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Thermal conductivity enhancement of phase change materials for thermal energy storage: A review

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ABSTRACT

Thermal energy storage systems have been recognized as one of the most efficient ways to enhance the energy efficiency and sustainability, and have received a growing attention in recent years. The use of phase change materials (PCMs) in building applications can not only improve the indoor thermal comfort but also enhance the energy efficiency. The necessity to enhance thermal conductivity of the PCMs is evident due to its low energy charging/discharging rates. Therefore, the high thermal conductivity additives or inserts to enhance thermal conductivity or to form the composite PCM are sought to achieve high energy charging/discharging rates. In this paper, the experimental and theoretical methods to enhance the thermal conductivity of the PCMs are summarized, and the thermal conductivity inserts/additives in recent investigations are listed and summarized. The evaluation of each thermal conductivity enhancement method is discussed.

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1. Introduction

Recently greater energy demand of stable supply of fossil fuels and growing awareness of environmental issues have contributed to a serious attention on various renewable sources of energy. The unpredictability of the endothermic and exothermic process demands the strong, reliable and efficient storage units in the thermal system. Among various forms of energy, thermal energy is widely spread in nature as in solar radiation, geothermal energy and building applications. Thermal energy is the model in the energy field in correcting the gap between supply and demand and improving the performance and reliability of the thermal system.

Because of its abundance, thermal energy is generally categorized as a low-grade form of energy and is associated with waste in industrial processes. Storage of thermal energy can efficiently improve the industrial processes, which significantly decreases the consumption of thermal energy.

1.1. Phase change materials (PCMs) for thermal energy storage

Thermal energy can be stored as latent energy by heating and cooling the material without much visible temperature change. The stored energy can be retrieved when the process is reversed. Phase change materials are widely used to store such thermal energy due to their high latent heat during phase change process. A number of articles [1–5] introduced the PCMs with large phase change temperature range, including their thermophysical behavior, encapsulation, thermostability, heat transfer enhancement and system-related issues. Thermal conductivity enhancement is the point of focus in this review.

1.2. Thermal conductivity enhancement of phase change material

The necessity to enhance thermal conductivity of the PCMs is evident due to its low energy charging/discharging rates. Therefore, the additives to enhance thermal conductivity or to form the composite PCMs are searched to achieve high energy charging/discharging rates. Conventional additives are categorized into carbon type and metal type in terms of the composing element. The heat transport mechanisms involved in phase change systems are drawn attention, and existing studies are mainly performed by thermodynamics and molecular dynamics [6–8]. The efforts are helpful in deciding the employment of the additives and anticipating the effective thermal conductivity of the composite PCM. In addition, different methods to enhance the thermal conductivity by experiment are also presented.

1.3. Scope and coverage of the present review

There are already some reviews focusing on the fixed high-conductivity inserts and free-form, particle-dispersed systems [2,5] presented to enhance the thermal conductivity of PCMs. Metallic fins, foams, wools are considered as conventional stationary inserts and metallic foam and graphite based PCM systems are newly developed methods in the last few years. Lately, the approaches using nanotechnology introduce nanostructures (nanoparticles, nanotubes, nanofibers, etc.) into PCMs, which has shown great extra functionalities and improvements including thermal conductivity enhancement. The large coverage of thermal conductivity graphite based PCMs are not completely summarized in the former review. On the other hand, mathematical modeling for porous structure and models to calculate effective thermal conductivity of nanofluids has been investigated [9,10]. It can be stated that the pertinent parameters influencing the thermal conductivity are concentration, particle size, viscosity, shape, temperature and the material properties, etc.

In this work, the extra information contained is included as follows:

(1) Tables containing the relative thermal conductivity enhancement of different PCMs are listed in detail, giving a clear overview of different categories of conductivity-enhancement technologies. Thus it is easier to compare different methods to enhance thermal conductivity.
(2) Different effective medium models for many featured situations are introduced in order to calculate the effective thermal conductivity of the PCMs with complex nanostructures.
(3) Nano-stucture, porous structure, nanofluids and aligned-molecule structure enhanced PCMs are all included in this work.

Therefore, the objective of the present work is to provide a comprehensive review of the various kinds of enhanced composite PCM including simple mixture, foam, nanofluids, fibrous aggregates composed by the additives and PCM. The models to calculate the thermal conductivity of the nanostructures of the newly developed composite PCMs are elaborate in this work, and the influential factors are discussed as well. By enumerating the thermal conductivity enhancement data of different lately works and making comparison, this work presents a clear overview of different categories of conductivity-enhancement technologies.

2. Theoretical study on thermal conductivity enhancement of phase change materials

2.1. Microstructure of different kinds of additives or its composite

Since the thermal conductivity of most thermal conductivity promoter can be known from the manufacturer, it is not intriguing to obtain the value of thermal conductivity of different types of additives themselves. Thermal conductivity of some common additive materials is summarized in Table 1, from where an overview of the thermalphysical properties of some common additives can be gotten.

On the other hand, some approaches come out to theoretically deduce thermal conductivity of some featured material with aligned structure. Bagchi and Nomura [24] concluded several equivalent continuum models for a multi-walled carbon nanotube (MWCNT) among the past work, as shown in Fig. 1. The MWCNT can be replaced by a solid fiber with the same shape, thus the equivalent conductivity can be calculated from the corresponding equation. Huang et al. [25] conducted the effective thermal conductivity of salt/expanded graphite (EG) composite material by a fractal approach. By use of this approach, the microstructure of the composite is presented, then the ratio of volumes between graphite and the porous EG matrix can be expressed. Moreover, with the help of turning these fractal units into corresponding thermal