Latent heat energy storage system using phase change materials and techniques for their performance improvement: A Review

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Abstract. Entire world is struggling to explore newer methods to overcome the energy crisis. With limited and exhausting energy resources researchers around the world are finding efficient ways to store thermal energy. One of the efficient ways is to store thermal energy in the form of latent heat energy using phase change materials (PCMs). Latent heat storage (LHS) units have been widely adopted owing to superior energy storage density and constant operating temperature. But the thermal performance of these systems is limited due to low thermal conductivity of the PCMs. Researchers across the globe working on approaches to improve the thermal performance of these systems. The present review paper is concerned with a review on PCMs, methods to improve performance of LHS system using PCMs with special emphasis on use of various additives such as nano particles and porous materials to increase the thermal performance of PCMs and types of PCMs for specific applications. The factual data presented in this paper would be helpful in selection of appropriate PCM for specific application, and to adopt suitable performance enhancement technique to obtain most optimal LHS system.

Key words: Solar energy, Energy storage and recovery, Porous material, PCM-Nano composite, thermo physical properties, Thermal Conductivity

1. Introduction
Owing to ever increasing demand of energy and increasing levels of green house emissions, energy conservation and storage become more imperative. Many researchers are working towards effective harnessing of renewable energy for replenishing the depleting levels of energy. Solar energy is considered an important and abundant source of energy but efficient harnessing is still a challenge. Another way of meeting energy demands is energy storage in various forms in a way that it can be reused. For example storing and reusing different energies such as solar thermal energy, waste heat energy from processing plants, energy from electronic devices. One effective way is thermal energy storage (TES) by use of PCMs. Amongst available TES methods, LHS is most widely adopted methods due to salient benefits such as good energy storage density, excellent repeatability and little
variation of temperature associated with the process. LHS uses PCM as thermal energy storage medium. PCM undergoes phase change from solid to liquid and vice versa, and alternatively absorbs and releases energy.

Successful implementation of LHS is highly dependent on configuration of energy storage device and properties of PCMs such as thermal conductivity, specific volume, heat of fusion etc. Challenges associated with system and PCMs need to be addressed systematically to get high performing LHS systems. Available TES systems, PCMs for specific applications have been exhaustively investigated and reviewed by Sharma et al. [1]. PCMs were classified by Rathod et al. [2] into inorganic, organic and eutectics. Thermal stability of PCMs was reviewed by them and also carried out repeated thermal cycling tests to create holistic database. Experimental investigation of five grades of paraffin wax was conducted by Ukrainczyk et al [3] to determine thermo-physical properties. Thermal properties such as specific heat capacities, melting temperature and latent heat were measured by DSC tests. The issue of density change in liquid and solid phase, corresponding buoyancy effect was also addressed in detail.

PCMs typically are characterized by low thermal conductivity that drastically slows down the rate of charging and discharging. Lot of research work has been undertaken in recent years towards improvement in performance of LHS system by different adopting techniques. A detailed review has been carried by Jegadheeswaran and Pohekar [4] about various performance enhancement techniques reported in literature. A comparative review on PCMs, their characteristics and improvement techniques was done by Y.B. Tao et al. [5]. Certain research gaps were also identified by them. The review had classified enhancement techniques into certain categories and suitable suggestions were made for suitable selection of enhancement technique for particular applications.

2. Phase Change Materials (PCMs) for Energy Storage
PCMs are essential component of LHS as they store latent heat very efficiently. However they should possess certain desirable thermo physical, chemical and kinetic properties to be classified as energy storage materials[6][7]. PCMs can be organic, inorganic and eutectics as shown in Figure1. Organic PCMs can undergo large number of melting and solidification cycles without degradation of thermal properties. Their thermal behavior do not change even after its repeated use. Fatty acids and paraffins fall in this category are mostly used.

![Figure 1: Classification of PCMs](image)

Figure 1 shows broad classification of PCMs. Inorganic PCMs are characterized by good heat of fusion per unit volume and also possess good thermal conductivity compared to organic materials. But they bring adverse corrosive effect on metals that are in contact. Eutectic is a mixture of two or more
elements. They melt and freeze cohesively without separating from each other in the process of crystallization [8].

3. Performance enhancement techniques for LHS systems

PCMs typically possess low thermal conductivity and hence the heat transfer is slow during charging and discharging. LHS systems can be made more efficient by implementing techniques like modifications in geometry and design, enhance thermal conductivity of PCM and optimize process parameters. The performance evaluation of LHS system can be carried on the basis of energy analysis as well as by exergy analysis. Energy analysis is a well developed method that is widely used in thermodynamic analysis of thermal systems including LHS systems. Ezra et al. [9] have undertaken numerical investigation and optimization of multiple PCMs based LHS system. A mathematical model was developed and effect of operating parameters such as temperature and flow rate of HTF, number and arrangement of PCMs was studied. Tao and Carey [10] utilized orthogonal experimental technique to evaluate effect of PCM thermal properties on LHS system. Range and Regression analysis, optimization was carried out that helped them validate the results and establish selection criteria for PCMs for shell and tube LHS unit.

Review on exergy based evaluation of LHS systems was done by Jegadheeswaran et al. [11]. The effect of design and process parameters on exergy accumulated/retrieved and optimization was mainly addressed in the paper. The economics involved with the exergy based evaluation of LHS systems was also presented. Kouksou et al.[12] proposed a conceptual model for investigation and optimization of a PCM based solar system. Attempt was made to understand the system based on energy and exergy analyses. Heat transfer during a phase change process primarily is either conduction controlled or convection controlled or conduction and convection controlled modes. Heat transfer occurs by conduction during solidification and by convection during a melting process. Buoyancy effect also places a significant role during melting process [13].

From detailed literature studies, it has been found that researchers have focused on various geometrical configurations of LHS units, improvement strategies and applications. LHS have been developed using cylindrical, cuboidal and spherical containers. Prominent improvement methods in use are incorporation of fins, more number of tubes, collective PCMs, inclusion of high thermal conductivity particles.

Akgun et al. [14] studied the melting and solidification processes by altering the geometrical configuration. The process parameters considered are HTF flow rates and Stefan number. Thermal properties of PCM was measured using DSC. Kadri et al. [15] analyzed the progress of PCM melt front during the process. Yang et al. [16] worked on shell type LHS experimentally and confirmed that melting time in composite PCM is lesser compared to plain paraffin wax. Figure 2 shows pictorial representations of prevailing heat transfer improvement techniques.

3.1. Enhancement by addition of Nano material

PCM can be added with nano particles with high thermal conductivity to accelerate the charging and discharging process. This helps in improving the performance of the LHS system. Li-Wu Fan et al. [17] have prepared composite PCMs dispersed with graphene nanoplatelets (GNP) upto 3% by weight. Measurement of properties like thermal conductivity, dynamic viscosity and heat of fusion was for composite PCMs. It is observed that 3% loading of GNP increased the thermal conductivity by two times. Effect of temperature boundary conditions was also studied.

Fazel Yavari et al. [18] studied nano structured PCM graphene and 1-octadecanol composite for different fraction of graphene content. There is an increase in thermal conductivity of nano composite by 140% when 4% (by weight) graphene is added. Reduction in latent heat was 15%. Min Li [19] prepared Nano-graphite/paraffin composites to improve heat transfer rate. Microstructure studies were undertaken to study the dispersion pattern of nano material. A review about experimental studies is undertaken by Kibria et al. [20]. Effect of variation in thermophysical properties on thermal
performance is reviewed by them. Additives of carbon based nano materials can increase thermal conductivity of PCM, the homogeneity of dispersion being a significant factor.

![Techniques for heat transfer enhancement adopted in PCM](image)

Figure 2: Techniques for heat transfer enhancement adopted in PCM [13]

Thermal conductivity of various composites made with addition of carbon allotropes like multi-walled carbon nanotubes, graphene etc is studied using transient hot wire method and results interpreted in terms of thermal performance enhancement [21]. Nourani et al. [22] analyzed sodium stearoyl lactylate as surfactant added to PCM. It helps better dispersion of alumina nano particles in paraffin. Thermal behavior of paraffin wax embedded with copper oxide particles was interpreted in terms of melting and solidification profiles. Results indicate that thermal conductivity as well as dynamic viscosity increase with increase in loading fraction of CuO particles. Addition of CuO nano particles augments conduction as well as natural convection [23].

3.2. PCM with Microencapsulation

In this technique, the area exposed to heat transfer in LHS is extended. The PCM is surrounded with thin polymer layer in the form of capsule. This creates a seal tight enclosure and hence restricts the PCM leakage during phase transformation. PCM microcapsule techniques, manufacturing methods, microstructure characterization methods were studied by Xia et. al [24]. In this study, encapsulation of
paraffin as PCM was done using inorganic polymer. Experimental studies on paraffin reveal that performance of PCM depends on encapsulated PCM mass and energy storage during phase change [25].

![Microscopic image of Polystyrene/n-heptadecane microcapsules](image)

Figure 3: Microscopic image of Polystyrene/n-heptadecane microcapsules [26]

High temperature encapsulated NaNO3 as PCM was developed for high temperature applications for solar energy systems. Encapsulation is done with stainless steel. The studies were carried out experimentally and numerically [27] [28].

### 3.3. Use of porous material

Porous material having high thermal conductivity such as metal foams is excellent candidate for PCMs. Some commonly used are Cu foam, Al foam and Ni foam. They are used with organic PCMs such as paraffin wax having low melting point [29][30]. Composite PCM of paraffin wax with aluminium foam is used in Li-ion battery. Aluminium foam has significantly accelerated the melting process and improved the thermal management of battery [31]. Although porous material as additives enhance the thermal performance of PCM, its porosity and pore density have significant effect on performance.

### 3.4. Use of multiple PCMs

Incorporating multi PCMs in LHS ensures uniform heat transfer in the direction of transfer fluid (HTF) flow. Numerical and experimental validation for multi PCM based solar power units suggested that use of multiple PCMs produce better performing results [32]. Performance of such LHS systems greatly depends upon melting temperatures and layout of PCMs. The PCM proportions and their phase change temperatures largely affect the performance of shell and tube type LHS unit [33]. The two solid-liquid boundary movement is tracked and liquid fractions were analyzed for a three stage LHS unit and suggestions were given about the optimum lengths of stages [34].

| PCM1 | PCM2 | PCM3 | PCM4 |
|------|------|------|------|
| HTFin |      |      |      |
| PCM1 | PCM2 | PCM3 | PCM4 |
|      |      |      | HTFout |

Figure 4: Schematic for using multiple PCMs in LHS system
4. Application of PCMs
Model creation and analysis of Shape stabilized PCM was undertaken for solar building. Effect of parameters like melting temperature, layer thickness, latent heat conducting performance of PCM was explored [35]. Analysis of solar heater with and without PCM was done based on type of storage and collector [36]. Thermoelectric cooling was studied using matrix based enthalpy formulation in 3D perspective. Aluminum containers were used as the heat storage unit; Water flows in inner tube and PCM in a porous aluminum matrix is contained in the outer one. The charging and discharging process are analyzed. A direct application of the studied system is vaccine conservation in solar powered thermoelectric cooling systems [37].

5. Conclusion
This review paper presents the overview on PCMs used for energy storage systems, methods to enhance thermal performance of LHS units with special emphasis to improvement in thermal conductivity by use of additive materials. Based on requirement by a particular LHS unit, suitable enhancement techniques can be adopted. Additives accelerate the heat transfer rates their by making the melting and freezing processes faster, in turn improve the efficiency of the LHS systems The additives vary for low and high temperature applications. Carbon nano materials are suitable for low as well as high temperature range.

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