers a comprehensive overview of the principles and classification of Phase Change Material (PCM), including organic PCM, inorganic PCM, and composite PCM. It discusses their applications in solar thermal energy storage, cooling of photovoltaic panels, building materials, and industrial waste heat recovery. The article also highlights China's research and development efforts in these areas, emphasizing the country's significant contributions to advancing PCM technology.

Keywords: Phase Change Materials; Energy Storage; Solar Energy; Photovoltaic Panels; Building Applications; Industrial Waste Heat Recovery.

1. Introduction

With the rapid development of China, the country's demand for energy has been increasing significantly. The "World Energy Outlook 2020" indicates that the annual average growth rate of primary energy consumption is 1.9%, and it is predicted that China's energy consumption will account for over 20% of global energy consumption by 2050.[1] Statistics show that 90% of the energy budget is allocated to thermal energy conversion, transmission, and storage [2]. Faced with the looming energy crisis, enhancing energy production while minimizing energy loss has become a matter of widespread concern. Phase Change Material (PCM), also known as phase change energy storage materials, have garnered attention as a novel energy-efficient and environmentally friendly material. Phase change materials refer to substances that undergo a change in state and provide latent heat without changing their temperature. Phase change thermal storage materials utilize phase transitions during heat exchange processes to store energy by means of these phase changes. Compared to chemical energy storage materials, PCMs offer high thermal efficiency and energy storage density, maintain constant temperature, and are more easily controllable. They hold great potential as a promising material in the field of thermal energy storage and have been widely applied in areas such as solar energy, lithium batteries, building insulation, and medical applications.

The technical background of PCM can be traced back to the late 19th century, when researchers discovered that certain substances undergo phase transitions at specific temperatures. In the first half of the 20th century, the application of phase change materials began to expand into various fields. For example, shape memory alloys, materials that can remember and recover their original shapes, found widespread applications in the medical, aerospace, and mechanical engineering fields. In recent years, driven by the need for carbon neutrality strategies, China has continuously researched PCM, leading to significant advancements in the field.

In conclusion, PCM thermal energy storage technology stands as one of the most extensively utilized and cost-effective solutions for energy storage. It holds significant importance in enhancing overall energy utilization efficiency, harnessing renewable energy sources, and making effective use of waste heat resources.

2. Materials Principles and Classification

2.1. Principles of Phase Change Materials

PCMs can release (or absorb) large amount of thermal energy by changing the state while the temperature is constant. It can store energy through phase change during heat exchange, which is called latent heat of phase transition. These phase transitions can occur between solid-solid, solid-liquid, gas-solid, liquid-liquid, and gas-liquid states. Though there are many types, only solid-liquid and solid-solid transitions hold practical application value. The capacity of PCMs to store and release energy during these phase transitions forms a fundamental characteristic that underpins their diverse array of applications.

2.2. Classification of Phase Change Materials

According to the division of phase change materials, they are generally categorized as: organic PCMs, inorganic PCMs, and composite PCMs.

2.2.1. Organic Phase Change Materials

Organic PCMs exhibit advantages such as high heat storage density per unit mass, chemical stability, good cycling stability, low corrosiveness, and resistance to "supercooling" and "phase separation". The "supercooling" phenomenon refers to the behavior of a substance that does not crystallize at its "condensation point" upon cooling, but instead requires a certain temperature below the "condensation point" to initiate crystallization. This leads to fluctuations in the phase change temperature, affecting its practical performance. On the other hand, the phase separation phenomenon occurs during repeated phase change cycles, where the process can cause the separation of salt and water. Some salts will sink to the bottom of the container after repeated use without combining with the crystal water. This results in a stratified effect, significantly reducing the energy storage capacity and shortening the usable lifecycle of the material [3].

These can be further categorized into two types: organic solid-liquid PCMs and organic solid-solid PCMs. Examples of organic solid-liquid PCMs include paraffin wax, fatty acids, aromatic hydrocarbons, long-chain alkanes, advanced fatty hydrocarbons, and polymeric materials. Organic solid-solid phase change materials primarily absorb and release energy through the orderly-disorderly transition of their internal crystalline structure, with the process being reversible. The main components are polyhydric alcohols, including pentaerythritol (PE), trimethylolpropane (TMP), neopentyl glycol (NPG), triethanolamine (TEM), and tri(hydroxymethyl)aminomethane (TAM) [4].

2.2.2. Inorganic Phase Change Materials

Inorganic PCM exhibits superior thermal conductivity and cost-effectiveness in comparison to their organic counterparts. However, they grapple with challenges such as heightened corrosiveness, toxicity concerns, supercooling tendencies, and the propensity for phase separation. Common inorganic PCMs include crystalline hydrates, molten salts, water, silicon, and metals. Crystalline hydrates (e.g., Na2SO4·4H2O, MgCl2·6H2O, Al (NO3)3·9H2O) are mainstream materials for medium-to-low-temperature thermal storage. The phase change mechanism involves the absorption of heat and release of water when the material is heated, and the absorption of water and release of heat when it cools. Inorganic molten salts, on the other hand, are applied in the medium-to-high-temperature range and offer broad temperature ranges, high latent heat density, ease of control, and low saturated vapor pressure. They have found initial applications in solar power generation and heating.

2.2.3. Composite Phase Change Materials

Composite PCMs use a combination of multiple PCMs to overcome individual material limitations. While phase change thermal storage technology effectively enhances energy utilization efficiency and plays a role in conserving finite resources and developing functional products, it's important to note that there are inherent drawbacks in the utilization of PCMs. Inorganic PCMs, for instance, face the problem of "supercooling" and phase separation issues, while organic PCMs often have low thermal conductivity. These limitations significantly restrict the effectiveness and scope of phase change materials, and can even cause them to lose their energy storage capabilities and shorten their lifespan within their designated temperature range.

To address these challenges, various strategies have been employed. For inorganic phase change materials, modifying agents like thickeners and crystal structure modifiers have been added to counteract supercooling and phase separation phenomena. Additionally, improving the heat transfer properties of organic PCMs has been achieved through the incorporation of thermally conductive metal particles or carbon fibers, aiming to meet the requirements of practical applications. They can be divided into two types: one involves directly mixing two or more phase change materials to create a blend, and the other involves encapsulating phase change materials in structured forms. While mixed materials are simpler to prepare, they may have leakage risks. Structured composite phase change materials, enclosed in capsules or capillaries, are less prone to leakage and offer higher safety. Common examples include nanoencapsulated composite PCMs, fiber-based composite PCMs, and graft copolymer materials.

3. Applications

3.1. Solar Thermal Energy Storage

In contrast to finite and environmentally damaging fossil fuels like coal, clean and sustainable energy sources like solar power have emerged as a new frontier in China's energy development landscape. Solar thermal storage systems are widely utilized in regions with abundant sunlight. They find application in various scenarios such as indoor heating, hot water supply, and meeting thermal demands in social production and daily life settings like greenhouses and agricultural structures. However, there are challenges to overcome in the utilization of solar energy. Solar energy, as a widely distributed renewable energy source in China, has an annual potential of 1.47 × 10^8 GJ [5], equivalent to about 24,000 billion tons of standard coal. Nonetheless, solar energy is characterized by its intermittent nature, leading to temporal and spatial misalignments between energy supply and demand. To tackle these challenges, efficient phase change thermal storage materials can be integrated into solar energy systems. These materials play a crucial role in storing excess heat generated during periods of high solar irradiance and releasing it when energy demand exceeds supply, thus mitigating the temporal and spatial discrepancies between energy availability and consumption.

Utilizing PCMs for solar thermal storage offers a highly beneficial solution. According to Kozelj's research, when only 15% of PCMs are evenly mixed in a thermal storage water tank compared to a thermal storage system without PCMs, significant enhancement of thermal performance, up to 70%, can be achieved [6]. Encapsulated PCMs in thermal storage systems are widely employed in solar thermal storage setups to store sufficient heat for daily use [7].

In solar thermal energy storage systems, the fundamental principle of heat storage revolves around the exchange of energy between the PCMs heat transfer medium and the heat transfer medium. When the need arises to store heat energy, the heat transfer medium within the storage container absorbs solar heat and subsequently transfers this heat to the PCMs. The phase change material absorbs the heat and undergoes a phase transition, typically from solid to liquid. During the melting process of the phase change material, natural convection is initiated, aiding in heat transfer. The rate of heat transfer during this phase transition is influenced by the extent of natural convection and thermal conductivity. Conversely, when heat needs to be released, the process is reversed. The stored thermal energy within the is transferred through a heat exchange process with the heat transfer medium. This exchange effectively converts the thermal energy into usable forms such as hot water or molten salt. Subsequently, these converted materials are supplied to meet the heat energy demands on the user's end.

Solar thermal phase change storage units are commonly employed to address the hot water demands for domestic use. However, these systems often face challenges including low thermal conductivity, substantial losses of phase change materials, and high production complexity. At present, many researchers are actively exploring ways to improve the thermal performance of phase-change storage units. Some approaches include embedding fins within the phase change storage unit, incorporating porous materials, foam, or graphite, optimizing the arrangement of phase change material pipes, redesigning the surface shape of the storage unit, modifying the shape of the heat-carrying fluid pipes, and utilizing encapsulation and packed bed technologies. The mechanisms underlying these methods generally aim to improve the heat storage performance by enhancing the thermal conductivity of the phase change material.

Furthermore, Organic Rankine Cycle (ORC) stands out as a new technology for low-temperature power generation in low temperature, and its primary application lies in harnessing medium-temperature solar energy. This valuable source of low-temperature heat can be derived from diverse origins, including gas turbines and internal combustion engines. Notably, the ORC system can be seamlessly integrated with eco-friendly renewable energy sources, such as solar energy. This becomes particularly significant when considering its implementation in solar ORC systems, which can assume a pivotal role in the context of decentralized power generation, particularly within microgrid configurations. Moreover, it finds relevance in various other applications, including combined heat and power generation for both community and industrial settings [8].

3.2. Cooling of Photovoltaic Panels Using Phase Change Materials

Another application of solar energy is photovoltaic (PV) power generation. PV power generation is clean and pollution-free, but it is characterized by high conversion costs and low efficiency. Most commercial monocrystalline silicon solar cells only achieve an efficiency of 15%-18%. Factors affecting photovoltaic conversion include solar irradiance, photovoltaic cell materials, and the temperature of the photovoltaic cells [9]. Among these factors, temperature has a significant impact on power generation efficiency. The PV-PCM (Photovoltaic-Phase Change Material) cooling system offers a promising solution, characterized by zero energy consumption, low maintenance costs, and no pollution. This method is receiving global attention as an efficient cooling technique. In the PV-PCM system, when the PV panel absorbs heat and its temperature rises, the heat is transferred to the phase change material. At night, the heat energy is released back from the PCM to the PV panel.

In regions with abundant sunlight, photovoltaic (PV) cells often operate at temperatures significantly higher than the surrounding ambient temperature. The heat generated can cause non-cooled PV cells to reach working temperatures within the range of 60-80°C, leading to a substantial drop in their efficiency, typically around 10% [10, 11]. It's important to note that as the operational temperature of crystalline silicon PV cells exceeds the standard testing temperature of 25°C, there's a notable reduction in power generation efficiency, typically in the range of 0.4%-0.65% for every 1°C increase in temperature [12].

As a result, there is a growing emphasis on the research and development of Phase Change Materials (PCMs) that undergo phase transitions around 25°C. The aim is to employ these PCMs strategically to cool PV panels, thus effectively enhancing their overall efficiency. This approach becomes particularly significant in regions where PV panels are subjected to substantial temperature differentials due to prolonged exposure to sunlight.

Savvakis and Tsoutsos conducted a year-long cooling performance experiment in Chania, Greece, using a PV-PCM system with RT27 as the PCM. The final data demonstrated that the working temperature of the PV panel in the PV-PCM system decreased by up to 26.6°C, resulting in an increased total generated electricity of 12.43 kWh [13]. Additionally, Royo et al. reported that effective cooling of PV panels in hot and humid areas can extend their lifespan to 48 years [14]. Recently the Ali team [15,16] has placed significant emphasis on investigating the physical properties of nanocomposite phase change materials. The primary objective of their research has been to improve the thermal conductivity of these materials by strategically introducing nanoparticles. Additionally, they conducted an in-depth investigation into the cooling capabilities of these nanocomposite PCMs when applied to solar photovoltaic (PV) panels. The findings from their research revealed that nanocomposite PCMs, which had been enriched with graphene nanosheets, exhibited notably superior cooling properties. Notably, as the concentration of nanoparticles increased, the cooling effect became more pronounced.

3.3. Building Applications

The share of building energy consumption in the overall energy consumption is on a steady rise, particularly in the context of heating and cooling energy usage, which encompasses air conditioning and contributes to around 50% to 70% of the total energy consumption in buildings. Phase change energy storage technology is urgently needed for energy-saving in buildings. Incorporating PCMs into the construction industry demands specific criteria to be met. These criteria encompass several key factors, including excellent thermal conductivity, a substantial latent heat of phase change, reliable reversibility of the phase change process, non-toxicity, non-corrosiveness, environmental friendliness (non-polluting), a prolonged service life, and an appropriate phase change temperature range.

In recent years, China's research on PCM has expanded and has been applied to phase change energy storage mortar, phase change concrete, phase change coatings, functional phase change wall panels, phase change electric underfloor heating, and phase change roofs. The Central Institute of Building Science and Technology added urea to sodium acetate trihydrate (SAT) to adjust the phase change temperature and introduced expanded graphite to enhance thermal conductivity, resulting in SAT-urea-expanded graphite composite phase change material. During heating experiments conducted within a simulated room, a comparative analysis was performed between two scenarios: one with the installation of the composite phase change material and the other without. The results demonstrated a notable reduction in total electricity consumption within the room equipped with the composite phase change material, with a significant decrease of 12.1% [17]. This reduction in electricity consumption highlights the energy-saving potential and efficiency of utilizing composite phase change materials in heating applications. Huang Zhen et al. [18] integrated PCMs with energy-efficient prefabricated wall panels equipped with fresh air ventilation capabilities. They designed a novel ventilated energy-efficient wall panel containing PCMs and studied the thermal performance of the panel using Computational Fluid Dynamics (CFD) numerical simulations. The outcomes of the study revealed a noteworthy increase in the equivalent thermal resistance of the phase change composite wall panel, with an approximate increment of 1.5 times. This finding suggests that the introduction of phase change materials into the wall panel has a substantial impact on its thermal resistance properties. This panel could absorb around 87.01% of the heat coming from the exterior, effectively reducing the heat flux through the interior wall of the structure.

In recent years, research on energy-saving phase change building materials has been active. However, much of the research remains in the realm of experimental calculations and theoretical simulations. A considerable journey remains before industrialization and large-scale implementation can be achieved.

3.4. PCM for industrial waste heat

Industrial waste heat is primarily categorized into various types, including flue gas waste heat, waste steam from exhaust, waste heat from cooling media, high-temperature product and slag waste heat, thermochemical reaction heat, waste steam, and combustible waste, among others. Industrial waste heat can be categorized based on temperature into three main types: high-temperature, medium-temperature, and low-temperature waste heat. High-temperature waste heat corresponds to heat with temperatures surpassing 500°C, whereas low-temperature waste heat encompasses heat with temperatures below 200°C. Medium-temperature waste heat falls within the range of 200°C to 500°C. The recovery and effective utilization of industrial waste heat present substantial challenges due to variations in working media and disparities in time and location, making it a complex endeavor. Despite the relatively mature technology for recovering high-temperature waste heat after years of research and development, the utilization of medium- and low-temperature waste heat remains insufficient and requires further advancement. However, medium- and low-temperature phase change energy storage materials have been gaining increasing attention due to their advantages of low phase change temperature. In the example of the steel industry, high-, medium-, and low-temperature waste heat account for 39.8%, 25.9%, and 34.2% of the total waste heat, respectively [19]. The research on PCMs is currently advancing rapidly, and storage devices utilizing these materials hold great promise for improving the utilization of low-temperature industrial waste heat.

At present, phase change materials have been applied in various fields for waste heat absorption, such as cement plants, steel mills, engine waste heat, electronic device waste heat, fuel cell waste heat, and industrial flue gas waste heat. Wu Keyi et al. [20] utilized the excellent thermal conductivity of foam metal and the turbulence-inducing capability of spiral tubes to design a spiral tube-type flue gas waste heat recovery device with thermal storage functionality. This design effectively addresses limitations faced in recovering waste heat from offshore oil platforms, such as spatial constraints and intermittent waste heat resources. The pioneering work by Saeed R M et al. [21] led to the development of an innovative heat storage vessel. This vessel is designed as a plate-type heat exchanger unit, with water serving as the working fluid and PCM as the energy storage medium. What sets this system apart is its potential for substantial cost savings across various aspects including infrastructure, equipment, maintenance, and operational expenses, particularly when compared to conventional systems. In a significant research effort, Wilson J et al. [22] undertook the task of recovering waste heat from diesel engine exhaust. They achieved this by employing a shell-and-tube heat exchanger equipped with triangular fin tubes, complete with vortex generators maintained at 20°C. This innovative approach allowed them to efficiently capture both sensible and latent heat energy. The heat was stored using a specially designed storage tank that incorporated phase change material (PCM) and CuO nanoparticles. This novel method demonstrates the potential for harnessing and reusing waste heat effectively in various applications. The primary aim of these research endeavors is to capitalize on the distinctive properties of phase change materials, enhancing the overall efficiency and performance of industrial waste heat recovery systems.

4. Summary

The article discusses the significant role that Phase Change Materials (PCMs) play in addressing China's growing energy demands and sustainability challenges. It begins by highlighting China's rapid development and the projected increase in its energy consumption, emphasizing the need for more efficient energy production and reduced energy loss. PCMs, which undergo phase transitions while maintaining a constant temperature, are introduced as a novel and eco-friendly material that can store and release thermal energy efficiently. The article delves into the principles and classification of PCMs, categorizing them into organic, inorganic, and composite materials. Each category's advantages and limitations are explained, setting the stage for their diverse applications. Several key applications of PCMs are explored in detail. In conclusion, the article underscores the significance of PCMs in China's pursuit of sustainable energy solutions. These versatile materials offer a path to improved energy utilization efficiency, harnessing renewable energy sources, and recovering valuable waste heat. China's ongoing research and development efforts in this field demonstrate its commitment to addressing energy challenges while promoting sustainability.

References

[1] E-SMALL DATA. "BP World Energy Outlook: Peak Coal Consumption Reached in China in 2013, Carbon Emissions Expected to Peak by 2025." New Energy Economic and Trade Observation, 2018(3):13

[2] .GE Z W, LI Y L, LI D C, et al. Thermal energy storage: challenges and the role of particle technology [J]. Particuology,2014, 15(4):2-8.

[3] Dai, Y., & Tang, L. M. (2001). Advances in research on phase change thermal storage materials. Chemical World, 2001(12), 662-666.

[4] Shen, X. Z., & Zhang, R. Y. (2006). Research and application of phase change energy storage materials. Energy Conservation Technology, 24(5), 460-463.

[5] Zhou, N., & Xiong, X. F. (2015). Electric power meteorological technology and application. In Electric Power Meteorological Technology and Application (p. 2015).

[6] Koželj R, Mlakar U, Zavrl E, Stritih U, Stropnik R. An experimental and numerical analysis of an improved thermal storage tank with encapsulated PCM for use in retrofitted buildings for heating [J]. Energy and Buildings, 2021, 248:

[7] Liu L, Li J, Niu J, Wu J-Y. Evaluation of the energy storage performance of PCM nano-emulsion in a small tubular heat exchanger [J]. Case Studies in Thermal Engineering, 2021, 26:

[8] Seto, D.B. et al. (2021) ‘Solar cell cooling with phase change material (PCM) for Enhanced Efficiency: A Review’, IOP Conference Series: Materials Science and Engineering, 1096(1), p. 012052. doi:10.1088/1757-899x/1096/1/012052.

[9] Biwole P, Eclache P, Kuznik F. Improving the Performance of Solar Panels by the Use of Phase-Change Materials; proceedings of the Proceedings of the World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden, F, 2011 [C].

[10] Radziemska E. Performance Analysis of a Photovoltaic-Thermal Integrated System [J]. Int J Photoenergy, 2009, 2009: 1-6.

[11] Huang M. Two Phase Change Material with Different Closed Shape Fins in Building Integrated Photovoltaic System Temperature Regulation; proceedings of the Proceedings of the World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden, F, 2011 [C].

[12] Biwole P, Eclache P, Kuznik F. Improving the Performance of Solar Panels by the Use of Phase-Change Materials; proceedings of the Proceedings of the World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden, F, 2011 [C].

[13] Savvakis N, Tsoutsos T. Theoretical design and experimental evaluation of a PV+PCM system in the mediterranean climate [J]. Energy, 2021, 220: 119690.

[14] Royo P, Ferreira V J, López-Sabirón A M, et al. Hybrid diagnosis to characterise the energy and environmental enhancement of photovoltaic modules using smart materials [J]. Energy, 2016, 101: 174-89.

[15] Jamil F, Ali H M, Nasir M A, et al. Evaluation of photovoltaic panels using different nano phase change material and a concise comparison: An experimental study [J]. Renew Energ, 2021, 169: 1265-79.

[16] Ejaz A, Jamil F, Ali H M. A novel thermal regulation of photovoltaic panels through phase change materials with metallic foam-based system and a concise comparison: An experimental study [J]. Sustainable Energy Technologies and Assessments, 2022, 49: 101726.

[17] [Huang, R., Fang, X. M., Ling, Z. Y., et al. (2020). Preparation of High-Performance Sodium Acetate Trihydrate-Urea-Expanded Graphite Composite Phase Change Material and Its Application Performance in Electric Floor Heating. Chemical Engineering Journal, 71(6), 2713-2723. DOI: 10.11949/0438-1157.20200229.

[18] Hu, Z. P., & Huang, Z. (2019). Thermal Performance Study of Ventilated Wall Panels with Phase Change Materials. New Building Materials, 46(2), 88-91. DOI: 10.3969/j.issn.1001-702X.2019.02.022.

[19] [Cang, D. Q. (2015). New Methods and Technologies for Utilizing Waste Heat in the Steel Industry at Home and Abroad. Hebei Metallurgy, 2015(09), 1-7.

[20] Wu, K. Y. (2020). Simulation of Foam Metal Phase Change Heat Storage Heat Exchanger in Waste Heat Utilization. Journal of China University of Petroleum (Edition of Natural Science), 44(05), 153-15

[21] Saeed R M, Schlegel J P, Sawafta R, et al. Plate type heat exchanger for thermal energy storage and load shifting using phase change material[J]. Energy Conversion and Management, 2019, 181: 120-132.

[22] Wilson J , Singh A, Singh A, et al. Waste heat recovery from diesel engine using custom designed heat exchanger and thermal storage system with nanoenhanced phase change material[J]. Thermal Science, 2016, 21:264-264.