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A review on current status and challenges of inorganic phase change materials for thermal energy storage systems

Shamseldin A. Mohamed[a], Fahad A. Al-Sulaiman[a,b,*], Nasiru I. Ibrahim[a], Md. Hasan Zahir[a], Amir Al-Ahmed[a], R. Saidur[a], B.S. Yılbaş[a,b], A.Z. Sahin[a,b]

[a] Center of Research Excellence in Renewable Energy (CoRERE), King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[b] Mechanical Engineering Department, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia

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A B S T R A C T

Latent heat energy storage system is one of the promising solutions for efficient way of storing excess thermal energy during low consumption periods. One of the challenges for latent heat storage systems is the proper selection of the phase change materials (PCMs) for the targeted applications. As compared to organic PCMs, inorganic PCMs have some drawbacks, such as corrosion potential and phase separation; however, there are available techniques to overcome or minimize these drawbacks. On the other hand, inorganic PCMs are found to have higher thermal conductivity and storage capacity over organic PCMs. As a result inorganic PCMs have a great potential in thermal energy storage field, especially in medium to high temperature applications where organic PCMs are not a viable option. In this study, a detailed review of research outcomes and recent technological advancements in the field of inorganic phase change materials is presented while focusing on providing solutions to the associated disadvantages of this class of PCMs. Long term stability, thermal cycling performance, and heat transfer enhancements are also discussed in the context of this review.

1. Introduction

Currently, the problems of energy shortage and environmental pollution resulting from fossil fuel burning are becoming more vital; meanwhile we need to balance between energy supply, environmental protection, and economic development. In such a situation, countries around the world have been searching for renewable energy sources as alternatives, such as solar, wind, hydro, tidal power, geothermal energy etc.

Solar energy is considered one of the promising renewable energy sources in many countries around the world. However, during night the sunlight is not available and thus, there is a strong need for energy storage means to store the solar energy during the day to be used later at night. Energy storage also covers the gap created by the difference between the energy supply and the consumption, beside enhancing the reliability and performance of energy systems [1–3].

Different methods of storing energy are available including: electrical, mechanical, chemical, and thermal energy storage (TES). Thermal heat energy storage is associated with the solar thermal energy. It is divided for non-reactive materials into sensible energy storage (SHS) and latent heat energy storage (LHS) as illustrated in Fig. 1.

Latent heat thermal energy storage (LHS) is considered an effective methods for thermal energy storage. The latent heat storage depends on absorbing or releasing heat from the storage material when it undergoes a phase change process from solid to solid, solid to liquid, liquid to gas or the opposite. When the material is heated until it reaches the temperature corresponding to phase change, it will absorb large amount of energy to carry out the phase change process, which is known as the latent heat of vaporization or latent heat of fusion depending on the phase of the material.

In this work only the transformation from solid to liquid or vice versa is considered, in which the energy absorbed or released is called the latent heat of fusion. This phase transformation is a promising one that can be utilized to store the energy to be used later for several applications. Fig. 2 depicts the latent heat storage mechanism for solid-liquid process.

When the solid storage material is exposed to heat, the temperature starts to rise according to the amount of energy absorbed until the material temperature reaches the phase transformation (melting) temperature, which in turn the storage material will start to melt and transform from the solid phase to the liquid phase. The phase transformation process occurs at a constant temperature and the amount of heat required to carry out the process is known as latent

* Corresponding author at: Mechanical Engineering Department, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia.
E-mail address: fahadas@kfupm.edu.sa (F.A. Al-Sulaiman).

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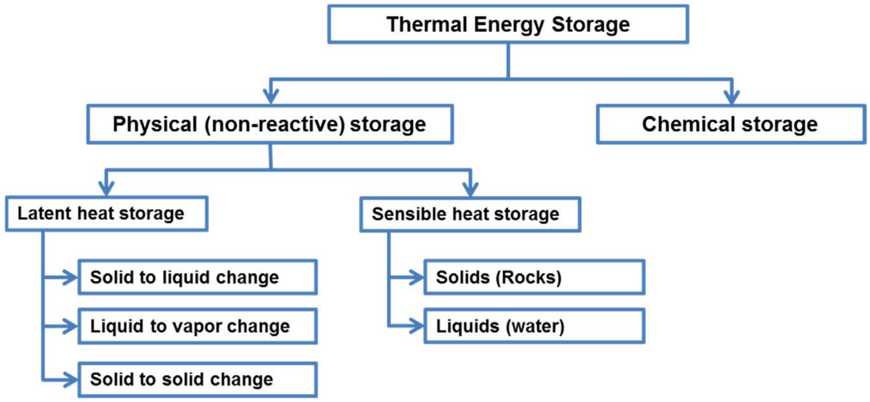

Fig. 1. Thermal energy storage methods.

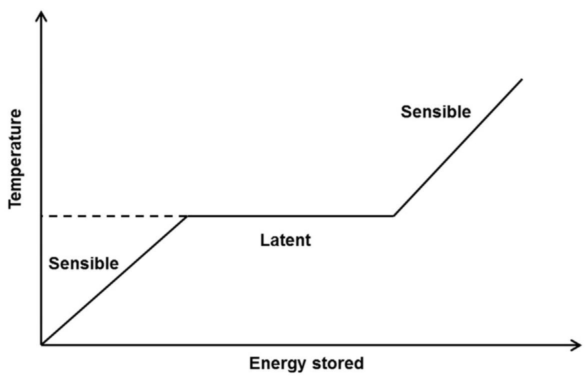

Fig. 2. Latent energy storage for solid-liquid phase change.

heat of fusion. After the completion of the transformation process, the temperature rises again as long as the storage material absorbs more heat [4].

The heat storage capacity of LHS system with PCM medium is given by the following equation:

$$Q= \int_{Ti}^{Tm} mCpdT+ma_m\Delta h_m+ \int_{Tm}^{Tf} mCpdT \tag{1}$$

where m is the mass of the storage material (kg), C_p is the specific heat capacity (kJ/kg K), T is temperature (K), a_m is the melted fraction of the material and Δh_m is the enthalpy of fusion (latent heat of fusion) (kJ/kg). The first part of the equation corresponds to the sensible amount of energy stored by the material as it is heated in the solid state; the second term is for the latent heat absorbed or released during the phase transformation process; while the third part is similar to the first part except the rise in the temperature occurs in the liquid phase in the case of solid to liquid LHS.

Compared with sensible heat storage, LHS has a very large energy storage capacity; thus, it requires relatively a small storage volume, which decreases the amount of the storage material needed and the volume of the storage container. Another advantage is that the thermal energy stored can be recovered at almost constant temperature due to the nature of the phase transformation process [5,6]. In addition, latent heat storage enables to store a large amounts of energy even when the difference in temperature between the source of heat and the heat sink is low as compared with sensible heat storage systems. Due to these advantages, LHS is considered to be an excellent choice for solar thermal energy applications [7].

2. Phase Change Materials

The materials used to store the energy in LHS systems are known as phase change materials (PCMs). For a solid-liquid LHS the PCM initially act similar to sensible heat storage materials, where the PCM temperature increases while it absorbs energy, until it reaches the phase transformation temperature where it absorbs a large amount of heat to carry the transformation from solid to liquid phase [8]. Large number of PCMs are available with varying melting temperatures to suit different applications. In this review, only inorganic class of PCMs will be covered.

2.1. Material selection

The selection of a PCM for LHS application depends on different factors as the PCM material must show desirable properties that are associated with the kinetic, thermodynamic, chemical, and economics of PCM [9,10]. Several researchers proposed different thermal, physical, kinetic, chemical, and economical properties affecting the choice of PCMs for latent heat storage applications [11–14]. The thermal properties involve:

- Suitable phase-transformation temperature;
- High latent heat of transition; and
- High thermal conductivity and heat capacity of both phases.

The phase transition temperature of the PCM must match the operating temperature for a specific application. The latent heat per volume of the material should be high to help minimize the size of the storage containers and the amount of the PCM used, while the higher specific heat and thermal conductivity would provide an additional sensible energy storage and lower charging and dis-charging times, in addition to, the uniform distribution of the temperature across the storage unit [15].

The desired physical properties of PCMs include:

- Favorable phase equilibrium;
- High density;
- Small volume change;
- Low vapor pressure; and
- Congruent melting.

The high density and small volume change during phase transition process is preferable to maintain smaller and simpler design of the storage containers. The contamination problems can be reduced with small vapor pressure PCMs at operating temperatures. The PCMs also must melt congruently in order to prevent irreversible segregation, which leads to the loss of the storage capacity with the cycling.

The desired kinetic properties of PCMs are:

- No supercooling and
- Good crystallization and nucleation rate.