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Performance enhancement of thermal energy storage system with paraffin wax as phase change material: a review

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ABSTRACT

Thermal energy can be stored as latent heat in which energy is stored when a substance changes from one phase to another by either melting or freezing. Paraffin wax has been widely used for latent heat thermal energy storage system applications due to large latent heat and desirable thermal characteristics. Paraffin wax has lower heat transfer rates during melting/freezing processes due to its inherent low thermal conductivity. This paper reviews and summaries the recent experimental and theoretical works on the thermal conductivity enhancement of paraffin wax.

Introduction

Developing efficient and inexpensive energy storage devices is as important as developing new sources of energy. The thermal energy storage (TES) can be defined as the temporary storage of thermal energy at high or low temperatures. Energy storage improves performance of energy systems by smoothing supply and increasing reliability. One of the important characteristics of a storage system is the length of time during which energy can be kept stored with acceptable losses. If solar energy is converted into a fuel such as hydrogen, there will be no such a time limit. Storage in the form of thermal energy may last for very short times because of losses by radiation, convection and conduction. Another important characteristic of a storage system is its volumetric energy capacity, or the amount of energy stored per unit volume. The smaller the volume, the better is the storage system. Therefore, a good system should have a long storage time and a small volume per unit of stored energy.

The technology of thermal energy storage has been developed to a point where it can have a significant effect on modern life. The major nontechnical use of thermal storage was to maintain a constant temperature in dwelling, to keep it warm during cold winter nights. Large stones, blocks of cast iron, and ceramics were used to store heat from an evening fire for the entire night. With the advent of the industrial revolution, thermal energy storage introduced as a by-product of the energy production. The thermal energy storage systems can be sensible heat storage or latent heat storage, or combination of both. In the sensible heat storage, the temperature of the storage material increases as the energy is stored while the latent heat storage makes use of the energy stored when a substance changes from one phase to another. “[18]”

Phase change energy storage

Latent heat storage is one of the most attractive because large amounts of energy can be stored in a small volume with a small temperature change. In latent heat storage the principle is that when heat is applied to the material it changes its phase from solid to liquid by storing the heat as latent heat of fusion or from liquid to vapor as latent heat of vaporization. When the stored heat is extracted by the load, the material will again change its phase from liquid to solid or from vapor to liquid. The latent heat of transformation from one solid phase into another is small. Solid-vapor and liquid-vapor transitions have large amounts of heat of transformation, but large changes in volume make the system complex and impractical. The solid-liquid transformations involve relatively small changes in volume. Such materials are available in a range of transition temperatures. “[19]” “[21]”

Table 1. Desirable properties of Phase Change Materials

Thermal properties	Suitable phase-transition temperature High latent heat of transition Good heat transfer
Physical properties	Favorable phase equilibrium High density Small volume change Low vapor pressure
Chemical properties	Long-term chemical stability Compatibility with materials of construction No toxicity No fire hazard
Economics	Abundant Available Cost effective

Phase change materials

A large number of materials are known to melt with a high heat of fusion in any required temperature range. However, their use as heat storage material depends on the desirable thermal, physical, chemical properties and economic factors. “[20]”

Paraffin wax

Paraffin wax consists of a mixture of mostly straight chain n-alkanes CH3–(CH2)–CH3. The crystallization of the (CH3)-chain release a large amount of latent heat. Waxes are the most commonly used commercial organic heat storage PCM used for LHTES applications due to their large latent heat, moderate

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thermal energy storage density, little or no undercooling, low vapor pressure, good thermal and chemical stability, lack of phase separation, self-nucleating behavior, varied phase change temperatures, environmental harmlessness, having no unpleasant odor, non-toxicity and low price. “[3]” They show some undesirable properties such as: (i) low thermal conductivity, (ii) non compatible with the plastic container and (iii) moderately flammable. All these undesirable effects can be partly eliminated by slightly modifying the wax and the storage unit. “[1]” Some selected paraffins are shown in table below:

Table 2. Group of Phase Change Materials

Organic substances	Inorganic substances	Fatty acids	Commercial PCMs
Paraffin C_{13}	$Mn(NO_3)_2$-$6H_2O$	Capric–lauric acid (45-55%)	RT25
1-Dodecanol	$CaCl_2$-$6H_2O$	Vinyl stearate	STL27
Paraffin C_{18}	$LiNO_3$-$3H_2O$	Capric acid	S27
1-Tetradecanol	Na_2SO_4-$10H_2O$	Lauric acid	RT30
Paraffin $C_{16–28}$	Na_2CO_3-$10H_2O$	Myristic acid	TH29
Paraffin wax	$CaBr_2$-$6H_2O$	Palmitic acid	RT40
	Na_2HPO_4-$12H_2O$	Stearic acid	RT50
	K_3PO_4-$7H_2O$		TH58

Table 3. Thermophysical properties of some paraffin wax

Paraffin type	Melting(°C)	Heat of fusion(KJ/Kg)
C18	28 “[2]”	244 “[2]”
	27.5 “[2]”	243.5 “[2]”
Paraffin C16–C28	42-44 “[2]”	189 “[2]”
C20–C33	48-50 “[2]”	189 “[2]”
C22–C45	58-60 “[2]”	189 “[2]”
Paraffin wax	64 “[2]”	173.6 “[2]”
C21–C50	66-68 “[3]”	189 “[3]”
C19–C36	48-68 “[3]”	147-163 “[3]”

Methods of increasing thermal performance of paraffin wax

- Dispersion of high conductivity nano particles.
- Placing of metal structures
- Use of high conductivity, low density materials.

Dispersion of high conductivity nano particles

Nano fluid is a new kind of heat transfer medium, Containing nanoparticles which are uniformly and stably distributed in a base fluid. These distributed nanoparticles with high thermal conductivity greatly enhance the thermal conductivity of the nanofluid “[4]”.

Jesumathy et al. “[5]” investigated the thermal characteristics of paraffin wax with an embedded nano size copper oxide (CuO) particle. 40 nm mean size CuO particles of 2, 5 and 10% by weight were dispersed in PCM for this study. The results suggested that the thermal conductivity enhances 6, 6.7 and 7.8% in liquid state. The analysis of experimental results reveals that the addition of copper oxide nanoparticles to the paraffin wax enhances both the conduction and natural convection very effectively in composites and in paraffin wax.

Arasu et al. “[6]” investigated numerically the thermal performance enhancement of paraffin wax with Al2O3 and CuO nanoparticles. The computed dynamic viscosity and effective thermal conductivity of paraffin wax dispersed with 0%, 1%, 3%, 5% and 10 % by volume of nanoparticles both Al2O3 and CuO is studied. The effects of nanoparticle volume fraction on both the melting and solidification rates of paraffin wax are analysed and compared for Al2O3 and CuO nanoparticles. Results show that dispersing nanoparticles in smaller volumetric fractions increase the heat transfer rate. The enhancement in thermal performance of paraffin wax is greater for Al2O3 compared with that for CuO nanoparticles.

Karunamurthy et al. “[7]” studied the use of CuO nano-material for the improvement of thermal conductivity of PCM. The thermal conductivity of LHTES is determined both analytically and experimentally. The result shows that dispersing CuO nano particles with paraffin had resulted in the improved thermal conductivity of the PCM. The increase in thermal conductivity of the PCM is observed with increasing concentrations of CuO nanoparticle. For a concentration of 0.15% of CuO in paraffin results in thermal conductivity of 0.3802 W/mK and 0.3222 W/mK as per experimentally and analytically. Higher the concentration of CuO nano particle dispersed in the PCM, the performance is better. It is also observed that there is almost 50% reduction in charging time and discharging time of the PCM for a volume concentration of 0.16%.

Arasu et al. “[8]” investigate numerically a latent heat energy storage systems using paraffin wax. A numerical analysis has been carried out to study the performance enhancement of paraffin wax with Nano-alumina (Al2O3) particles in comparison with simple paraffin wax in a concentric double pipe heat exchanger. Thermal conductivity of the nanoPCM during charging or melting process is increased by 3.5%, 2.3%, and 3.5% for paraffin wax with 2%, 5%, and 10% Al2O3,respectively, while during discharging or solidification process it is increased by 28.1%, 29.8%, and 33.3% for paraffin wax with 2%, 5%, and 10% Al2O3, respectively, as compared to the simple paraffin wax case. Numerical analysis indicates that the charge-discharge rates of thermal energy can be greatly enhanced using paraffin wax with alumina as compared with a simple paraffin wax as phase change materials.

Table 4. Studies of Methods of increasing thermal performance of paraffin wax

Researcher	Method used	Nano-material	% Dispersion by weight/ volume	Conclusion
Jesumathy et al	Experimental	CuO	2,5,10	E
Arasu et al	Numerical	Al_2O_3 & CuO	1,3,5,10	E
Karunamurthy et al	Experimental & Analytical	CuO	0.15	E
Arasu et al	Numerical	Al_2O_3	2,5,10	E
Liu et al	Experimental	Boron Nitride	1.9,4.0,6.2,8.6	E
Mahmud et.al	Experimental	Aluminum powder	5	E

E=Thermal conductivity enhancement

Liu et al. “[9]” has investigated the paraffin wax filled with Boron Nitride Particle. Hexagonal boron nitride (BN) particles (5–11μm) were inserted into paraffin wax with 0, 1.9, 4.0, 6.2, and 8.6 vol. % BN. The results show that thermal contact conductance was significantly increased by the presence of BN. The thermal contact conductance increased with increasing BN content up to 6.2 vol. % (due to the thermal conductivity of BN), but decreased upon further increase of the BN content to 8.6 vol.

% (due to increased viscosity and the consequent reduced conformability).

Mahmud et.al "[10]" investigated theoretically thermal and physical properties paraffin wax with 5% aluminum powder used as a thermal storage compound in a solar air heater. The result shows that there is considerable increment in heat transfer process.

Placing of metal structures

Placing of metal structures into the paraffin wax has also been addressed as one of the thermal conductivity enhancement techniques by few researchers. Velraj et al. "[11]" placed thin walled hollow cylindrical steel structures into paraffin stored in a cylindrical LHTES system. The results indicated considerable reduction in solidification time due to the addition of lesser rings. The time for complete solidification with lesser rings was approximately 1/ 9th of that without lesser rings.

Ettouney et al. "[12]" studied Heat transfer enhancement by metal screens and metal spheres in phase change energy storage systems. Enhancement is achieved by use of metal screens/spheres placed inside the phase change material (PCM), which is paraffin wax and results in increasing the effective thermal conductivity of the combined media of PCM and metal screens/spheres. The experiments are conducted as a function of the diameter and number of spheres inserted in the phase change material. Also, the experiments investigate the effect of increasing the temperature of the heat transfer fluid (HTF).The result show that Nusselt number increases with the increase in the HTF temperature, which results in the increase of the driving force for heat transfer, as well as the heat transfer coefficient in the HTF and the PCM.

Use of high conductivity, low density materials

Fan et al. "[13]" investigated experimentally the effects of various carbon nanofillers on the thermal conductivity and energy storage properties of paraffin-based nanocomposite PCM for TES. The results show that filler material for preparing nanocomposite PCMs with greatly enhanced thermal conductivity and moderately decreased energy storage capacity. Elgafy et al. "[14]" has prepared a composite adding carbon nanofiber of 100 nm average diameter and 20mm average length into paraffin wax. The thermal conductivity of the composite was found to be increasing almost linearly with increase in mass fraction of nanofiber. Result shows that high solidification rate was observed with 1% mass fraction of carbon fiber, the reduction in solidification time is reported as 23%.

Sanusi et al. "[15]" examined experimentally the effect that graphite nanofibers (GNFs) both thermal storage and solidification time of a PCM which is embedded between two sets of aluminum fins. It was found that for aspect ratios of 1, the GNF enhancement shortens solidification time by as much as 61% over the paraffin samples. Results also showed that for a smaller mass at an aspect ratio of 1 GNF enhancement played a large role in the reduction in solidification time of the PCM. The research indicates that GNF impregnation into phase change materials is an effective method for the enhancement of the thermal energy storage and the solidification of paraffin- based phase change materials. Kim et al.[16] has studied High latent heat storage using paraffin and exfoliated graphite nanoplatelets (xGnP). XGnP of 1, 2, 3, 5 and 7 wt% was added to pure paraffin. The result reveals that thermal conductivity of paraffin/xGnP composite PCMs was increased as xGnP loading contents.

Conclusions

This paper reviews the various techniques of heat transfer enhancement in a phase change thermal energy storage system using paraffin wax. Various techniques reviewed in this paper include dispersion of nanomaterial, placing a metal structure, using high conductivity low density materials. It is found that dispersion of nanomaterial in paraffin wax results in enhancement of thermal conductivity. Also placing a metal structure and high conductivity low density materials like graphite significantly reduces solidification (discharging) and melting (charging) time of paraffin wax.

More work is needed to understand the heat transfer enhancement in PCM by using different metal structure and different nanomaterials in future.

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