Volume 5, Issue 1 (2017) 104-109 ISSN 2347 - 3258
International Journal of Advance Research and Innovation

Performance enhancement of solar water heater using phase change materials (PCM): A Review

Paras Sachdeva
Department of Mechanical Engineering, BCET Gurdaspur, Punjab-143521, India

Article Info
Article history:
Received 25 January 2017
Received in revised form
20 February 2017
Accepted 28 February 2017
Available online 15 March 2017
Keywords
Solar water heater (SWH), Phase change material (PCM)

Abstract
Solar water heater (SWH), one of the most popular solar thermal systems, accounts for 80% of the solar thermal market worldwide. This review paper presents the previous work on solar water heater using phase change material. PCM had been used in different part of heating networks including shell and tube type collectors, flat pate collectors and evacuated tube collectors. Recent findings about the effects of phase change material on various solar collectors are discussed. This review highlights the need for further research in improving the solar water heater using materials for latent heat storage.

1. Introduction

Solar water heater (SWH) is most popular solar equipment in India. It is a relatively mature solar thermal technology. In solar water heating system incident solar radiation is converted to heat and transmitted through a transfer medium such as water. SWH are often viable for the replacement of electricity and fossil fuels used for water heating.

Though it meets the requirement of hot water still it has very low thermal efficiency. In order to increase the thermal efficiency phase change material (PCM) is used. The study of PCM was introduced by Telkes and Raymond in the 1940s, and received much interests in the period of late 1970s and early 1980s during the energy crisis when it had been extensively studied for use in different applications especially in solar heating systems due to their distinct operational advantages, e.g., small temperature variation, small size of volume/mass and high energy storage capacity. PCM thermal energy storage is based on the energy absorbed/generated when a material undergoes phase change from solid to liquid, liquid to gas, or vice versa. To lower the energy consumption cost of conventional electrical heaters, PCM thermal energy is stored during the off-peak load period. This energy is then released during the peak period.

1.1. Solar Water Heater

A Solar water heater (SWH) is an advanced solar thermal technology. In solar water heater incident solar radiation is converted to heat and transmitted through a transfer medium such as water. SWH are often viable for the replacement of electricity and fossil fuels used for water heating.

A typical solar water heating system consists of a hot water storage tank and flat plate collector(s). The most common collector for solar hot water is the flat plate collector, which is a rectangular box with a transparent cover, installed on a building's roof. Small tubes run through the box, and the tubes are attached to a selectively coated absorber plate. The flat plate collectors absorb solar radiation and heat up cold water flowing through the tubes, which is collected in an water flowing through the tubes, which is collected in an insulated storage tank. Solar water heating systems using flat plate collectors can meet almost any direct/indirect-heating load up to a maximum temperature of 90–95 °C. In small systems, circulation of water from the tank through the collectors and back to the tank may take place automatically due to the density difference between hot and cold water (thermosyphon effect). In larger systems, a small electric pump may be required to circulate water through the collectors.

***Corresponding Author,**
E-mail address: parassachdeva1211@gmail.com;
Phone No--+91- 9646630141

Flat plate collectors are easy to install and maintain. Savings in the conventional fossil fuel requirements are the main economic contribution of using a solar water heating system. Fig. 1 shows the schematic of solar water heating systems (thermosyphon and forced flow). The auxiliary heater is installed either in the tank or at the user point for the different systems available in the market. The cost of solar energy collecting systems differs depending upon the type of material used for the case of the collectors, absorbent plate and water storage tank. A typical solar energy collecting system used for water heating contains two collectors (total 4–6m^2 surface area) and a 160–200 l capacity water storage tank.

Fig. 1. Flat glazed solar collector

The water-in-glass evacuated tubular solar water heater (Fig. 2) is the most widely used form of evacuated tube collector because it has higher thermal efficiency than other evacuated tube collectors employing metal-in-glass manifolds and has simpler construction requirements and lower manufacturing costs. A water-in-glass evacuated tube solar water heater typically consists of 15–40 flooded single-ended tubes in direct connection to a horizontal tank. The solar absorber tube consists of two concentric glass tubes sealed at one end with an annular vacuum space and a selective surface absorber on the outer surface (vacuum side) of the inner tube. The heat transfer in this collector is driven purely by natural circulation of water through the single-ended tubes. Water in the tubes is heated by solar radiation, rises to the storage tank and is replaced by colder water from the tank. The major difficulty with the application of all glass evacuated tube collectors is the problem of heat extraction from the long narrow single ended absorber tube. Many heat extraction methods such as heat pipes, U-tube inserts or integrated collector/storage in the tube have been developed by the International Energy Agency [1]. However, the most successful method is the simple water-in-glass concept. Heat extraction from a water-in-glass evacuated tube is driven by natural circulation of the fluid between the collector and the storage tank. The limitation of this concept is that it can only be used for a low-pressure system, as the tubes can only withstand a few meters of water head. The performance of solar water heating system is influenced by the product configuration and the local meteorological conditions. Solar water heaters can operate as a solar pre-heater in series with a boost tank or instantaneous gas heater or as a single-tank system with a boost element incorporated in the solar tank. The collector is usually mounted at a standard roof inclination, but can also be adjusted to optimize the performance during winter months when the hot water demand is the highest.

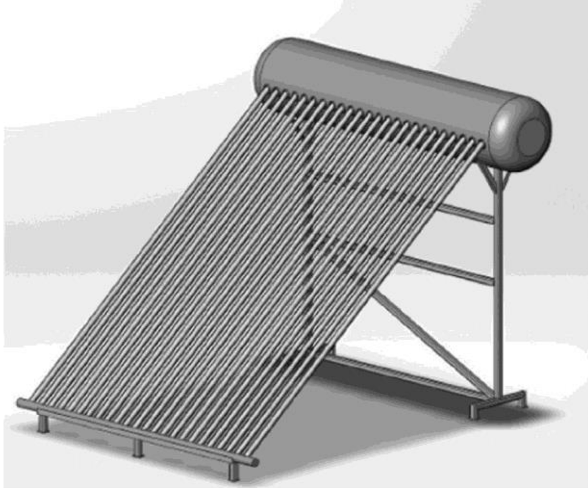

Fig. 2. Evacuated tube solar collector

1.2. Phase change material (PCM)

1.2.1. Introduction to PCM

Phase change material (PCM), also called latent heat storage material, has high capability to store and release large amount of heat within the constant or a narrow temperature range, which is one of the most attractive functional materials among various heat storage materials [2,3]. The application fields include electronic cooling, waste heat recovery, smart housing, temperature-control greenhouse and textile, telecommunication and microprocessor equipment [4-7]. Most recently, PCM has been widely used in solar energy utilization systems (e.g., SWH).

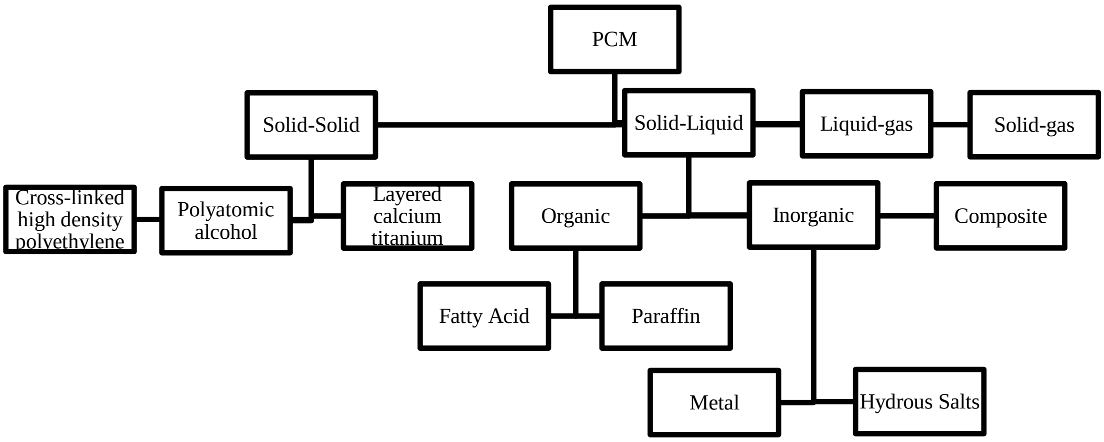

Fig. 3. Classification of PCM

1.2.2. Classification of PCM

All kinds of PCM can be classified as in Fig. 3 and described as follows. PCM can be divided into solid–solid, solid–liquid, solid–gas and liquid–gas types. Of which, the solid–solid and solid–liquid types are most commonly found in the global market. Solid–solid type of PCM are fairly developed functional material, which have the characteristics of no liquid or gas generation, small volume change, small chance of occurrence of sub-cooling, no corrosion, non-toxicity, high heat efficiency and long service time, although they are expensive, have poor thermal conductivity and easy to turn into volatile plastic crystal over the phase change temperature. The advantages of the solid–liquid type exist in low cost, and the disadvantages include the phenomenon of phase separation and super-cooling, large volume change, easy leakage, and environmental pollution. Typical solid–solid type includes cross-linked high density polyethylene, layered calcium titanium and polyatomic alcohol, and solid–liquid type involves three subcategories, i.e., inorganic (e.g., hydrous salt and metal or metal alloys), organic (e.g., paraffin and fatty acid), and composite, based on the thermal and chemical properties of the material. It should be mentioned that due to the solid–liquid type undergoing large volume change during melting and solidification, an encapsulation structure is always selected for the filling of the solid–liquid PCM. This structure could contain the material in liquid and solid phases, prevent possible variation in chemical composition by interacting with the environment, increase compatibility with other materials of the storage, increase handiness and provide suitable surface for heat transfer.

1.2.3. Properties of PCM

The main criterion of selecting the proper PCM for SWH application is the phase change temperature of the material. Other parameters, e.g., values of latent heat and thermal conductivity, should also be taken into account for the structural characterization and design of the SWH system.

2. Review works

Kaygusuz [8] conducted an experimental and theoretical study to determine the performance of phase change energy storage materials for solar water-heating systems. A storage vessel filled with 1500 kg of encapsulated PCM ($CaCl_2.6H_2O$ or $Na_2SO_4.10HO$) inside tubes was investigated over the entire heating season. Variations of the solar-supplied fraction of the load with storage mass and collector area for water-based systems with sensible and latent heat storage were examined. It was concluded that the PCM storage was preferable than the water and rock storage.

Chaurasia [9] presented a comparative study of solar energy storage systems using the latent heat storage and sensible heat storage techniques. Two identical storage units were studied: one containing 17.5 kg paraffin wax (with melting temperature of 54°C) packed into a heat exchanger made of the aluminum tubes, and the other simply containing water. Both units were separately charged during the day by flat plate solar collectors of equal areas. The study revealed that the latent heat storage system comparatively yields more hot water on the next day morning when compared with the sensible heat based storage system.

Canbazoglu et al. [10] calculated the total heat (sensible and latent) to compare the storage capacity of SDHW systems with PCMs to the conventional systems. Polyethylene bottles were filled with hydrated salts and set into the vessel in three rows. The bottles did not let the water flow in a horizontal direction due to their close arrangement, and it instead allowed flows through the vertical cavities between the bottles. The results indicated that the water temperature has a constant value of 46°C during the night until sunrise, as hot water was not drawn from the vessel. The temperature difference between the midpoint of the heat storage tank and the outlet of the collector was approximately 6°C greater than that in the system without PCM. Heat storage performances of the same solar water-heating system combined with the other salt hydrates-PCMs such as zinc nitrate hexahydrate, disodium hydrogen phosphate dodecahydrate, calcium chloride hexahydrate and sodium sulfate decahydrate (Glauber's salt) were examined theoretically by using meteorological data and thermophysical properties of PCMs with some assumptions. It was concluded that the total energy stored in the SDHW system containing PCM were about 2.59–3.45 times of that in the conventional solar water-heating system.

Li et al. [11] developed the mathematical model of shell-and-tube latent heat storage unit with three types of PCM as shown in fig. 4 (characterizing in different melting temperatures of 983 K, 823 K and 670 K, respectively). This was based on the enthalpy method. The results showed that the melting rate of the PCM with the highest melting temperature were the slowest. Considering actual application in solar thermal system, the optimum lengths of the three types of PCM were suggested at 250 mm, 400 mm, and 550 mm when the total length of the storage was at 1200 mm.

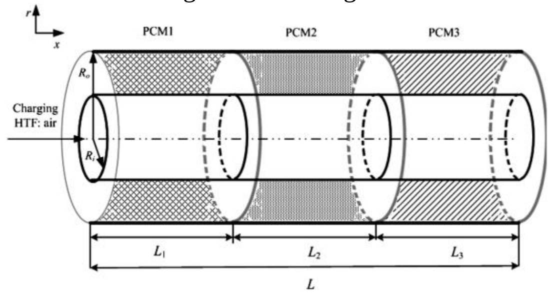

Fig. 4. Physical model of the LHTES unit with three PCMs

Khalifa et al. [12] researched the domestic solar hot water system numerically and experimentally with the paraffin attached to the back of the solar collector. The performance of the system had been identified with the influence of the collector temperature and the heat transfer between the heat transfer fluid (water) and paraffin.

Han et al. [13] proposed the metal-foam-embedded PCM for latent thermal energy storage. The coupled heat transfer between PCM and metal foam was resolved based on the non-equilibrium heat transfer theory. The proper metal selection and structure design of the metal foam could enhance the heat transfer of the PCM.

Biwole et al. [14] experimented and simulated the solar system with the impure PCM situated at the back of the solar collector using the CFD. The detailed mathematical and numerical model of heat and mass transfer was setup, and the simulation results were compared well with the testing results. It presented that adding PCM to the back of the solar collector can maintain the operating temperature of the collector under 40°C for 80 min with the constant solar radiation of 1000W/m^2.

Fazilati & Alemrajabi [15] experimentally investigated the effect of using PCM as storage medium to the performance of the solar water heater. Schematic of experimental setup is shown in fig. 5. It was observed that using PCM in the tank, the energy storage density was increased upto 39%, the exergy efficiency was enhanced upto16%, and the service period of the supply hot water with specified temperature was longer by 25% compared with the system without PCM. This research made a significant improvement on the system energy and exergy efficiencies compared with Ahmet Koca et al.

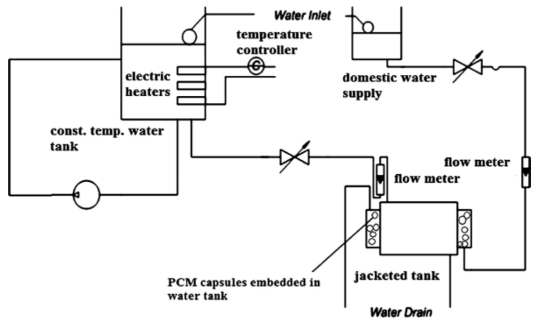

Fig. 5. Schematic of experimental setup

Lopez et al. [16] designed and fabricated a versatile storage tank for PCMs whose melting temperatures ranged from10°C to 100°C. The physical properties of the PCM (paraffin) were obtained, including specific heat, density, and enthalpy–

temperature curve. The researchers incorporated sensible and latent heat energy storage, and experimentally analyzed storage tank performance based on the vertical stratification of the PCM tank, effectiveness, there active fraction, and the total heat transfer in the tank. The findings indicated that the maximum capacity of the system reaches 78% within 4h. Moreover, a full phase change could not be achieved during solidification at 6K less than the PCM melting point.

Table 1: Summary of review work

S. No.	Reference	Collector type	Type of study	PCM Description	Parameter studied	Major findings
1	Y.Q. Li (2013)	Shell & tube type solar collector	Numerical	PCM with high melting temperature	PCM melting temperature and rate	melting rate or PCM with the highest melting temperature ere the slowest
2	Abdul Jabbar N. Khalifa (2013)	Flat Plate solar collector	Experimental	Paraffin (impure)	Collector temperature	Nearly steady variation in the system's useful efficiency is noticed for all months
3	X.X. Han (2013)	Latent Thermal energy storage	Experimental	Metal foam embedded PCM	Metal design structure design	Effectiveness Map was produced for a deeper understanding of material selection.
4	Pascal Henry Biwole (2013)	Collector operator temp under 40c for 80min	Numerical	Impure PCM		Max operating temp a system can achieve
5	Fazilati (2013)	Energy storage density	Experimental	Pcm for use in storage		It is observed that by using PCM in the tank the energy storage density is increased in the tank up to 39% and the exergy efficiency is enhanced up to 16%.
6	A. Lopez-Navarro (2014)		Experimental	Paraffin (organic)	Performance characteristics of PCM in storage tank	Maximum capacity of system reaches 78% within 4 hours
7	Roberta Padovan (2014)	Shell & tube type solar collector	Numerical		Designing parameters, PCM melting temperature point and insulation thickness	the effects of tank geometry and insulation thickness on energy saving in thermal storage are limited
8	Dan Nchelatebe Nkwetta (2014)		Numerical	Three different types of PCM are compared	Effect of PCM in hot water tanks	sodium acetate trihydrate +10% graphite seems to be the best PCM to be integrated into the hot water tank
9	Serali (2014)	PCM slurry based collector	Experimental	PCM slurry	sensitivity analysis to study nominal melting temperature of the PCM	The improvement in the instantaneous efficiency is in the range 5-10%
10	Mahfuz (2014)	Shell & tube type solar collector	Experimental	paraffin		System efficiency: 63–77%; exergy efficiency: 6.02–9.58%; total lifecycle cost: decreased with the increase of the flow rate of the heat transfer fluid.
11	Yang (2014)	PCM for use in storage	Experimental & Numerical	Composite of three types of spherical encapsulated PCM	PCM melting temperature	High system efficiency and low exergy efficiency compared with single- PCM system.
12	Chaabane (2014)		Experimental	Myristic acid, Rubitherm 42 graphite		Myristic acid storage performed better than Rubitherm 42 graphite storage.
13	H. Sheng Xue (2016)	Evacuated tube solar collector	Experimental	$Ba(OH)_2.8H_2O$	Thermal performance of solar system	Thermal performance of the DSWHSCPHES under exposure is inferior to that of the TWGETSWH with an identical collector area.
14	Alexios Papadimitratos (2016)	Evacuated tube	Experimental	Tritriacontane & Erythritol		Efficiency Improvement of dual-PCM solar water heater for both static and stagnation temperature

Padovan & Manzan [17] generated an optimization tool for PCM thermal energy storage in a DHW system to enhance energy saving and to reduce the volume/space required by the system. They analyzed different designing parameters, such as tank dimensions, PCM melting temperature point, and insulation thickness. The findings indicated that the effects of tank geometry and insulation thickness on energy saving in thermal storage are limited.

Nkwetta et al. [18] numerically studied the performance of a DHW tank integrated with different PCM types in various locations (sodium acetate trihydrate +10% graphite, industrial grade granulated paraffin wax, RT58-Rubitherm, and Paraffin wax) using TRNSYS simulation software.

Serale et al. [19] compared The PCM-slurry-based solar collector with the water-based solar collector. The PCM slurry, as the heat transfer fluid, could improve the system efficiency about 20–40%.

Mahfuz et al. [20] experimentally studied the performance of the SWH system with the shell-and-tube thermal energy storage using paraffin. It was found that the energy efficiency of the system was in the range of 63–77% and the exergy efficiency was between 6.02% and 9.58%. The total life cycle cost decreased with the increase of the flow rate of the heat transfer fluid.

The composite of three types of spherical-encapsulated PCM with different melting temperatures was compared with single PCM for use in the storage tank of the SWH system by Yang et al. [21]. The experimental setup is as shown in fig. 6. The multi-PCM system was found with higher collection efficiency, but lower exergy efficiency than the single-PCM system.

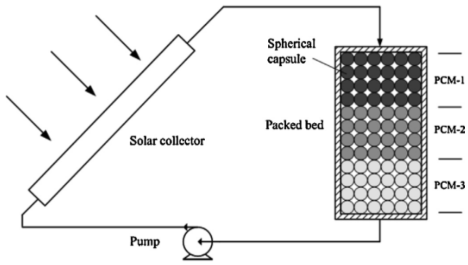

Fig. 6. Schematic diagram of the solar storage packed bed with multi PCM

The compound parabolic concentrating solar collector with the PCM stored in the tank had been proposed by Chaabane et al. [22]. The myristic acid and Rubitherm 42 graphite were theoretically and experimentally investigated and compared, and the myristic acid was concluded with better performance than the rubitherm 42 graphite for use in the system.

Xue [23] performed Tests of exposure and constant flow rate to investigate the thermal performance of a domestic solar water heater with solar collector coupled phase-change energy storage (DSWHSCPHES). Due to the low thermal conductivity and high viscosity of PCM, heat transfer in the PCM module is repressed. The thermal performance of the DSWHSCPHES under exposure is inferior to that of traditional water-in-glass evacuated tube solar water heaters (TWGETSWH) with an identical collector area. DSWHSCPHES also performs more efficiently with a constant flow rate than under the condition of exposure. Thermal energy storage unit is shown in fig. 7.

Papadimitratos [24] and others presented a method of integrating phase change materials (PCMs) within the evacuated solar tube collectors for solar water heaters (SWHs). In this method, the heat pipe is immersed inside the phase change material, where heat is effectively accumulated and stored for an extended period of time due to thermal insulation of evacuated tubes. The proposed solar collector utilized two distinct phase change materials (dual-PCM), namely Tritriacontane and Erythritol, with melting temperatures of 72°C and 118°C respectively. Beyond the improved functionality for solar water heater systems, the results from this study show efficiency improvement of26% for the normal operation and 66% for the stagnation mode, compared with standard solar water heaters that lack phase change materials.

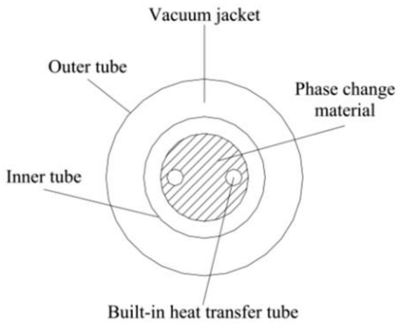

Fig. 7. Schematic diagram of thermal energy storage unit using $Ba(OH)_2.8H_2O$ PCM.

5. Conclusions

In this paper, the review on the SWH system with the PCM was carried out. The review works relating to the SWH system using PCM was analyzed involving structural characteristics and research methods. Different types of collectors are observed along with experimental and numerical study. As described in the table 1 the integration of PCM with components of SWH was analyzed. This research will help identify the potential in the SWH system, indicate the research gap in the SWH system with PCM for the researchers, promote the application of the SWH system in the market and contribute to the energy-saving and carbon emission reduction globally.

1. Improving characteristics of PCM, e.g., eliminating super-cooling phenomenon, maintaining stable over long period, and inventing cost-effective categories, for the application in SWH system.
2. Developing new SWH system for integration with PCM, e.g., solar collector, and delivering pipes.
3. Performing long-term and real-weather testing for optimizing operational and structural parameters of novel system.
4. Proposing standardization of new system for design, manufacture, utilization and marketing.

References

[1] IEA, SHC Programme. Solar heat worldwide, edition 2009

[2] Xi P, Duan Y, Fei P, Xia L, Liu R, Cheng B. Synthesis and thermal energy storage properties of the polyurethane solid–solid phase change materials with a novel tetrahydroxy compound. Eur Polym J 48, 2012, 1295–303.

[3] Oro E, Gracia de A, Castell A, Farid MM, Cabeza LF. Review on phase change materials (PCMs) for cold thermal energy storage applications. Appl Energy; 99, 2012, 513–33.

[4] Whitman CA, Johnson MB, White MA. Characterization of thermal performance of a solid–solid phase change material, di-n-hexylammonium bromide, for potential integration in building materials. Thermochim Acta 531, 2012, 54–9.

[5] Cai Y, Hu Y, Song L, Kong Q, Yang R, Zhang Y, et al. Preparation and flammability of high density polyethylene/paraffin/organophilic montmorillonite hybrids as a form stable phase change material. Energy Convers Manag; 48, 2007, 462–9.

[6] Sari A, Karaipekli A, Alkan C. Preparation, characterisation and thermal properties of lauric acid/expanded perlite as novel form-stable composite phase change material. Chem Eng J 155, 2009, 899–904.

[7] Sari A, Bicer A, Karaipekli A. Synthesis, characterisation, thermal properties of a series of stearic acid esters as novel solid–liquid phase change materials. Mater Lett 63, 2009, 1213–6.

[8] Kaygusuz K. Experimental and theoretical investigation of latent heat storage for water based solar heating systems. Energy Convers Manage 36, 1995, 315–23.

[9] Chaurasia P. Phase change material in solar water heater storage system. In: Proceedings of the 8th international conference on thermal energy storage, Stuttgart, Germany; 2000.

[10] Canbazoglu S, Sahinaslan A, Ekmekyapar A, Aksoy ÝG, Akarsu F. Enhancement of solar thermal energy storage performance using sodium thiosulfate pentahydrate of a conventional solar water-heating system. Energy Build 37, 2005, 235–42.

[11] Y.Q. Li, Y.L. He, H.J. Song, C. Xu, W.W. Wang. Numerical analysis and parameters optimization of shell-and-tube heat storage unit using three phase change materials. Renewable Energy;59, 2013, 92-99

[12] Khalifa AJN, Suffer KH, Mahmoud MS. A storage domestic solar hot water system with a back layer of phase change material. Exp Therm Fluid Sci 44, 2013, 174–81.

[13] X.X. Han, Y. Tian, C.Y. Zhao. An effectiveness study of enhanced heat transfer in phase change materials (PCMs). International Journal of Heat and Mass Transfer;60, 2013, 459–468.

[14] Pascal Henry Biwole, Pierre Eclache, Frederic Kuznik. Phase-change materials to improve solar panel's performance. Energy and Buildings;62, 2013, 59–67.

[15] Mohammad Ali Fazilati, Ali Akbar Alemrajabi. Phase change material for enhancing solar water heater, an experimental approach. Energy Conversion and Management;71, 2013, 138–145.

[16] López-Navarro A, Biosca-Taronger J, Corberán JM, Peñalosa C, Lázaro A, Dolado P, et al. Performance characterization of a PCM storage tank. Appl Energy 119, 2014, 151–62.

[17] Padovan R, Manzan M. Genetic optimization of a PCM enhanced storage tank for solar domestic hot water systems. Solar Energy 103, ,2014, 563–73.

[18] Dan Nchelatebe Nkwetta, Pierre-Edouard Vouillamoz, Fariborz Haghighat, Mohamed El-Mankibi, Alain Moreau, Ahmed Daoud. Impact of phase change materials types and positioning on hot water tank thermal performance: Using measured water demand profile. Applied Thermal Engineering; 2014:67:460-468.

[19] Gianluca Serale, Sara Baronetto, Francesco Goia, Marco Perino. Characterization and energy performance of a slurry PCM-based solar thermal collector: a numerical analysis. Energy Procedia; 48, 2014, 223 – 232.

[20] Mahfuz MH, Anisur MR, Kibria MA, Saidur R, Metselaar IHSC. Performance investigation of thermal energy storage system with phase change material (PCM) for solar water heating application. Int Commun Heat Mass 57, 2014, 132–9.

[21] Lei Yang, Xiaosong Zhang, Guoying Xu. Thermal performance of a solar storage packed bed using spherical capsules filled with PCM having different melting points. Energy and Buildings; 2014:68:639–646.

[22] Monia Chaabane, Hatem Mhiri, Philippe Bournot. Thermal performance of an integrated collector storage solar water heater (ICSSWH) with phase change materials (PCM). Energy Conversion and Management;78, 2014, 897–903

[23] H. Sheng Xue. Experimental investigation of a domestic solar water heater with solar collector coupled phase-change energy storage. Renewable Energy; 86, 2016, 257-261

[24] Alexios Papadimitratos, Sarvenaz Sobhansarbandi, Vladimir Pozdin, Anvar Zakhidov, Fatemeh Hassanipour. Evacuated tube solar collectors integrated with phase change materials. Solar Energy; 129, 2016, 10–19