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A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges

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HIGHLIGHTS

- Latent heat thermal energy storage is an attractive technique.
- State-of-the-art review on PCMs and their application under various working temperature range.
- The application of PCMs from negative temperature range to high temperature range.

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ABSTRACT

Latent heat thermal energy storage is an attractive technique as it can provide higher energy storage density than conventional heat energy storage systems and has the capability to store heat of fusion at a constant (or a near constant) temperature corresponding to the phase transition temperature of the phase change material (PCM). This paper provides a state-of-the-art review on phase change materials (PCMs) and their applications for heating, cooling and electricity generation according to their working temperature ranges from (−20 °C to +200 °C). Four working temperature ranges are considered in this review: (1) the low temperature range from (−20 °C to +5 °C) where the PCMs are typically used for domestic and commercial refrigeration; (2) the medium low temperature range from (+5 °C to +40 °C) where the PCMs are typically applied for heating and cooling applications in buildings; (3) the medium temperature range for solar based heating, hot water and electronic applications from (+40 °C to +80 °C); and (4) the high temperature range from (+80 °C to +200 °C) for absorption cooling, waste heat recovery and electricity generation. Different types of phase change materials applied to each temperature range are reviewed and discussed, in terms of the performance, heat transfer enhancement technique, environmental impact and economic analysis. The review shows that, energy saving of up to 12% can be achieved and a reduction of cooling load of up to 80% can be obtained by PCMs in the low to medium–low temperature range. PCM storage for heating applications can improve operation efficiency from 26% to 66%, depending on specific applications. Solar thermal direct steam generation (DSG) is the most common electricity generation application coupled with PCM storage systems in the high temperature range, due to the capability of PCMs to store and deliver energy at a given constant temperature. The recommendations for future research are also presented which provide insights about where the current research is heading and highlights the challenges that remain to be resolved.

1. Introduction

Nowadays, with the rapid growths in world population and economy, the world energy demand and consumption have increased enormously which led to a wide variety of harsh environmental impacts [1]. Higher usage of conventional fossil fuels is the main underlying cause of global warming and immense damage to environment due to the greenhouse and harmful pollutants emitted during their combustion. According to the data from the International Energy Agency (IEA) [2], the primary energy production has increased by 49% over the past 20 years resulting in an increase of carbon dioxide (CO_2) emissions by 43%. Engineers and scientists all over the world are motivated to solve these challenging issues by developing new technologies to decrease the dependence on fossil fuels and improve the energy use efficiency, and simultaneously avert from environmental hazards, expensive power generation and establishing new power generation plants [3].

As a potential solution for energy conservation storing the excess energy to fill the gap between energy supply and demand, using PCMs

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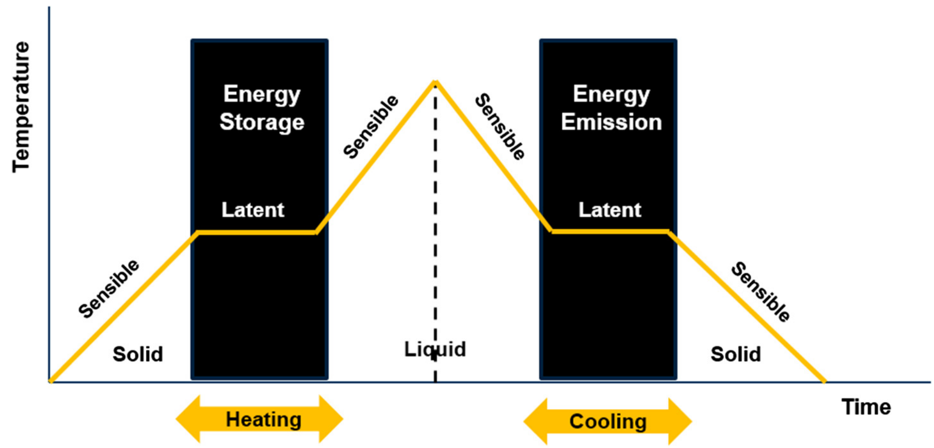

Fig. 1. Schematic diagram of the phase change transition of PCM [15].

has received much attentions. Thermal energy storage with PCM is a promising technology based on the principle of latent heat thermal energy storage (LHTES) [4], where PCM absorbs or releases large amounts of energy at a certain temperature during the phase change transition period (charging and discharging process), with a high heat of fusion around its phase change temperature range [5], as shown in Fig. 1. According to the experimental results of Morrison and Abdel-Khalik [6] and Ghoneim [7], the mass of rock (sensible heat storage) was 7 times larger than paraffin 116 wax (latent heat storage & PCM), 5 times larger than medicinal paraffin (LHS&PCM) and 8 times larger than Sodium Sulfate Decahydrate ($Na_2SO_4 \cdot 10H_2O$, latent heat storage & PCM) to absorb equal amount of thermal energy. Currently, the application of PCM has been widely developed in different fields including, heating and cooling of domestic buildings [8], solar power plants [9], solar drying systems [10], photovoltaic electricity generations [11], refrigerators [12], waste heat recovery [13] and domestic hot water systems [14].

Applications of PCMs within specific temperature ranges have been widely reviewed by many researchers [3,10,16–25]. Kasaeian et al. [23] reviewed the applications of PCMs and nano-PCMs in buildings for cooling, heating and air-conditioning/ventilation at a relatively low temperature ranging from 10 °C to 40 °C. Agyenim et al. [24] conducted a review of theoretical, experimental and numerical studies of PCMs within three temperature ranges that were classified as 0–65 °C for domestic heating and cooling, 80–120 °C for absorption cooling, and over 150 °C for direct steam electricity generation. Oró et al. [25] completed a review of the applications of PCMs at temperatures lower than 20 °C. Liu et al. [26] reviewed PCM energy storage systems for concentrated solar thermal power plants where PCM has a relatively high melting temperature of up to 300 °C. However, no one has reviewed the application of PCMs covering the temperature ranges from the freezing temperature range to the high temperature range, summarised the classifications of PCMs and applications in these different temperature ranges and discussed the performance improvement, environmental impact and cost of PCM applications.

This paper reviews and discusses the application of phase change materials for heating, cooling and electricity generation within the four working temperature ranges, shown in Fig. 2. The low temperature range from −20 °C to 5 °C is for the applications of domestic refrigerators and commercial refrigerated products (Section 2), the medium–low temperature range from 5 °C to 40 °C is for the applications of free cooling, building passive heating and cooling, solar absorption chiller, evaporative and radiative cooling, and air conditioning systems (Section 3), the medium temperature range from 40 °C to 80 °C is for the applications of solar air heaters, solar stills, solar domestic hot water systems, and electric devices (Section 4), and the high temperature range from 80 °C to 200 °C is for the applications of solar absorption cooling, on-site waste heat recovery, off-site waste heat recovery, and solar thermal electricity generation (Section 5). The thermal properties of phase change materials and various thermal performance enhancement techniques employed on phase change thermal storage systems for each of the four temperature ranges are reported and summarised. Moreover, an analysis of the environmental impact and economics of the PCM applications is also carried out. Finally, a summary of the findings and the potential future research needs are presented in Section 6.

2. Applications of PCMs in the low temperature range from −20 °C to 5 °C

This section reviews the applications of phase change materials in the low temperature range from −20 °C to 5 °C, including PCMs integrated into domestic refrigerators for operation performance improvement and integrated into refrigerated products for enhanced thermal protection. Freezers integrated with PCM storage were reported to provide energy saving up to 12% and COP improvement up to 19% [27,28]. Although the cost of a PCM cold storage tank was higher than traditional storage options, the potentials of PCM cold storage were significant in energy savings, CO_2 mitigation, and economical savings [29].

2.1. Domestic refrigerators

PCMs are incorporated into a domestic refrigeration system on the condenser side as heat storage, and on the evaporator side or compartment as cold storage to improve the operation performance. Fig. 3 shows a schematic diagram of PCMs integrated into domestic refrigerators, where PCMs are placed on the evaporator, the freezer internal wall surface and the condenser heat dissipation tubes.

A condenser in a domestic refrigerator is a heat exchanger which is utilised to reject heat of compression to the ambient air and the more heat removed from the condenser, the better refrigeration cycle achieved. Incorporation of PCM into the condenser enhances the heat transfer by the extending of the heat rejection process to the compressor off time, resulting in a lower temperature in the condenser. The shape-stabilized phase change materials (such as PCMs containing with Linear Low Density Polyethylene (LLDPE) [33], epoxy [34], Poly-Hexadecyl Acrylate (PHDA) [35], etc.) are developed to solve the problem of leakage and deformation, where PCMs are contained in thermoplastic elastomer poly to keep the shape in a solid state. The shape stabilized paraffin exhibits the same performance of pure paraffin and up to 80% of its latent heat, but the heat storage performance is still limited by low thermal conductivities [28].

Cheng et al. [27] experimentally studied the performance of Shape