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Morphological characterization and applications of phase change materials in thermal energy storage: A review

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ABSTRACT

Phase change material (PCM), stores and releases heat at a particular required temperature as it undergoes phase change at that temperature. Because of their large latent heat and constant temperature during the phase change process, the PCMs are extensively used in latent thermal energy storage system (LTES) and thermal management system (TM). Due to its virtue of competitive performance, PCM has been used extensively in heat recovery, solar energy, aerospace industry, buildings, textile industry etc. However, the PCM has limitations like low thermal conductivity and low heat transfer rate, which decrease the performance of LTES and TM systems. In this work, ways of improving thermal conductivity and heat transfer rate of the composite PCMs (CPCMs) are summarized from perspective of three kinds of CPCMs' morphologies (fiber, porosity and sphere). This review paper presents morphological characterization of the CPCMs, and several fabrication methods of the CPCMs with enhanced thermal properties.

1. Introduction

Faced with energy shortage and environmental pollution, renewable energy has gained increasing attention, due to its role in energy conservation and environmental protection. Developing new sources of renewable energy and improving the efficiency of energy utilization have become an important issue to the industry. During phase change process, PCMs absorb heat from environment or release heat to environment, so as to achieve the purpose of energy storage and release. Some investigations [1–5] in the past revealed that the PCMs have advantages like simple equipment, small size and flexible phase change temperature. Currently, solid–liquid PCMs are widely used due to their high compactness and small change in volume during phase change. Based on their chemical properties, the PCMs can be divided into organic and inorganic ones. Organic PCMs which include sugar alcohol, paraffin and fatty acid etc, have merits like low corrosiveness, but at the same time have demerits like phase separation is not easily achieved. Water, salt hydrate and molten salt are typical inorganic PCMs, more details about inorganic PCMs can be found in references [4,6–8]. Mixtures of two or more miscible components are called eutectics, which can melt and solidify simultaneously without separation of substances.

Various review articles have been presented in the past decade regarding PCMs, the classification and applications of PCMs were introduced fully in [4,10]. Khudhair and Farid [7] reviewed the encapsulation of PCMs. Naphon and Wongwises [11] described flow and heat transfer characteristics in curved tubes. The usage of PCMs in building fields were summarized in [14,21]. Verma et.al [16] gave mathematical modeling on latent heat thermal systems. Fan and Khodadadi [20] noted ways for improving thermal conductivity of PCMs. Form–stable latent heat storage system were introduced in [23,26]. Rathod and Banerjee [24] focused on the thermal stability of PCMs. Su et al. [28] and Liu et al. [30] paid attention to the latest encapsulation technologies of PCMs. The summary of review articles on PCMs are listed in Table 1.

Up to now, PCMs have been reviewed from above respects. However, little review articles emphasis on the links of thermal properties with the morphologies of PCMs. The objective of this work is to analyze PCMs in three aspects according to their morphologies: fiber, porosity and sphere. The contents of this review article are shown in Fig. 1.

Extensive research has been conducted on applications of the PCMs. In addition to applications in buildings, the PCMs are also widely used in solar energy, industrial heat recovery, liquefied natural gas, electric power peaking regulation, green house agriculture, textiles, health care and aerospace. Rabin et al. [34] summarized the thermal storage of solar energy. Ismail and Henriquez [35] investigated passive thermal energy storage in buildings. Buick et al. [36] presented the use of off–peak rates and reduction of installed power. Moreover, the investigation of spacecraft thermal systems has been carried out by

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Table 1
Summary of review articles on PCMs.

Author	Year	Topic of review article	Reference
Zalba et.al	2003	Classification, heat transfer and applications of PCMs	[5]
Papadopoulos	2003	Solar cooling	[9]
Farid et.al	2004	Classification and applications of PCMs	[10]
Khudhair and Farid	2004	Encapsulation of PCMs	[7]
Naphon and Wongwises	2006	Flow and heat transfer characteristics in curved tubes	[11]
Smyth et.al	2006	Solar water heaters	[12]
Kenisarin and Mahkamov	2007	Solar heating systems	[13]
Tyagi and Buddhi	2007	PCMs in building fields	[14]
Regin et.al	2008	Heat transfer characteristics of thermal systems using PCM capsules	[15]
Verma et.al	2008	Mathematical modeling on latent heat thermal systems	[16]
Sharma et.al	2009	Thermal energy storage systems	[4]
Jegadheeswaran and Pohekar	2009	Performance enhancement in latent heat thermal storage system	[17]
Paul et.al	2010	Measurements of the thermal conductivity of nanofluids	[18]
Kenisarin	2010	High-temperature phase change materials	[19]
Fan and Khodadadi	2011	Thermal conductivity enhancement of PCMs	[20]
Cabeza et.al	2011	PCMs used in buildings	[21]
Liu et.al	2012	thermal performance enhancement techniques for high temperature systems	[22]
Kenisarin and Kenisarina	2012	Form–stable latent heat storage system	[23]
Rathod and Banerjee	2013	Thermal stability of PCMs	[24]
Khodadadi et.al	2013	Introduction of nanostructures and enhancement of thermal conductivity of PCMs	[25]
Fang et.al	2014	Preparation, thermal properties and applications of shape-stabilized composite PCMs	[26]
Yuan et.al	2014	Fatty acids as phase change materials	[27]
Su et.al	2015	Encapsulation technologies of solid–liquid PCMs	[28]
Browne	2015	PCMs for photovoltaic thermal management	[29]
Liu et.al	2016	Preparation, heat transfer and flow properties of microencapsulated PCMs	[30]
Bose and Amirtham	2016	Thermal conductivity enhancement of paraffin wax	[31]
Alva et.al	2017	Thermal energy storage materials and systems for solar energy applications	[32]
Ahmed et.al	2017	Nanomaterials used in solar thermal energy storage	[33]

Mulligan et al. [37].

2. Morphological characterization of the PCMs

There is convincing evidence of a link between morphological characterizations and thermal properties of the PCMs. In some cases, the PCMs differ in shape such as fiber, porosity and sphere [38].

2.1. PCMs with the fibers structure

2.1.1. Nanomaterial PCMs

PCM fibers can be prepared by sol–gel, microencapsulation and electrospinning [39,40]. Electrospinning is a simple and convenient technique to fabricate nanomaterials such as poly fibers embodied with nanoparticles, ceramics and metal fibers.

Babapoor et al. [41] used polyamid 6 (PA6) and some nanoparticles such as SiO_2, Al_2O_3, Fe_2O_3 and ZnO as raw materials and polyethylene glycol (PEG) as PCM to fabricate a novel composites via electrospinning. The PEG has the advantages of high thermal storage capacity and low supercooling. The experiment data showed that the diameter of the fiber lessened as the electrical conductivity of the solution increased. Thompson et al. [42] explained that the diameter of the fiber was affected by various factors, such as experiment temperature, the magnitude of applied voltage, air velocity, the polymer type and surface tension. Morphological images of the composites are shown in Fig. 2. The fibers are distributed randomly in a three–dimensional web. Each fiber looks like a long cylinder with a smooth surface. The diameter of the fiber was reduced as the nanoparticle loading was raised. The minimum diameter occurred in Fe–4 composite, of which the diameter was 59 nm. There were some nanoparticles on the fiber surface in Fig. 2c and d, while most particles were embedded within the fiber. Conclusions were made that Al and Fe fiber composites possessed higher properties, the thermal conductivity of Al–4 composite increased by 41.75% comparing to original PEG. Besides, results proved that the presence of PA6 had a good effect of preventing PEG leakage.

Cai et al. [43] used SiO_2 nanofibers as raw material and a mixture of capric–lauric–palmitic acid as PCM to fabricate a novel composite. SiO_2 nanofibers were prepared under a high temperature annealing procedure to support the CA–LA–PA mixture via electrospinning. The CA–LA–PA mixture was placed at 60 °C until completely melted, then 12 h was required for electro–spun SiO_2 nanofibers immersed into the molten CA–LA–PA mixture, finally the composite was hung in the oven at 60 °C for 10 h. Morphological images of the composites are shown in Fig. 3. Experiments found that SiO_2 nanofibers were capable of

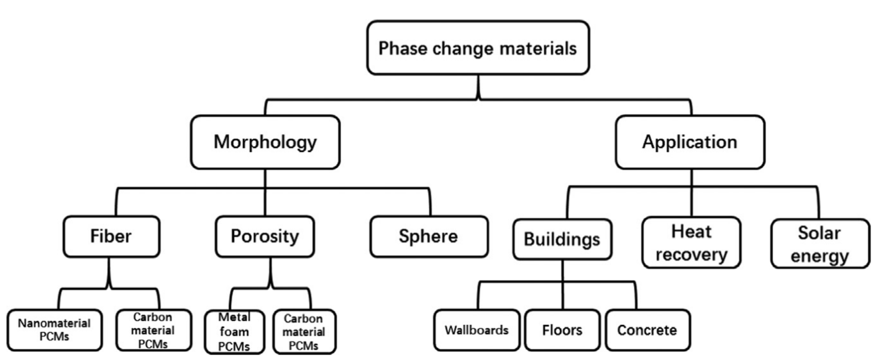

Fig. 1. Flow chart of this work.