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Thermal Energy Storage Using Phase Change Materials for Solar Heating Applications: A Review

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Abstract— Limited reserves of fossil fuels and various other drawbacks of exhausting energy sources like pollution and harmful environmental impacts has led to growing research interest in development of use of renewable energy sources . Solar thermal energy storage refers to converting solar energy of sun directly into thermal energy and storing it for later use. Phase change materials(PCMs) are used as storage media due to their high latent heat and storage capacity. This review paper deals with thermal energy storage(TES) using phase change materials and its application in various domestic and industrial solar heating applications. Classification and properties of phase change materials are also presented in this article. Recent advancements in use of phase change materials are also given attention in this paper.

Index Terms—Classification of PCM, Thermal energy storage, PCM in Solar heating applications

1 INTRODUCTION

As fossil fuels are non-renewable in nature and their use causes serious threats to environment like global warming, research in utilization of renewable energy sources like wind energy, solar energy etc. has become of utmost importance. Solar energy is present in abundance in nature and can be used for different applications like domestic solar water heating, solar air heating, solar cooking etc.[1] without causimg any harmful effects to environment.

Solar energy is intermittent as it is not available on cloudy days, in night time and on rainy days[2]. Fig1 shows the different methods opted to store energy[4]. Various technologies for energy storage are researched and developed by scientists to bridge the gap created due to intermittency of sources between energy demand and supply [3],[5],[10]. Latent heat storage using phase change materials provides satisfactory results in thermal energy storage applications[7],[9].

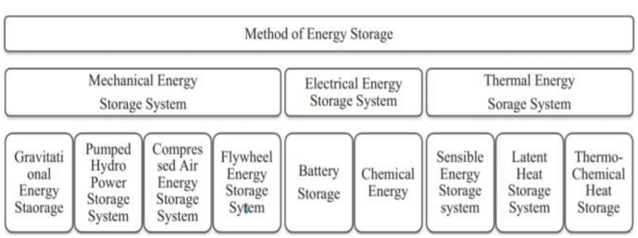

Fig1: Various methods of energy storage[4]

Nomenclature	
m	**Quantity of material**
T_p	**Phase change temperature**
C_s	**Specific heat of solid at constant pressure**
ΔH_f	**Heat of fusion**
C_l	**Specific heat of liquid at constant pressure**
C_p	**Specific heat at constant pressure**
T_1	**Initial temperature of material (°C)**
T_2	**Final temperature of material (°C)**
Q	**Energy stored**

2 THERMAL ENERGY STORAGE SYSTEM

Thermal energy storage is basically classified into three categories: Sensible energy storage, latent heat storage and thermo-chemical heat storage and their further classification is shown in fig2 [4].

Sensible heat storage is the direct way of storing sensible heat and is based on the increase of enthalpy of the material in the store, without any physical state transformation, either in liquid or solid form. The sensible effect is change in temperature and heat stored is given by the equation:

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$$\Delta Q = m \int_{T1}^{T2} c_p(T)\, dT$$

Water is the most commonly used sensible heat storage medium having good thermal characteristics and other SHS materials are sand, rock, concrete, granite, brick etc.

Latent heat storage uses a phase change materials (PCM) to absorb or release heat while undergoing physical transformation keeping temperature constant, solid to liquid phase change being mostly used. Heat absorbed or released during phase change is given by equation:

$$Q = \int_{T1}^{Tp} c_s + \Delta H_f + \int_{Tp}^{T2} c_l$$

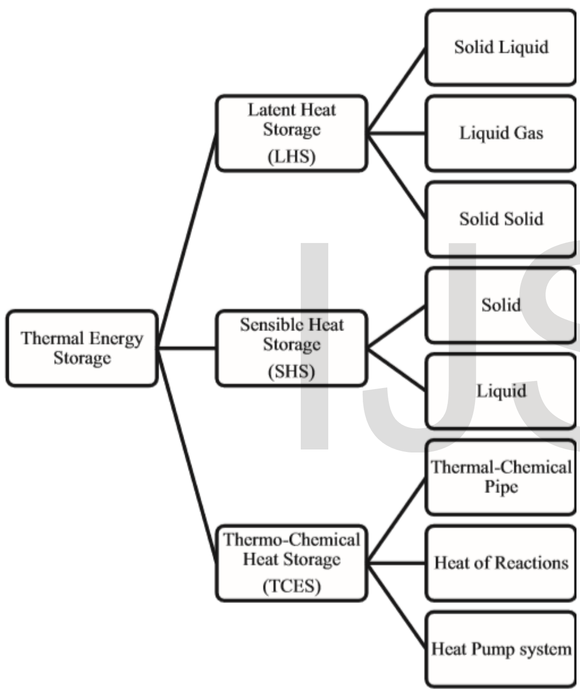

Fig2: Thermal energy storage classification[4]

Latent heat storage using phase change material are preferred over sensible heat storage as they are diverse and they have the capacity to store heat at constant temperature. Fig3 shows comparison between LHS and SHS temperature-heat graph.

Soheila Riahi et al.[7] used both sensible and latent heat storage methods and compared the exergy output, LHS method provided high volumetric energy density and high exergy recovery over SHS. Many researches are being conducted to improve the performance of LHS method[8]. The properties to focus on in sensible heat storage materials are specific heat, volume and change in temperature of materials while in latent heat storage materials thermophysical, kinetic and chemical properties are of critical importance. Properties important in LHS are shown in table1 [4], [6].

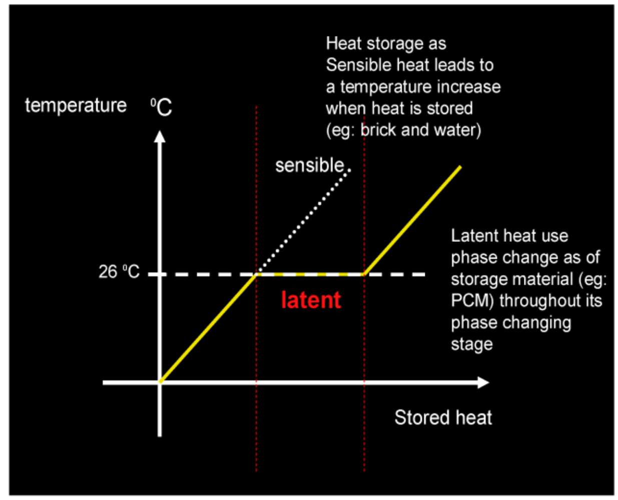

Fig3: Temperature-heat graph for LHS and SHS

Thermal properties	1. Suitable phase transition te 2. High latent heat of transiti 3. Good heat transfer
Physical properties	1. Favourable phase equilibrium 2. High density 3. Small volume 4. change low vapor pressure
Kinetic properties	1. no supercooling 4. optimum crystallization rate
Chemical properties	1. good chemical stability 2. compatibility with materials 3. no toxicity, non-explosive 4. no fire hazard, non-flammabl 2. non-corrosive material
Economics	1. abundant 2. commercially available 3. cost-effective 5. wide range application

Table1: Properties of LHS material

3 CLASSIFICATION OF PHASE CHANGE MATERIAL(PCM)

Phase change materials(solid-liquid phase change) are broadly classified into three main categories : organic compounds, inorganic compounds and eutectics. Further classification of these are shown in fig4.

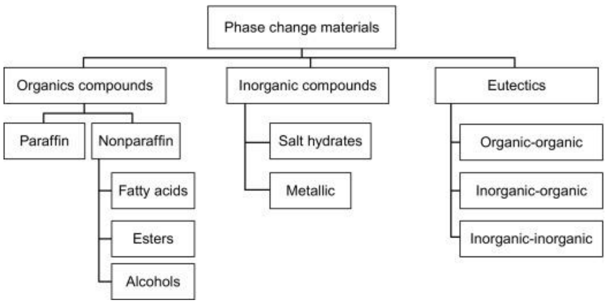

Fig4: Classification of PCM

Organic phase change materials have good nucleation property, good chemical stability and are non-corrosive in nature[11] but their thermal conductivity is low. In order to improve their performance, they are merged with other materials, resulting in enhanced properties and storage capacity[12], [13], [14]. They are further classified into paraffins and non-paraffins(fatty acid, esters, alcohols).

Inorganic phase change materials include salt, salt hydrates and metal alloys which have high thermal conductivity, high latent heat of fusion but they suffer from phase separation and supercooling which is undesirable [15]. By addition of additives like nanoparticles phase change rate can be increased [16] and storage properties can be enhanced. Metal alloys have good corrosion resistance property [17], high thermal conductivity and thermal stability[18].

However, organic phase change materials have advantages like corrosion resistance, thermally stable over inorganic PCMs which lack in thermal stability and phase separation occurs. But inorganic materials have greater phase change enthalpy and high energy storage capacity against organic PCMs [12].

Eutectic pcm are formed by combining organic and inorganic materials with themselves and with each other. A. Karthick et al.[19], investigated a eutectic mixture of pcm and the usage of pcm improved output power. Eutectic phase change materials are advantageous over organic and inorganic materials as different components are combined which reduces the possibility of phase separation and properties like thermal conductivity and reliability are good [3], [20], [21].

4 PCM IN SOLAR HEATING APPLICATION

Solar energy is stored in phase change materials and is discharged whenever needed. The main goal of using LHS materials is to provide continuous supply of energy for 24 hrs.Phase change materials are widely used in solar heating applications in different areas like solar water heating, solar cooking, solar heating of buildings, solar greenhouse etc. Some of the applications are discussed here.

4.1 Solar water heating

Solar water heating(SWH) is commonly used for domestic and industrial applications. Ziye Ling et al.[22] used Mannitol as PCM for obtaining hot water and concluded that TES performance are affected by temperature of heat transfer fluid(HTF) and inlet flow rate of HTF. They also found that with PCM the temperature rises from 30℃ to 50℃ within 6 hrs. A. Jamar et al.[23] in their paper discusses the various types of collectors used in SWH and concluded that the best overall performance is given by parabolic dish reflector collectors. Mouna Hamed et al.[24] in their paper evaluated energy and exergy of collector integrated with LHS material. They found that the melting time was shorter than solidification time and exergy efficiency decreased during night. Ruixiaoxiao Zhang et al.[25] in their paper studied the importance of economic feasibility of using SWH systems. Economic feasibility is as important as technical feasibility and they found 7 positive and 9 negative effects that affect the payback period of SWH system. AbdellahShafieian et al.[26] conducted study to analyze the performance of SWH system in cold season under real conditions. They found that pattern of hot water consumption plays a significant role in designing optimum SWH system and its extraction has a positive effect on thermal efficiency of system. They also found that at the beginning of the day highest exergy destruction takes place. Jyoti Prakash et al.[27] studied real time performance of paraffin wax, puretemp68 and stearic acid/palmitic acid eutectic mixture. They found that charging efficiency of water from stearic acid/ palmitic acid is higher(55%), from paraffin wax was 20% and from puretemp68 gave 45% charging efficiency. Stearic acid/palmitic acid showed better performance during discharging process without supercooling unlike paraffin wax.

4.2 Solar heating of buildings

Various researches are conducted to optimize the heating energy consumption and to provide human comfort [28]. Lidia Navarro et al.[29] in their paper experimented on an active slab with PCM coupled with solar air collector in order to melt the PCM, to provide heating supply. Results found significant decrease in energy consumption. Mohammad Saffari et al.[30] in their paper studied the performance of residential buildings in various climatic conditions and found that if PCM properly selected for various climatic conditions yields higher annual energy savings. Thermal behavior of vertical enclosure using PCM was studied and the temperature inside the test cell was found to be 28℃ [31]. The results also showed that by reducing thermal fluctuations and increasing thermal inertia of walls, thermal comfort can be improved. A double layered PCM system was designed to improve indoor thermal conditions in different climatic conditions [32]. It was found that energy consumption reduced by 17.5% and10.4% in dry and semi-arid climate, respectively. Xiangfei Kong et al.[33] investigated pcm wallboard coupled with solar thermal system, to maintain comfortable indoor conditions in cold season. The results showed that the daily energy consumption was reduced by 44.16%, enhancing building energy efficiency.

4.3 Solar cooking

Geoffrey John et al.[34], investigated Galactitol as a PCM in solar cookers and they found that the used PCM was not fit for the application and had too short lifespan of less than 100 days. Lameck N Khonjeraet al.[35] investigated Pentaerythritol as PCM for evaluating charging and discharging performance of TES unit. They found that charging rapidity and discharging performance balanced and cooking power was decent. A portable solar box cooker was coupled with double-wall stainless steel with erythritol as PCM [36]. Cooker performance was evaluated in the off-sunshine hours. Improvement in average load cooling-time of around 351.16% was observed. Theoretical investigations were conducted on box -type solar cooker using PCMs [37]. It was found that thickness of container material had insignificant effect on melt fraction and that the melting time is not affected by initial temperature of PCM. During melting boundary wall temperature plays an important role and has noteworthy effect on melt fraction. A collapsible parabolic solar cooker with PCM incorporated cooking pot was used to keep the cooked food warm for subsequent meals [38]. Cost benefit analysis of this system was analyzed and for a family of 4 members payback period was found to be 52 weeks or less. S. D. Sharma et al.[39] investigated erythritol as a PCM in solar cooker based on evacuated tube solar collector. Heat stored in PCM in day time was utilized for evening cooking and they found that cooking using PCM in evening was faster than noon cooking.

4.4 Solar green house

ZainebAzaiziaet al.[40] studied solar greenhouse system with and without PCM and in open sun for drying red pepper. Paraffin wax was used as a PCM and the results show that solar greenhouse with PCM is an appropriate method for drying pepper. Behrooz M. Ziapuret al.[41] enhanced the solar greenhouse by using a thin cover over curved glass roof and PCM was applied in collector for saving energy. Economic factors and energy consumption were noteworthy using the proposed enhanced solar greenhouse system. An active-passive ventilation wall integrated with PCM was developed and studied [42]. They found that in the proposed system the wall' s heat storage and heat release capacity was increased and plant height, fruit yield and stem diameter suggestively improved. Liguo Li et al.[43] investigated Chinese style solar greenhouse using butyl stearate as a PCM and spinach of F1 was used as a test plant. They concluded that greenhouse with PCM make the fluctuations in temperature smaller and is a feasible option. In a greenhouse, the north wall was incorporated with PCM($CaCl_2 \cdot 6H_2O$)[44] and the thermal performance was investigated. Results shows that the relative humidity was less inside and temperature fluctuations were less.

4.5 Solar distillation

PCM incorporated in solar still was investigated [45] for energy and exergy efficiency. The results show that by using PCM daily fresh water yield increased and an increment in exergy and energy efficiency was noted. Passive solar still system with PCM stored in copper cylinder was analyzed [46]. Paraffin wax, stearic acid and lauric acid were used and they found that total distillate increases in paraffin wax, stearic acid and lauric acid was 1202, 1015, and 930 ml/m^2, respectively. Total distillate was found to be linearly decreasing with depth of water and at the depth of 1cm maximum distillate obtained for all three PCMs. In a review by Vikrant P. Katekar and Sandip S. Deshmukh [47], they observed that paraffin wax has the excellent capability in productivity, energy and exergy efficiency. Copper oxide nanoparticles mixed with paraffin wax increased the productivity by 125%. In order to increase the performance of solar still it is important to increase the productivity of fresh water[48]. A solar still with PCM and another without PCM were investigated and they found that daily freshwater productivity of still with and without PCM reached 7.54 L/m^2 and 4.51 L/m^2, respectively. Ravi Gugulothuet al.[49] investigated solar distillation with Sodium Sulphate, Paraffin Wax (white) as PCM together with internal reflectors and found that paraffin wax is the efficient PCM for solar distillation.

4.6 Solar air heater

SalwaBouadilaet al.[50] investigated solar air heater with spherical PCM capsules which stored thermal solar energy in day time to be used at night time. They found that the daily energy efficiency, exergy efficiency varied between 32% and 45%, 13% and 25%, respectively. Paraffin wax was used as a thermal storage media integrated with double pass solar air heaters and for different configurations the system was studied [51]. The efficiency of air heater increased significantly and they found that best configuration is PCM at absorber plates. A.E. Kabeelet al.[52] investigated flat and v-corrugated plate solar air heaters with paraffin wax as PCM and without PCM. Different thermal performance parameters were studied for mass flow rates of 0.062, 0.028 and 0.009 kg/s and they concluded that the daily efficiency of v-corrugated plate was 12% higher with PCM and from flat plate with and without PCM 15% and 21.3% higher, for mass flow rate of 0.062kg/s. Absorber plates of solar air heater with and without baffles with paraffin wax as a PCM [53] was investigated. They found that sequence-arranged baffle-equipped and unequipped solar air heater had maximum energy efficiency of 26.78% and least energy efficiency of 14.30%, respectively, for mass flow rate of 0.017kg/s. Metallic macro-encapsulated PCM integrated with double pass solar air heater system [54] was investigated. Rectangular and cylindrical macro-encapsulates equipped system were found to have an average encapsulate efficiency of 47.2% and 67%, respectively. They also found significant improvement in overall cost.

4.7 Solar chimney

Shuli Liu et al.[55] investigated performance of solar chimney integrated with PCM for three configurations. They found that with PCM, air flow during charging period reduced and during discharging period improved significantly. Liu Bin et al.[56] investigated a solar chimney with PCM in hybrid wall and studied the effects of position of PCM in hybrid wall. They found that when PCM was in front of the absorber the air gap temperature was higher, air velocity was found to be higher when simulation solar lights on and lower when simulation solar lights off compared to PCM behind the absorber. NiloufarFadaeiet al.[57] used paraffin as a PCM was used in 3m height and 3m collector diameter chimney and investigated to improve solar performance of chimney. The results show that maximum absorber temperature of 72℃ , maximum air velocity of 2m/s and 8.33% increase in mass flow rate were achieved with PCM in solar chimney. PisutThantong et al.[58] investigated a double wall solar chimney integrated with PCM. The results obtained shows that the system was efficient in inducing ventilation and significant reduction in heat gain was observed. Researches are conducted to make the implementation of PCM in solar chimney economically affordable [59].

5 Conclusion

Phase change materials as thermal energy storage medium with solar energy applications is one of the cleanest and efficient way to provide necessary human comfort and plays a significant role in energy savings. This paper deals with application of PCM in solar water heating system, solar cooker, solar chimney, solar air heater, solar distillation, solar greenhouse and solar heating of buildings and recent advancements in these fields are explored. Technologies used to enhance the properties of PCM and to improve the already existing systems and phase change materials are reviewed in this paper. PCM is also used in solar furnaces, in thermal energy generation etc. and investigations are carried out using prevailing technologies and newly discovered techniques to maximize the efficiency of systems. The goal is to make use of clean energy sources proficiently in day-to-day life without compromising with quality of life.

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