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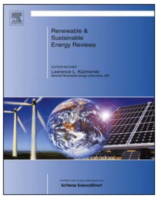

Selection principles and thermophysical properties of high temperature phase change materials for thermal energy storage: A review

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ABSTRACT

Phase change thermal energy storage (TES) is a promising technology due to the large heat capacity of phase change materials (PCM) during the phase change process and their potential thermal energy storage at nearly constant temperature. Although a considerable amount of research has been conducted on medium and low temperature PCMs in recent years, there has been a lack of a similar systematic and integrated study on high temperature PCMs and high temperature thermal energy storage processes. Analyzing the available literature, this review evaluates the selection principles of PCMs and introduces and compares the available popular material selection software options. The thermophysical property data of high temperature PCMs is comprehensively summarized, including high temperature molten salts and metal alloys. Several heat transfer and performance enhancement techniques are summarized and discussed as potential alternative methods to overcome poor thermal conductivity when using high temperature molten salt as the PCM. The common thermophysical property measurement methods used in literature are also summarized and compared. This review gives a broad overview of material selection, innovation and investigation of thermophysical properties for high temperature PCM development, and will be a helpful reference for the design of high temperature phase change TES systems.

1. Introduction

As science and technology rapidly develop and living standards around the world advance, global primary energy consumption has increased dramatically. Excessive exploitation and use of fossil energy has caused serious environmental pollution and ecological damage, and in recent years these issues have attracted the attention of governments and research institutions around the world. Actively promoting and developing renewable energy has certainly become an important means of solving these ecological issues. Concentrated solar power (CSP), which uses a solar collector to produce high temperature and pressure steam that can drive a turbine to generate electric power, is one of the most promising forms of renewable energy. The technology has numerous advantages, such as emitting no pollution or greenhouse gases and possessing huge energy reserves. Many believe that actively developing CSP technology is one of the most effective ways to solve current global energy supply problems.

Exploitation of a cost-effective thermal energy storage (TES) system is a crucial part of CSP technology development. Since there is typically a mismatch between available solar energy supply and electrical energy demand, heat energy storage systems play a very important role in CSP technology. An effective TES unit can improve the thermal management level of a CSP system, and ensure that the system can safely provide a given load even during overcast days and at night. Thus, an efficient TES system is critical for large-scale switching to CSP technology and for improving system efficiency by improving the initial steam parameters [1,2].

High temperature TES systems, which can be used with current CSPs, can be classified into three types: sensible heat storage systems, latent heat storage systems, and thermal chemical storage systems. Sensible heat storage technology stores and releases thermal energy by raising and lowering the material's temperature. Latent heat storage technologies realize thermal energy storage and release through endothermic and exothermic phase change processes of the medium (e.g., solid to liquid or liquid to gas and vice versa). Thermal chemical storage achieves thermal energy storage by relying on completely reversible chemical reactions of the medium, in which the molecular bonds are damaged and reorganized repeatedly while accompanied by endothermic and exothermic processes. To date, only sensible heat storage systems have been used in commercial CSP systems. A typical

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Nomenclature

CES	Cambridge engineering selector
CNF	Carbon nanofiber
CNT	Carbon nanotube
CSP	Concentrated solar power
DSC	Differential scanning calorimeter
DTA	Differential thermal analysis
ENEL	Ente Nazionale per l'Energia eLettrica
GHP	Guarded hot plate
HTF	Heat transfer fluid
LFA	Laser flash analysis
LHS	Latent heat storage
PCM	Phase Change Materials
TES	Thermal energy storage
TG	Thermogravimetry
THS	Transient hot-strip
THW	Transient hot-wire
TPS	Transient plane source
URL	Uniform resource locator

example is the Andasol solar power station in Spain [3,4], which uses a molten salt mixture consisting of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3) as the heat storage medium.

Latent heat storage has many advantages over sensible and chemical thermal storage [3–6]. Latent heat storage can achieve heat storage and release even when there is almost no temperature variation, and its storage capacity per unit volume is 5–14 times higher than sensible heat storage (e.g. when using water, refractory brick or rock). Researchers have studied latent heat storage extensively, since the beginning of the 21st century, and remarkable achievements have been made in this field in terms of material selection, basic performance and application.

Although high-temperature phase change TES has huge potential in CSP systems, it remains an immature technology yet to see commercial application. The main drawbacks of such systems include high investment costs to develop and implement the technology, and non-ideal performance of the energy storage material since most phase change materials have a relatively low thermal conductivity that seriously affects the speed of heat adsorption and release. Therefore, developing phase change materials that possess dramatically improved thermophysical properties and stable performance while being low cost, optimizing heat exchanger design and expanding operations management research are the most likely research topics for advancing TES systems.

Current research indicates that a large number of materials can experience a phase change at a specific temperature simultaneously with heat release or absorption [7–9]. However, if used as a thermal energy storage medium, many other factors must be comprehensively evaluated, including thermophysical properties, corrosion, economical efficiency and so on. In the face of the sheer number of potential phase change materials (more than 160,000 species) and the fact that various factors must be considered simultaneously, determining the most optimal storage material is a complicated and time-consuming process. However, this is a crucial issue that must be solved to effectively exploit phase change TES systems.

In this review, the selection principles for phase change TES materials are evaluated through a related literature summary and analysis, mainly focused on the high temperature PCM which can be widely used in CSP project and whose phase change temperatures are above 300 °C. The research and development status and future trends of the high-temperature molten salts and metal alloys with the most potential are analyzed, and we introduce the digital tools available for phase change TES material selection. This work also summarizes the thermophysical properties of some potential high temperature molten salts and discusses the results from some thermophysical property enhancement studies. The goal of this work is to provide an in-depth discussion of the key problems currently facing the exploitation of high-temperature phase change TES.

2. Selection of high temperature phase change materials

The requirements for a thermal storage system include: high energy storage capacity per unit volume, good heat transfer ability between the heat transfer fluid (HTF) and the storage medium, very high mechanical and chemical stability of the storage materials, good compatibility between the HTF, heat exchanger and/or storage medium (safety), complete reversibility over many charge/discharge cycles (lifetime), low thermal loss, ease of control and operation strategies, maximum load, nominal temperature and specific enthalpy drop in load and rational integration with thermal power plants [6]. In addition, low initial investment and controllable maintenance cost is also very important for thermal energy storage system. The whole system must be considered when selecting prospective heat storage materials.

2.1. Selection principles

The selection of phase change materials for TES systems depends on many factors: material properties, storage capacity of the system, operating temperature, the performance of the HTFs and the design considerations of the heat exchangers [7]. The performance of the selected materials in various aspects will directly affect the heat storage ability and thermal storage/release efficiency. Fig. 1 illustrates the relationship between the performance of the heat storage device and the properties of the heat storage materials. The figure clearly shows that the performance of the heat storage device and the properties of the heat storage materials are intertwined and significantly influence one another. Clearly, a large number of factors must be considered when measuring the overall performance of a heat storage system.

Kemick [8] indicated that any selection of PCMs must comprehensively consider the integrated performance of the materials on the basis of thermodynamics, kinetics, chemistry and economics. Many PCMs

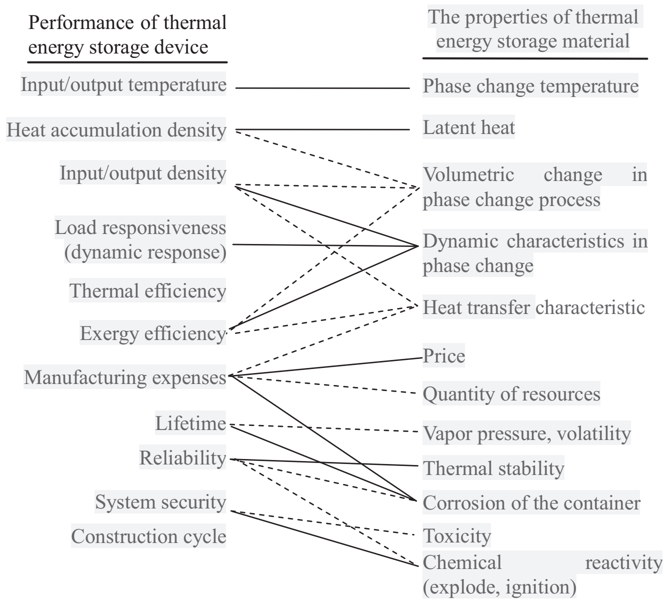

Fig. 1. Relationship between heat storage device performance and the heat storage material properties [5].