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A Study on Thermal Energy Storage and Phase Change Materials

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Abstract
The storage of thermal energy in the form of sensible and latent heat has become an important aspect of energy management with the emphasis on efficient use and conservation of the waste heat and solar energy in industry and buildings. Latent heat storage is one of the most efficient ways of storing thermal energy. Solar energy is a renewable energy source that can generate electricity, provide hot water, heat and cool a house, and provide lighting for buildings. Paraffin waxes are cheap and have moderate thermal energy storage density but low thermal conductivity and, hence, require a large surface area. Hydrated salts have a larger energy storage density and a higher thermal conductivity. In response to increasing electrical energy costs and the desire for better lad management, thermal storage technology has recently been developed. The storage of thermal energy in the form of sensible and latent heat has become an important aspect of energy management with the emphasis on the efficient use and conservation of the waste heat and solar energy in the industry and buildings. Thermal storage has been characterized as a kind of thermal batter. The focus of this paper is to present the theoretical study of a latent heat thermal energy storage unit that uses phase change material (PCM) as storage medium. Paraffin is used as a PCM and water was used as the heat transfer fluid (HTF). The equations for the HTF and the PCM during the solid and liquid phase were obtained using the logarithmic mean temperature difference method.

Keywords: *Phase Change Material, Latent Heat, Heat Transfer Fluid, Thermal Energy, Solar Energy*

1. Introduction

In recent years, due to the problems of rapid depletion of conventional energy sources which are a finite source of energy, the need to develop new modern methods to provide the means to employ clean sources of energy arose. Thermal energy storage (TES) can take the form of sensible heat storage (SHS) or latent heat storage (LHS). To store the same amount of energy, significantly larger quantities of a storage medium are required for SHS in comparison to LHS. When LHS is used to store solar energy, it can increase the thermal storage efficiency. Phase change materials (PCMs) are materials that store energy in the process of changing the aggregate state from solid to liquid. PCMs are latent heat thermal storage materials. They use chemical bonds to store and release heat. The latent heat thermal energy storage (LHTES) method that is suitable for solar heating and air conditioning has received considerable attention due to its advantages of storing a large amount of energy as a phase transition at a constant temperature. The selection of the heat storage material as a PCM in the LHTES method plays an important role from the points of view of thermal efficiency (Sarı et al., 2004). Solar energy applications require an efficient thermal storage. The latent heat of melting is the large quantity of energy that needs to be absorbed or released when a material changes phase from a solid state to a liquid state or vice versa (Khudhair and Farid, 2004).

Energy can be stored in materials through three main ways: sensible heat, latent heat and thermochemical reactions. In sensible heat storage, the energy is stored by rising of substance temperature. It has been found that inorganic salt hydrates are particularly suitable for use in thermochemical energy storage as they generally undergo a transition from a fully hydrated (or more hydrated) phase to an anhydrous or less hydrated phase at a characteristic transition temperature usually within the range of 10° C to 100° C. Energy storage through the latent heat is based on the large amount of energy that can be stored/released during the phase change process (solid to liquid or liquid to solid) at a nearly constant temperature. The latent heat thermal energy storage using a phase change material (PCM) has the advantages of high-energy storage density, isothermal operating characteristics during melting and solidification processes, low vapour pressure at the operational temperature and chemical stability. In a latent heat storage system, energy is stored during melting and recovered during solidification of a PCM. The use of latent heat of a PCM has gained a lot of attention recently with applications in the area of space craft, recovery and use of waste industrial energy and natural resources, refrigeration and air conditioning systems and heating/cooling of buildings, cooling of electronic devices and clothing industry [2].

2. Phase Change Material Properties

PCMs can be classified as organics, hydrates, molten salts, and metal alloys. For thermal storage, the melting temperature, latent heat, and thermal conductivity of the PCM are important thermophysical parameters. The melting temperature determines the temperature range for which the PCM thermal storage is effective. The latent heat indicates the energy density of the PCM during store or release cycles. The thermal conductivity governs the charge or discharge rate of thermal energy, sometimes labeled as the cooling power.[3] Figure 1 shows the volumetric latent heat and thermal conductivity of different PCMs in the solid phase. Compared with organic PCMs, metal alloy PCMs have higher melting temperature, volumetric latent heat, as well as thermal conductivity. This makes metal alloys more promising for high temperature and high heat flux applications. However, for applications requiring high specific power density, organics and salts with higher specific latent heat are appropriate (Figure 1).The molar latent heat delta H strongly depends on the melting temperature T_m delta S, where the molar entropy change during phase change (delta S) is<4.5R for salts, <3R for semiconductors, and <1.5R for metals where R is the ideal gas constant (8.314 J/(mol $ K)) by the thermodynamic correlation of delta H = T The entropy change is difficult to predict accurately due to contributions from multiple factors such as configurational, volumetric, rotational, mixing and electronic entropic terms associated with the melting process. The entropy change of polymers can be predicted using the Clapeyron equation by deltaS = deltaV/ (dT/dP) near the melting temperature. Several methods have been proposed to predict the entropy change of salt mixtures or metal alloys by taking the summation of individual entropy change components along with the entropy of mixing. However, these prediction methods either require extensive experimental data or suffer from large errors. One of the main challenges to predicting PCM thermophysical properties is the lack of understanding of the relationships between constituent properties and molecular and microstructural compositions. At the molecular or atomic levels, quantum mechanics-based calculations are used to solve for force fields and energy parameters via approximations of the Schrodinger equation using the principles of thermodynamic hypothesis, additivity, and transferability. The quality of the results depends critically on the quality of the approximations use.

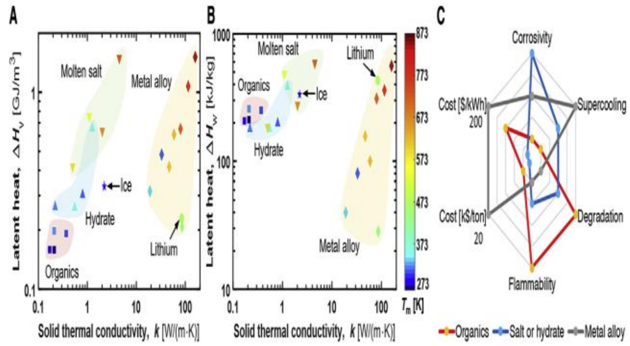

Figure 1. Thermophysical properties of PCMs

3. Thermal Energy Storage

Storage of thermal energy in the form of sensible and latent heat has become an important aspect of energy management with the emphasis on efficient use and conservation of the waste heat and solar energy in industry and buildings. Energy storage of all types plays an important role in energy conservation. In processes that are wasteful of energy, energy storage will result in saving premium fuels. Energy may be stored in many ways, e.g., mechanical energy, kinetic energy, and chemical energy, but because in so much of our economy it is produced and transferred as heat, the potential for storage of thermal energy warrants study in detail. TES deals with the storing of energy by cooling, heating, melting, solidifying, or vaporizing a material; the energy becomes available as heat when the process is reversed. Storage by causing a material to rise or lower in temperature is called SHS; its effectiveness depends on the specific heat of the material and, if volume is important, on the density of the storage material. Passive solar space heating systems commonly use dense materials, such as brick, concrete, and adobe, as thermal storage materials. Heat storage materials absorb heat through standard heat transfer mechanisms, e.g., radiation, conduction, and convection [4].

4. Related Work

Naghavi et. al. [5] made of comprehensive review on analytical investigations on hybrid HP-PCM configurations applied to various thermal systems over the years. Akgun et. al. [6] conducted a study in order to observe the melting and solidification processes of paraffin as a phase change material in a tube in shell heat exchanger system. They concluded that in order to improve the heat transfer during melting and solidification, outer surface of the PCM storage container should be tilted with an inclination of 5%. As a result of this, the melting time was reduced by 30%. Esapour et. al. [7] studied the melting of a phase change material (Paraffin RT 35) in a multi tube heat exchanger (MTHX) for a different number of inner tubes. It was observed that in a multi-tube heat exchanger the time needed for complete melting is considerably large. With the increase of inner tubes, the bottom region of the shell is influenced by the extra effective heat transfer surface, as a result the total melting time decreases up to 29% for the four tube MTHX. Avci and Yazici [8] studied the thermal energy storage system of a horizontal shell and tube storage unit. They reported that melting behaviour differs dramatically for the points located in the upper region than those located in the lower region. The melt region extends radially upward which leads to an asymmetric temperature field. As a result, the points in the upper region reach the melting temperature earlier than those in the lower region. Hosseini et. al. [9] have realized an experimental and numerical study on the thermal behaviour and heat transfer characteristics of Paraffin RT 50 as a phase change material, during the melting and solidification processes inside a shell and tube heat exchanger. They concluded that the rate of heat transfer and the time for the complete melting process are directly related to the inlet water temperature. It is demonstrated that by increasing the inlet HTF temperature, the total melting time decreases. Hosseini et. al. [10] conducted an experimental and numerical study to understand the role of buoyancy-driven convection during constrained melting of PCMs inside a shell and tube heat exchanger. It was observed that the heat transfer from the heat exchanger to the PCM is largely influenced by natural convection at the melting layer section. Seddegh et. al. [11] studied the heat transfer mechanism inside a vertical shell and tube LHTES unit using a pure conduction and a combined conduction-convection model. The results show that natural convection is the dominant mode of heat transfer in the phase change material in the charging process, while the heat transfer in the discharging process is dominated by conduction. Zhao et al. [12] studied the influence of different key design parameters on the performance of a packed bed PCM system for a CSP tower plant. Those authors withdraw interesting conclusions on the effect of the design parameters of the packed bed PCM tank in the costs of the storage plant, such as the dimensions of the storage tank or the needed volume of PCM to shorter operation duration while not increasing too much the capital costs. Caceres et al. [13] calculated the levelized cost of energy when using copper foams in PCM tanks, to reduce the storage volume and increase the thermal conductivity of the storage material. This economic analysis showed that using copper foams in PCM storage systems can reduce the required storage volume by 77%, however the cost of the copper foam significantly increases the total cost of the plant. Also considering the low thermal conductivity of PCM storage systems, Jacob et al. [14] compared environmentally and economically two storage system in CSP plants: a packed be PCM system and a liquid metal-based TES system. In that study, only the capital expenditure (CAPEX) was calculated, finding that the PCM system had a lower CAPEX than previous studies about encapsulated PCM systems that could be found in the literature. Those authors already highlighted that the CAPEX of the PCM system would benefit from further optimization with new concepts such as the cascade PCM systems.

Yesilyurt and Çomakl [15] proposed encapsulated phase change materials (ePCM). The findings of early studies and subsequent research revealed that the use of ePCM slurries (ePCM-Ss) as the working luid in PVT systems increased the thermal efficiency, electrical efficiency, and overall efficiency without a notable increase in pumping power. However, preparation of ePCM-Ss is much more complex in many aspects compared to conventional HTFs, as it involves numerous parameters, including but not limited to the use of various shell and core materials, the variety of production methods, the homogeneity of the resulting capsules, the use of additives, the core to shell ratio, and the mass fraction of ePCM in the slurry. All these require an extensive and exhaustive study with quite a lot of background knowledge and interdisciplinary collaboration, as the proper selection of PCM materials and synthesis methods, as well as the correct concentration in the best CF, involve several aspects and expertise in a number of other fields. These parameters also significantly diversify and differentiate ePCM-S by affecting its suspension stability, rheological properties, and thermal properties. In recent years, PCMs have become an attractive research field for researchers due to their advantages. Although there are quite a number of studies addressing ePCM-S, none provides a holistic approach, and they just deal with a certain aspect of this broad topic. This study, therefore, aims to constitute a fundamental guide to refer to from the very beginning to the final implementation of the ePCM-Ss as the working fluid in PVT systems by addressing all steps, aspects, and almost all effective parameters in terms of advantages, disadvantages, challenges, and opportunities.

King and Miljkovic [2] perspective outlines the needs for better understanding of multi-physics phase change phenomena, engineering PCMs for better overall transport and thermodynamic properties, co-optimizing device design, and integrating PCMs with potential applications. We start by covering the heat transfer fundamentals of PCMs. We then discuss PCM property characterization and need for materials design. We conclude by discussing higher-level device design and integration principles, as well as emerging applications and requirements. We also identify future research opportunities for PCM in thermal energy storage.

5. Application of PCM

As far as solar energy, applications are concerned PCMs play major role in capturing the solar energy. Both solar water heater and solar cooker use the PCMs to store heat energy, which is available only in daytime, as we know that. During late evening and night-time (i.e., absence of solar energy) these systems can be made to operate by means of releasing the heat energy stored in the PCMs [16, 17]. Though solar water heater is more popular in many countries but still it has some issues of less efficiency and low heat storage etc. To overcome these challenges, PCMs are employed. A solar cooker is an environmental friendly and cost effective device for harnessing solar energy. In order to assess the performance of PCM in solar cooking application [18, 19], solar cooker with PCM storage and solar cooker without PCM storage were compared for same quantity of load during summer and winter seasons experimentally [20]. Space heating system integrated with PCM has been developed that store heat energy from ambient air during daytime and release it indoors when it is required. With this arrangement, energy consumption of the buildings can be cut down considerably [21, 22]. Numerical simulation was carried out to determine the thermal performance of composite PCMs in a building for passive solar heating [23]. It was found that both mixed type PCM-gypsum and shape-stabilized PCM plates effectively cut off the indoor temperature swing by 46% and 56%, respectively. Unlike space heating system, space cooling system incorporated with PCM absorbs cool energy from ambient air during the night and releases it indoors during summer [24, 25]. This process is called as free cooling. This arrangement can reduce the energy consumption of the buildings during summer [26]. PCMs with two typical construction materials (conventional and alveolar brick) in real conditions were examined for passive cooling application [27]. Several cubicles were constructed and their thermal performance throughout the time was measured. The cubicles have a domestic heat pump as a cooling system and the energy consumption was observed for ensuring the energy savings. Energy efficient ventilation technique for improving the performance of latent thermal energy storage system in buildings was carried out experimentally [28].

6. Conclusion

In this paper, the theoretical study of a latent heat thermal energy storage unit during the charging process was presented. The phase change material used in this study was paraffin wax with a melting temperature in the range of 58-60ºC. In the solid phase, the outlet temperature of the HTF increases, because the energy that is being transferred from water to paraffin becomes lower over time. In the liquid phase of the paraffin, the outlet temperature of the HTF increases, for the same logic as in the first phase of the process. The heat exchange coefficient has the highest value during the melting phase. This is generated by the high value of the paraffin enthalpy of fusion. The amount of energy stored (Q) in the melting phase, is determined by the value of the latent heat of fusion. A high value for the latent heat, leads to larger amounts of energy that can be stored. The storage of thermal energy in the form of sensible and latent heat has become an important aspect of energy management with the emphasis on efficient use and conservation of the waste heat and solar energy in industry and buildings. Thermal storage has been characterized as a kind of thermal battery.

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