A Review on Augmentation in Thermal Performance of Solar Water Heater using Phase Change Material

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Abstract. The nature of solar energy is intermittent due to its variable magnitude in daytime and zero throughout the night or during overcast conditions, which limiting its use in hospitals and in various industrial and domestic applications particularly in water heating. Because of inconsistent nature of solar energy some type of thermal energy storage (TES) system is essential for its effectual utilization and to meet the energy demand at all the times. Phase change material (PCM) is a very good option for latent heat TES because of its high thermal storage density and isothermal behaviour at the time of charging and discharging. The PCM absorb 5 to 14 times more heat as comparison to sensible heat storage material such as water, stone, bricks or rocks etc. The PCM with nano-sized-particle can enhanced the performance of LHTS systems. In this review, ongoing research and development on the performance of solar water heater (SWH) incorporating with PCM’s and nano-embedded PCM is summarized and to provide viewpoint for future research and development.

Keywords: Solar energy, TES, PCM, SWH, Absorber plate, Energy efficiency.

1. Introduction

Solar energy is most promptly available, free, environmentally clean and ultimate auspicious alternate source of energy available since ancient times. The importance of solar energy and its magnitude are very well known to everyone. The available value of its magnitude is dependent on time and also dependent on the meteorological states of the location of that place. In the past two decades a wide variety of solar energy-based water heating innovations have been developed by the researchers through

![Diagram of Thermal Energy Storage](image1)

Fig.1 Thermal energy storage [18]
various ongoing research and development programs. The nature of solar energy is intermittent due to its variable magnitude in daytime and zero throughout the night or during overcast conditions, which limiting its use in hospitals and in various industrial and domestic applications particularly in water heating. In solar water heating the energy source and demand commonly mismatch each other especially in domestic applications. The peak demand of heated water is early in the morning and also in late evening while the peak solar radiation come about noon. So, because of inconsistent nature of solar energy some type of TES system is essential for its effecctual utilization and to meet energy demand at all the times. TES system provides a thermal energy reservoir to meet the energy demands consistently in day and night and reduces the gap between energy source and demand in domestic applications. The application of solar water heaters is mainly depending on efficient thermal storage unit of the system. The TES systems are sensible heat thermal storage system and latent heat thermal storage system. Because of non-isothermal behaviour in charging and discharging of energy and also small thermal storage capacity per unit volume sensible heat thermal storage system are not too much in use. Latent heat thermal storage system has high thermal storage density with solid-liquid phase change and they can store thermal energy at a constant temperature with respect to the phase change temperature of TES substance.

[29-31] The materials which can melt and solidify at particular temperature and also capable for storing and releasing huge amount of heat consistently by undergoing a phase transition are called phase change materials. [3, 14, 16, 23-26] PCM is a very good option for LHTS because of its high TES density and isothermal behaviour during charging and discharging. The PCM should possess the following properties:

1. High latent heat of fusion and thermal conductivity per unit volume
2. Should have small vapour pressure.
3. Should have marginal change in volume during phase transformation.

4. Should be chemically stable.
5. Should exhibit very small or no-subcooling.
6. Minimum variation in density during phase transformation.
7. They should be non-corrosive, nontoxic, non-inflammable and also non explosive.
8. Should have high heat transfer coefficients.

[32-37] The PCM absorb 5 to 14 times more heat as comparison to sensible heat storage material such as water, stone, bricks or rocks etc. the PCM absorbs and releases energy almost at constant temperature. They can store large amount of energy with a small change in temperature. The latent heat thermal storage (LHTS) tank is shown in fig.4. The latent heat is more or less 100 times higher
than the sensible heat. For example, the latent heat and sensible heat of water is about 334 kJ/kg and 4.18 kJ/kg (at 25 °C) respectively. The melting temperature of PCM should be lie in the range of operation. The various phases of PCM lies in a LHTS system is shown in fig.1. The classification of PCM is shown in fig.2.

Fig. 3 Shell material for encapsulation of PCM [25]

[40] Nano-embedded PCM shows remarkable increase in the thermal efficiency of various devices. The formation of nano-embedded PCM is shown in fig.5.

Fig.4 Latent heat thermal storage tank [11]

Fig. 5. Formation of Nano-embedded PCM [40]
2. Methodology and Experimental Investigations

The thermal performance of a SWH generally depends on absorption and conduction of solar radiation, transmittance and thermal conductivity of working fluid. [1] Experimentally studied the effect of PCM in a LHTS tank. They use a layer of encapsulated PCM at the bottom of a storage tank to store large amount of heat at the time of sunshine. They used paraffin wax as a PCM. The PCM filled metallic capsules form a thick layer of 4 cm parallel to the absorbing plate at the bottom of the tank. The metallic capsules of PCM are used because at the time of phase change from solid to liquid by PCM the melted layer of PCM would not be parallel to the absorbing plate and also necessitated because of inclination of the absorbing system. The PCM store energy in the form of latent heat by changing its phase from solid to liquid. At the time of early morning, evening, night and in overcast period the hot water is drawn out from the tank, which is substituted by cold water. The cold-water gains energy from the PCM. The PCM release energy by changing its phase from liquid to solid. The solar water heaters with PCM at the bottom of the tank meet the requirement of heated water during off-sunshine hours.[2] used paraffin as a PCM in encapsulated spherical capsules with melting temperature 60 ± 1°C and water as working fluid. The LHTS system remarkably reduces the size of TES tank as compared to ordinary TES system. As the time increases during charging of PCM the efficiency and cumulative heat stored

![Graph showing Cumulative heat storage and efficiency Vs. Time at ε = 0.49](image)

**Fig. 6** Variation in Cumulative heat storage and efficiency Vs. Time at ε = 0.49 [2]

of LHTS system decrease and increases respectively at different mass flow rate of working fluid as shown in fig. 6. As time increases the temperature of the working fluid in the storage tank increases.

*Table 1: [2,4, 17] Properties of PCM.*

| S. No. | Type of PCM | Melting Temperature (°C) | Latent heat of fusion (kJ/kg) | Density (kg/m³) | Specific heat (J/kg.°C) | Thermal Conductivity (W/m°C) |
|-------|-------------|--------------------------|-------------------------------|-----------------|------------------------|-------------------------------|
|       |             |                          |                               |                 |                        | Liquid                       |
| 1     | H₂O         | 0                        | 333                           | 998             | 2384                   | 0.612                        |
| 2     | Paraffin    | 59                       | 213                           | 778             | 2384                   | 0.15                         |
| 3     | Erythritol  | 118                      | 339.8                         | 1300            | 1590                   | 0.326                        |
| 4     | Stearic acid| 58.1                     | 169                           | 847             | 1590                   | 0.29                         |
| 5     | Palmitic acid| 61                      | 203.4                         | -               | -                      | 0.165                        |
| 6     | CaCl₂ 6H₂O  | 29                       | 190.8                         | 1562            | -                      | 0.54                         |
| 7     | NaNO₃       | 307                      | 162                           | 2260            | -                      | 0.5                          |
| 8     | KNO₃        | 333                      | 266                           | 2110            | -                      | 0.5                          |
losses from the tank increases, hence efficiency of SWH decreases. The different material for encapsulation of PCM is shown in fig.3. [3] the charging of PCM during initial period of time is high and decreases as time increases because the difference in temperature of water and storage tank also decreases with time.[7] experimentally studied that if a PCM module at the top of the storage tank is added than it would give higher storage density.[8] The thermal storage system consists of two heat absorbing units. From which one is SWH which supplies hot water during sun-shine and other one is PCM thermal storage unit which supplies hot water during early morning, evening and in night time. They use paraffin as a PCM in small aluminium cylinders for thermal storage. During charging process gradual increase in the temperature of PCM is followed by the isothermal melting. The charging time of PCM can be reduced increasing the area of the absorbing plate. The LHTS system are reliable and viable option for storage of solar energy. [9,10] PCM based SWH come up with 23% more cumulative and life cycle savings as comparison to ordinary SWH. The experimental set-up is shown in fig.7. [12] Experimentally investigate that the cooling rate of water reduce due to PCM and remarkably increase the utilization of solar energy. The efficiency and thermal storage capacity of SWH increases from 31.25% to 44.63% and 3260.4 kJ to 4656.5 kJ respectively.[15] Experimentally studied that the cooling rate of water decreases with application of PCM. Due to increase in the thermal storage capacity the size of storage tank reduces.[18]

Table 2: Thermo-physical properties of paraffin wax, CuO, Sci and Paraffin wax nano composite [19]

| PCM/ Nanoparticle          | Melting point °C | Latent Heat kJ/kg | Thermal conductivity W/Mk |
|----------------------------|------------------|-------------------|---------------------------|
| Paraffin wax               | 60.5             | 166.7             | 0.172                     |
| CuO                        | 1201             | -                 | 20                        |
| Sci                        | 1750             | -                 | 3.8                       |
| Paraffin wax-nano composite| 59.6             | 160.3             | 0.226                     |
Experimentally studied the performance of SWH with paraffin wax as a PCM with and without nanofiller. They used aluminium oxide as a nanofiller in the paraffin wax. The hot water temperature is higher with nanofiller as compare to without nanofiller. Aluminium nanofiber also increases the thermal conductivity of the PCM.[19] Studied thermal performance of SWH with PCM and PCM nano-composite. They used paraffin wax as a PCM and paraffin wax nano composite with Sci and CuO as a nano-sized-particle. The energy efficiency of the system with PCM and PCM nano-composite are 38.3% and 41.7% respectively. The exergy efficiency of the system with PCM and PCM nano composite are 2.18% and 3.23% respectively. The thermal conductivity of paraffin wax nano composite remarkably increased to 22.53% as comparison to base paraffin wax. [20] Experimentally investigated thermal performance of SWH with a new design of shell and finned tube LHTS system which is shown in fig 8. They used paraffin wax as a PCM. The experiment is carried out by using thermal storage material as water, paraffin wax as a PCM and both paraffin wax and water. They achieved highest daily efficiency as 65% with PCM and water as a thermal storage material. The SWH is capable to provide hot water at all the times ranging from 50 to 60.4 °C. [21] Experimentally studied the effect of nano-embedded PCM on the performance of SWH. They used CeO$_2$ as a nano-sized-particles with mass fraction of 0.5%, 1.0% and 2.0% in paraffin. The thermal conductivity of nano-embedded PCM increased to 108.89% with 2.0% mass fraction of CeO$_2$ as comparison to paraffin. The nano-embedded PCM with mass fraction of CeO$_2$ 1.0% shows excellent thermal properties as compare to 0.5% and 2.0% mass fraction. They achieved highest daily efficiency and exergy efficiency as 79.2% and 5.1 % respectively for nano-embedded PCM with 1.0% mass fraction of CeO$_2$. 

![Fig. 8. Shell and Finned type thermal storage system [20]](image-url)
Conclusions

This paper shows recent development in the field of thermo-physical performances of SWH. On the basis of literature review the ongoing research and development on thermal performance of SWH and effect of distinct type of PCM and nano-embedded PCM on thermal storage and augmentation of heat transfer is summarized. The main conclusions are as follows:

1. The LHTS system are reliable and viable option for storage of solar energy.
2. PCM based SWH come up with 23% more cumulative and life cycle savings and also have less playback period as comparison to conventional SWH.
3. The PCM reduces the thermal losses and increase the efficiency of SWH.
4. The cooling rate of water reduces due to PCM and remarkably increase the utilization of solar energy.
5. The highest daily efficiency and exergy efficiency is achieved as 79.2% and 5.1 % respectively for nano-embedded PCM with 1.0% mass fraction of CeO$_2$. [21]
6. The thermal conductivity of PCM can be augment by adding nano-sized-particle in the base PCM. [27, 28, 38-42]
7. The PCM with nano-sized-particle can enhanced the performance of LHTS systems.

References

[1] J. Prakash, H. P. Garg, G. Datta. 1985 A solar water heater with a built-in latent heat storage. Energy Convers. Mgmt. Vol. 25, No. 1, 51-56.
[2] Nallusamy N., Sampath S., Velraj R. 2006 Study on performance of a packed bed latent heat thermal energy storage unit integrated with solar water heating system. University Science A 7(8):1422-1430.
[3] Mr. F.B.A. Amin, Prof. A.M. Patil, Prof. H.M. Dange. 2013 Comparative study of solar water heater with and without latent heat storage system. International Journal of Advanced Engineering Research and Studies E-ISSN2249–8974.
[4] N. K. Bansal and D. Buddhi. 1992 An analytical study of a latent heat storage system in a cylinder. Energy Convers. Mgmt. Vol. 33, No. 4, 235-242.
[5] M. S. Sodha, A. K. Sharma, R. L. Sawhney, Atam Kumar. 1997 Experimental performance of built-in-storage solar water heating systems in laboratory and field conditions. International Journal of Energy Research, vol. 21, 275-287.
[6] M. S. Sodha, G. N. Tiwari, R. L. Sawhney, A. K. Sharma, A. K. Singh, R. K. Goyal. 1998 Sizing of a multi-tank solar water heater. International Journal of Energy Research, vol. 22, 777-790.
[7] H. Mehling, L.F. Cabeza h, S. Hippeli , S. Hiebler. 2003 PCM-module to improve hot water heat stores with stratification. Renewable Energy 28 699–711.
[8] S. A. Vijay Padmaraju, M. Viginesh, N. Nallusamy. 2008 Comparative study of sensible and latent heat storage systems integrated with solar water heating unit. RE & PQJ, Vol. 1, No.6, 55-60.
[9] S. A. Khot, N. K. Sane, B. S. Gawali. 2012 Thermal Energy Storage using PCM for Solar Domestic Hot Water Systems: A Review. J. Inst. Eng. India Ser. C 93(2):171–176.
[10] N. Nallusamy, L.N. Rao, S. Sampath, R. Velraj. 2003 Effective utilization of solar energy for water heating applications using combined storage system”. In proceedings of the International Conference on ‘‘New Millennium-Alternative Energy Solutions for SustainableDevelopment (Coimbatore, India) pp. 103–108.
[11] N. Nallusamy, L.N. Rao, S. Sampath, R. Velraj. 2003 Effective utilization of solar energy for water heating applications using combined storage system”. In proceedings of the International Conference on ‘‘New Millennium-Alternative Energy Solutions for SustainableDevelopment (Coimbatore, India) pp. 103–108.
[12] M.H. Mahfuz, M.R. Anisur, M.A. Kibria, R. Saidur, I.H.S.C. Metselaar. 2014 Performance investigation of thermal energy storage system with Phase Change Material (PCM) for solar
Mr. M.V. Kulkarni and Dr. D. S Deshmukh. 2014. Improving efficiency of solar water heater using phase change materials. Pratibha: international journal of science, spirituality, business and technology (ijssbt), vol. 3, no. 1 39-44.

Sarvesh R.Sawant, Suprabhat A.Mohod. 2015 Review on solar water heaters using pcm (phase change materials) in tes (thermal energy storage) systems. International journal of advance research in science and engineering. Vol. No. 4, Issue 09 115-124.

S. Sadhishkumar and Dr. T. Balusamy. 2017 Comparison of Solar Water Heater with and without Phase Change Material as Latent heat storage. Advances in Natural and Applied Sciences. 11(4), Pages: 605-611.

Prafull Shahar, Dr A N Pawar, A A Karmarkar. 2017 Review of Application of Phase Changing Materials (PCMS) In Solar Water Heater and Proposed Work with Scope & Limitation. International Conference on Recent Trends in Engineering and Science. Volume 6, Special Issue 1 561-569.

Ling Xie, Liu Tian, Lulu Yang, Yifei Lv and Qianru Li. 2017 Review on application of phase change material in water tanks. Advances in Mechanical Engineering Vol. 9(7) 1–13.

A.S. Manirathnam, M.K. Dhanush Manikandan, R. Hari Prakash, B. Kamesh Kumar, M. Deepan Amarnath. 2020 Experimental analysis on solar water heater integrated with Nano composite phase change material (SCI and CuO). Materials Today: Proceedings xxx (xxxx) xxx.

S. Christopher, K. Parham, A.H. Mosaffa, M.M. Farid, Zhenjun Ma, Amrit Kumar Thakur, Huijin Xu, R. Saidur. 2020 A critical review on phase change material and its influence on the performance of evacuated tube solar water heater. Renewable Energy 162 662-676.

Sandro Nizetic , Miso Jurcevic, Muslum Arıcı , A. Valan Arasu , Gongnan Xie. 2020 Nano-enhanced phase change materials and fluids in energy applications: A review Renewable and Sustainable Energy Reviews 129 109931.
9

[31] Gupta N.K., Tiwari A.K., Ghosh S.K. 2018 Heat Transfer Mechanisms in Heat Pipes using Nanofluids-A review. *Experimental Thermal and Fluid Science*, 90 84–100.

[32] Gupta N.K., Mishra S. Tiwari A.K., Ghosh S.K. 2019 A review of thermo physical properties of nanofluids”, *Materials Today Proceedings* 18, 968-978.

[33] Gupta N.K., Tiwari A.K., Ghosh S.K. 2018 Experimental Study of Thermal Performance of Nanofluid-filled and Nanoparticles-coated Mesh Wick Heat Pipes. *Journal of Heat Transfer, (SCI), Transactions of ASME*, 140(10):102403-102403-7.

[34] Gupta N.K., Tiwari A.K., Verma S.K., Rathore P.K.S., Ghosh S.K. 2019 A Comparative Study of Thermal Performance of a Heat Pipe Heat Pipe Using Water and Nanofluid and Nanoparticles Coated Wick Heat Pipe Using Water”. *Heat Transfer Research*, 50(18):1767–1779.

[35] Gupta N.K., Sharma A, Rathore P.K.S., Verma S.K. 2020 Thermal performance optimization of Heat pipe using the nanofluid-Response surface methodology. *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 42:590 1-16.

[36] Gupta N.K., Verma S.K., Rathore P.K.S., Sharma A. 2020 Effects of CuO/H$_2$O nanofluid application on thermal performance of mesh wick heat pip, *Heat Transfer Research* 51(9):837–850.

[37] Rathore P.K.S, Shukla S.K., Gupta N.K. 2020 Yearly analysis of peak temperature, thermal amplitude, time lag and decrement factor of building envelope in tropical climate. *Journal of Building Engineering* 31 101459.

[38] Verma S. K., Gupta N. K., Rakshit D. 2020 A comprehensive analysis on advances in application of solar collectors considering design, process and working fluid parameters for solar to thermal conversion. *Solar Energy* 208 1114–1150.

[39] Rathore P.K.S, Shukla S.K., Gupta N.K. 2020 Potential of Microencapsulated PCM for Energy Savings in Buildings: A critical review” *Sustainable Cities and Society* 53 101884.

[40] Parvej Alam, Naveen Kumar Gupta, Al Rabbul Nizam. 2020 Characterization of nanoparticles embedded phase change materials. *Materials Today Proceedings* xxxx-xxxx.

[41] Verma S K, Sharma K, Gupta N.K, Verma P, Upadhyay N. 2020 Performance Comparison of Innovative Spiral Shaped Solar Collector Design with Conventional Flat Plate Solar Collector. *Energy* 116853.

[42] Rathore P.K.S, Shukla S.K., Gupta N.K. 2020 Synthesis and characterization of the paraffin/expanded perlite loaded with graphene nanoparticles as a thermal energy storage material in buildings. *Journal of Solar Energy Engineering* 142 (4): 1-33.