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Applications of phase change materials in solar water heating systems: A review

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Abstract

The use of a phase change material for the storage of latent heat is an ideal approach for the storage of thermal energy due to the high thermal density of storage, the isothermal nature of the storage process, and the ease with which it may be controlled. In recent years, there has been a rise in the use of latent heat storage systems for the purpose of energy conservation, solar heating systems, and waste heat recovery systems. The use of solar water heaters in practical settings has become more widespread. After providing a summary of the information that has been disseminated on the theoretical uses of water heaters, this article begins by examining the research that has been conducted on the practical applications of solar water heaters. This article includes covers methods to improve the efficiency of these systems as well as research on solar water heaters that combine phase change material with solar water collectors. This paper concludes with several suggestions for further research on phase change material-based water heaters. The completion of this review in a fruitful manner leads to a greater comprehension of the research and development of phase change material-based water heaters as well as the many methods by which these heaters might be improved.

Keywords: Phase change material; Composite phase change material; Solar water heating; Solar collector; Practical applications

1. Introduction

In recent years, it has been vital to look for new sources of energy due to the fact that the use of traditional sources of energy has a negative effect on the environment. This is in addition to the fact that there are finite sources of energy. One of the forms of energy that is least harmful to the surrounding ecosystem is solar thermal energy. Solar water heaters are one of the systems that convert solar energy into thermal energy for the purpose of storing water for home and industrial use. Solar energy may be used for a variety of applications, including heating water. This kind of application is regarded as being good to the environment since it satisfies the requirements for hot water without the use of conventional sources and at the lowest possible cost to run it. The expansion of the global business market for products requiring this kind of application has made it imperative that this kind of energy be developed. Solar heaters have poor efficiency, have substantial losses at night, and have limited storage capacity; as a result, there is a significant amount of area for improvement in this sort of application. In recent decades, there has been a growing amount of interest in the use of phase change materials due to the favorable thermal and physical characteristics that these materials possess, in addition to their high energy density. Because of their poor thermal conductivity, phase-change materials are not yet widely available in the commercial sector and cannot be used in sun heaters. There have been several research done that each recommend a different approach to solving this issue.

2. Experimental Studies on Domestic Solar Water Heaters

In order to deal with fast-depleting resources and the implications of climate change, a number of nations have put considerable effort into producing renewable energy. The solar water heater market exploded during this time period.

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This is according to Qiu et al (2015). Since demand has increased for them, numerous scientists have set out to perfect solar-powered water heating systems. To determine how collector tilt-angle affects the thermal performance of evacuated tube solar water heating systems (ETSWHs), Tang et al., (2011) performed an experimental investigation. Two sets of ETSWH were built and tested, each with the same specifications except for the inclination angle from the horizon. One set is slanted at an angle of 46 degrees, while the other is inclined at an angle of 22 degrees. Daily solar thermal conversion efficiency was found to be the same between the two collectors, and raising the collection tilt angle had little to no impact.

The core component of ETSWHs is a sealed glass tube. Within the inner glass tube of each tube is a uniquely shaped absorbent surface. An outer tube of larger diameter glass surrounds an inner tube of smaller diameter glass; the area between the two tubes is evacuated to minimize heat loss. There are two primary categories of ETSWHs, including water in glass and heat pipe. When it travels through the pipes, the water gets warmed (Morrison et al., 2004; Zambolin & Del, 2010). The vacuum between the absorber surface and the exterior glass minimizes heat loss due to convection. As a result, solar water heaters made using evacuated tubes are preferred over those made with flat-plate collectors (Budihardjo et al., 2007). Flat plate solar water heating systems (FPSWHSs) were evaluated by Budihardjo and Morrison (2009) and compared to evacuated tube solar heaters. Evacuated tube solar water heaters were tested using a computer model of the thermosyphon circulation in the tubes in addition to experimental studies of the optical characteristics. Evacuated tube solar heater performance was shown to be less sensitive to variations in tank capacity than that of flat plate collector systems.

Ayompe & Duffy (2013) investigated the thermal performance of a solar water heating system by collecting data from a year of field trial installation. A sub-system and electric immersion heater have been integrated to regulate draw-offs and deliver "additional" energy when there is sufficient solar radiation available in order to simulate the need for hot water in residential buildings. Water exiting the collector reached a maximum temperature of 70.3 °C, while the bottom tank was 59.5 °C. Supercritical carbon dioxide was proposed by Zhang and Yamaguchi (2008) for use as a working fluid in solar collectors. To estimate and study the solar collector, an experimental setup was built, and the collector was put through its paces in a variety of climates. The findings revealed that as the amount of solar radiation increased, so did the fundamental collector features, including the mass flow rate, pressure, and temperature of carbon dioxide. The average efficiency of a solar collector using supercritical carbon dioxide was determined to be 60%, which is more than the efficiency of a solar collector using water. Using a vacuum tube solar collector with an inside spherical coil, Ghaderian & Sidik (2017) propose employing an Al_2O_3/distilled water nanofluid. The system is made up of a horizontal tank that can hold up to 100 liters of liquid, a spiral coil within the tank, and 18 vacuum tubes that are all linked to the tank in some way. The findings demonstrated that the collector efficiency improved significantly along with the flow rate and nanoparticle size fractions. During the course of two months, Siuta-Olcha et al. (2021) tested the performance of an evacuated solar collector with 24 tubes of the heat pipe type and a gross area of 3.9 m^2. Lublin, Poland was the site of the trial. Over the months of July and August, it was determined that the average thermal gain was (163) and (145) W/m^2, respectively, at solar irradiation levels of (80) and (112.8) kWh/m^2. As the wind speed reached 0.86 m/s, thermal efficiency dropped by 67% and exergy efficiency dropped by 41%. Over the time period under study, the solar collector had an average monthly energy efficiency of between 45.3% and 32.9%.

Keeping warm without contributing to global warming is now the most pressing problem confronting humanity as a whole. Final energy consumption for heating accounts for 47% of the global total, greater than the combined totals for electricity generating (17%) and transportation (27%). The building is responsible for 35% of global final energy consumption, the emission of 25-33% of black carbon, 66% of halocarbons, and 10.6 GtC of CO_2. Climate change is increasing the building industry's need for energy to heat water and indoor spaces (Ürge-Vorsatz et al., 2015). Subzero temperatures, poor solar insulation, and frigid winds all pose challenges for solar energy harvesting in cold locales. Abas et al., (2017) developed a thermosyphon-driven supercritical CO_2 fluid-based solar water heating system for use in locations with subzero temperatures. The solar collector consists of a number of parallel U-tubes that are inserted into fins inside of evacuated glass tubes. When its temperature rises to its critical level, carbon dioxide becomes a more efficient heat conductor. At ambient temperatures of 30–35 degrees Celsius, the findings show that the CO refrigerant soon reaches 75 degrees Celsius, with a collector efficiency of 80–85%. Shafieian et al. (2019) conducted theoretical and practical tests of the effectiveness of a heat pipe solar water heating system to meet a real home hot water demand pattern under less-than-ideal climatic conditions on a cold day in Perth, Western Australia. Using a mathematical model, the ideal number of glass tubes for solar collectors was determined. Based on the collected data, an experimental rig consisting of 25 glass tubes was evaluated as the temperature fluctuated.

3. Numerical Studies on Domestic Solar Water Heaters

Many studies have been conducted to develop numerical models as an alternative to high-priced experimental research. As a result, expensive experimental labor may be reduced, allowing for more efficient performance analysis. The temperature and flow characteristics of single-ended ETSCs have been the subject of a number of reports, both experimental and numerical. Using computational fluid dynamics, Shah & Furbo (2007) looked into the flow structures and heat transfer inside all-glass evacuated tube collectors under different circumstances of operation. A total of five different intake mass flow rates, from 0.05 kg/min to 10 kg/min, were modeled at 333 K and applied to one of three different tube lengths (0.59 m, 1.47 m, or 1.47 m). Results showed that the collector with the shortest tube length performed best under these circumstances. An innovative domestic solar water heating system (DSWH) using an evacuated tube collector (ETC) was studied in Tunisia by Hazami et al., 2013. First, a comprehensive model was developed with the help of TRNSYS, which accounted for many pathways through which heat would be transferred inside the DSWH. To ensure the TRNSYS model is accurate, it was tested in the field for six days throughout two months under typical local weather circumstances (November and July 2010). It was found that the ETC produced around 9% more energy than the FPC. When comparing the ETC DSWH system to the FPC DSWH system, the ETC system clearly excels in terms of thermal performance. Compared to the FPC DSWH system, it performs better in environments with low temperatures for DHW use. Yao et al., (2015) used Computational fluid dynamics (CFD) to analyze and compare the performance of the all-glass evacuated tube solar water heater with twist tape inserts to normal ones. Numerical modeling was used to analyze the flow and heat transfer performance of evacuated tube solar water heaters with twist tape inserts at various beginning temperatures (ranging from 273K to 313K). Inside a single collector tube, a numerical model of fluid flow and heat transfer has been constructed. The twist tape inserts minimize the magnitude of the velocity and make the temperature field more uniform, according to the findings. At relatively high temperatures, the twisted tape inserts aid heat transfer; but, at relatively low temperatures, they hinder heat transfer. The mean Nusselt values of the evacuated tube solar water heaters with $y = 2.5$ and 4 are respectively 1.07 percent lower and 9.29 percent higher than the standard solar water heater across the range examined.

Sokhansefat et al. (2018) looked at the thermos economics of using two different solar hot water systems in Iran's cool climate, one using flat plate collectors (FPC) and the other using evacuated tube collectors (ETC). The annual energy production and collector temperature were calculated using the TRNSYS16 program. It is concluded that the input temperature and the weather conditions are the two most important aspects in determining the collector's output. Last, the thermal and economic analysis found that ETC systems outperformed FPC systems by 41% and that the annual useable energy gain for ETC systems in cold environments was 30% higher than that for FPC systems. Thus, ETC is recommended for use in cold climates. Sharma and Diaz (2011) created a mathematical model of a novel micro channel-based solar collector. The thermal performance of a novel micro channel-based solar collector was quantified. This collector is made up of a U-shaped flat-tube absorber with a selective coating on its outside surface. The model's findings show an improvement in efficiency when compared to a similar-sized evacuated-tube collector without microchannels. The heat path from the absorber surface to the working fluids is shortened, allowing for higher operating temperatures. The gap loss impacts the efficiency of the mini channel-based collector with a concentrator, which may be reduced by further refining the shape towards the bottom of the concentrator. The heat transfer and stable natural convection flow in a single-ended tube subjected to a non-uniform heat input were studied by Shahi et al., (2010) using a three-dimensional numerical simulation. Hydrodynamic and thermal characteristics have been studied in relation to the inclination angle and maximum heat input. A set of governing equations were developed from the conceptual model in cylindrical coordinates. A fully implicit finite volume control approach was then used to approximatively solve the governing equations on the collocated arrangement using the SIMPLE algorithm (FVM). The findings demonstrate that the maximum output mass flow rate increases as the angle of inclination increases, and that the overall mean Nusselt number is highest at an inclination of 35 degrees.

Kabeel et al., (2015) developed a method for modelling heat transfer processes and absorbed solar radiation in evacuated tube solar collectors. , Liu et al., (2017) employed a high-throughput screening (HTS) technique based on an ANN model. For the training and testing sets of the modeling technique, the 915 data groups were taken in Beijing in the springtime using the standard measurement criteria of GB191412011 (GB/T 19141, 2011). Using computational fluid dynamics, Essa & Mostafa (2017) investigated a transient, three-dimensional simulation of water flow within a single-ended evacuated tube solar collector coupled to a storage tank. Xu et al., (2012) assessed the thermal performance of all-glass evacuated solar water heaters utilizing air as a heat transfer fluid under dynamic situations outdoors. Multiple linear regression (MLR) was used to find parameters in the suggested dynamic model since it is a common and easy math technique.

4. Phase Change Materials Incorporated in Solar Water Heaters

Heat can be stored and regulated with ease with PCM since its phase change mechanism is temperature dependent. PCMs are of great interest because of their large heat storage density, almost isothermal heat release and absorption process, and simple control and management. The technique of storing energy may be classified as either solid-solid, solid-liquid, solid-gas, or liquid-gas, depending on the PCM used. Unfortunately, the high volume and pressure shift that occurs during the phase transition of liquid-gas and solid-gas processes renders them unsuitable for heat storage. This article focuses mostly on solid-liquid PCMs since they are the most promising for application as thermal energy storage. There are three types of solid-liquid phase transition materials (PCMs): organic phase change materials, inorganic phase change materials, and eutectics. In Table 1 we see a comparison of the various PCMs available. Phase change energy storage substances may be categorized as either greater, modest, or low temperature depending on the temperature at which the material undergoes its phase change. Solar PCMs operate in the 300 °C to 350 °C temperature range. Solar PCMs operate in the 300 °C to 350 °C temperature range. In this temperature range, PCMs are most often employed as energy storage materials and are the focus of research for a variety of different fields. Phase change energy storage is a kind of low-temperature energy storage that may be used with solar energy.

Table 1 A comparison of the benefits and drawbacks of different PCM types

Classification	Advantages	Disadvantages
Organics	-Excellent compatibility with a variety of substances -Accessibility throughout a wide temperature range -Very little or none of the undercooling -Stability both chemically and thermally -high heat of fusion with no corrosive elements	-Inflammability -a low coefficient of heat conductivity -Changes in volume that are somewhat significant -Reduced enthalpy of phase transition
Inorganics	-Higher enthalpy of the phase transition -Low costs and volume of the change -a high level of thermal conductivities	-The separation of phases -Instability in regard to temperature -Insufficient cooling, as well as corrosion
Eutectics	- rapid melting point - high-density thermal storage in volume	-An extremely poor heat conductivity -Corrosion that occurs at high temperatures

With the goal of optimizing the performance of a conventional evacuated tube collector, Algarni et al., (2020) investigated the application of composite phase change materials in an evacuated tube solar collector as a waste heat recovery device. This innovative device integrates the U-pipe of an evacuated tube collector with composite phase change materials to provide heat even when the sun's rays aren't strong enough to do it on their own. According to the findings, the efficiency of the evacuated tube collector was improved by 32% when a 0.33 wt% copper/PCM composite was added to it. In addition, the ETSC/Ne-PCM system, with a specific mass flow of 0.08 L/min, can provide hot water at 50 °C for around 2 hours longer than a standard ETC system. In 2016, Feliski and Sekret showed off their novel concept for a vacuum tube collector/storage system that makes use of a phase-change material. To create the PCM, tubes equipped with heat pipes were filled with commercial-grade paraffin. Paraffin's impact on the collector/storage thermal performance of evacuated tubes was investigated experimentally. The findings also showed that the total amount of usable heat collected from the paraffin-integrated evacuated tube collector/storage system increased by 45-79 percent compared to an evacuated tube collector, depending on the velocity with which the heating medium moved through the system during the discharge cycle.

It was shown in an experiment by Al-Hinti et al., 2010 how effective phase change materials (PCMs) are as water storage in conventional solar water heating systems. Paraffin wax stored in cylindrical metal containers. The cylindrical hot water storage tank was used to store the containers on two levels. It was found that by using the PCM, a higher temperature of 13-14 °C can be maintained in the hot water for an extended period of time. The efficiency of the storage was also evaluated when combined with flat plate collectors and used in a closed-loop system with conventional natural circulation. The water's temperature was at least 30 degrees Celsius greater than the ambient air temperature during the 24-hour test. In 2017, Feliski and Sekret presented research on how PCM affects the normal operating parameters of an evacuated tube solar water heating system. The solar percentage and internal tank temperature of a residential hot water system were monitored during a typical year in the Polish city of Czestochowa. The charging efficiency of the evacuated tube collector/storage varied from 33 to 66 percent depending on the PCM temperature and the amount of solar energy.

The effect of nano CuO at varying concentrations on paraffin's performance in a solar water heating system was studied and analyzed by Mandal et al. (2019). When the concentration of tiny CuO particles in CuO-PCM nanocomposite varies, the water's exit temperature, the CuO-PCM composite's temperature, and heat transmission in the solar water heater all decrease. Using three different volume concentrations of CeO_2 nanoparticles, 0.0666 percent, 0.0333 percent, and 0.0167percent, while maintaining a mean particle diameter of 25 nm, Sharafeldin & Gróf (2018) investigated the effect of using CeO_2 water on the efficiency of flat-plate solar water heaters. Using ultrasonics, we were able to keep the CO_2-water nanofluid stable. The performance of the collectors increased when the CeO_2-water nanofluid was utilized in place of plain water.

In order to determine how the use of Phase Change Materials as a storage medium influences the performance of a solar water heater, Fazilati & Alemrajabi (2013) have conducted studies. Heating energy was stored in PCM spheres, a form of paraffin wax, in the solar water heater's tank. The outcomes of low, medium, and high exposure to sunlight were analyzed. The energy and exergy efficiency of the water heater, as well as its ability to keep water hot for an extended period of time, have been evaluated before and after PCM was added to the tank. Using PCM in the tank was shown to enhance energy storage density by up to 39% and exergy efficiency by up to 16%. Theoretical and experimental investigations of a flat-plate solar collector operating with water and CeO_2/water nanofluid were performed by Michael et al. (2019). Experimental research included the construction of a flat-plate solar water heater with a 100-liter-per-day capacity and a 2-square-meter collecting area. It was assumed that the average particle size in nanofluids was 25 nm and that the volume percentage was 0.01 percent. Both water and nanofluids were flowing at speeds of 1-3 lpm. As a comparison to using plain water as the base fluid, the efficiency of a solar water heater using a CeO_2/water nanofluid is a whopping 21.5% higher, coming in at a whopping 78.2%. Experiments showed that 2 lpm was the optimal mass flow rate for nanofluid, yielding the highest collector efficiency.

An effective thermosyphon a flat plate solar collector was evaluated by Murali et al., 2015; they used PCM as the heat source and included it in the tank. A cylindrical aluminum container was used to store the PCM. It was installed in the tank's top. The wax from the paraffin industry was used as the PCM. In order to transport heat from the flat plate collector to the storage tank, water was used. According to the results of the stratification analysis, a PCM cylinder installed in a thermal storage tank improved the tank's efficiency. It took 1110 minutes without PCM and 1530 minutes with PCM to complete the discharge procedure. In addition, the efficiency of charging energy rises with increasing radiation, reaching a high of 82.44 percent in the afternoon, about 2 PM. Klçkap et al. (2018) built and evaluated a latent heat storage tank for use with a hot water collector in the Elazığ environment. The collector system's thermal efficiency was measured and compared to that of insulated tanks. The analysis found that the phase change material tank had the highest thermal efficiency (58%) in the middle of July, about 13:30. (PCM).

Dispersing copper nanoparticles 20 nm in size in paraffin wax allowed Lin & Al-Kayiem (2016) to create Cu-PCM nanocomposites. Five samples of Cu-PCM nanocomposites (Copper-Paraffin wax nanocomposites) were made and analyzed for their thermal properties. The thermal conductivity of Cu-PCM nanocomposites increased by 14%, 23%, 42%, and 46%, respectively, when the weight of nano Cu was dispersed at 0.5 wt%, 1.0 wt%, 1.5 wt%, and 2.0 wt% in the PCM, as determined by experimental characterization. The efficiency of a site test using an integrated solar-TES system rose by 1.7% when nano Cu at a concentration of 1% was added to paraffin wax. Our results suggested that the thermal properties of paraffin wax may be enhanced by using a nano Cu addition for solar thermal energy storage. Using ALEX WAX 600 as a storage medium, Abokersh et al. (2016) presented a revolutionary compact U-tube evacuated tube solar collector. The typical melting point and thermal conductivity of ALEX WAX 600, a PCM, are 60 °C and 0.21 W/m K, respectively. Paraffin wax is not good at conducting heat; hence the suggested setup makes use of a 0.1251 m^2 fin to compensate. According to the results, including fins into the system design greatly enhances the PCM's heat transfer capabilities and the overall stability of the system. The unfinned system releases 35.8 percent more effective energy than the forced recirculation solar water heating system under clear day weather conditions during simultaneous operation testing. For solar water heating, however, the finned system is 47.7 percent more efficient than the forced recirculation method. Using a heat pipe ETSC, Alshukri et al. (2021) conducted an experimental investigation into a unique method of integrating PCMs in either the ETSC or two separate tanks located adjacent to the water tank. Medical paraffin wax was used to fill the ETSC and the two other tanks used to store thermal energy (grade-A). Four heat pipe ETSCs were used in a comparative study. Both a 1 and 2L/h water flow rate was used in the trials. Results demonstrate that efficiency is increased by 55.7 percent when PCM is integrated into both the ETSC and the isolated tanks, and by 49.9 percent when PCM is integrated into the ETSC alone. By comparing the PCM-free reference collector to the one with PCM, the separate tanks showed a 36.5% improvement in efficiency.

5. Conclusion

The study on solar water heaters that use PCM has resulted in several successes, and it has been shown that these types of solar water heaters have significant potential for future expansion. Nonetheless, there are still many obstacles to overcome in the field of LHS research. Further investigation is required in the following areas for the solar water heater that is combined with phase change material:

- The numerical investigation of solar water heating systems. The results of CFD simulations are complete and dependable if the domain in which they are run is planned effectively and has exact boundary conditions, despite the fact that CFD simulations demand sophisticated computer resources and specific boundary conditions.
- Type of phase-changing materials. The majority of phase change materials have some degree of inadequacy in both their heat conductivity and their phase change enthalpy, which restricts the practical use of these materials. To address the issues described above, the primary focus of future research will shift to be on new types of PCM, such as composite PCM, MEPCM, and NEPCM. This shift is necessary in order to make up for the deficiencies mentioned above.
- Improve the rate at which heat is transferred through the PCM. The phase change material (PCM) that is utilized for energy storage often has a low thermal conductivity, which results in a poor heat transfer capacity. As a consequence, the efficiency of the phase change energy storage system is reduced. An increase in the thermal conductivity of PCM may significantly cut down on the amount of time it takes for PCM to solidify or melt, which in turn improves the efficiency of heat transmission. A significant amount of study has been carried out by a variety of specialists in the direction of enhancing the rate at which PCM transfers heat. The primary ways for improving heat transfer include the addition of fins, the addition of high thermal conductivity metal or metal particles, the creation of phase transition microcapsules, and other similar approaches.
- A proposal for improving the performance of solar heaters using PCM. The optimization of a PCM-based solar water heater comprises optimizing the selection of PCM physical qualities, phase change unit layout, phase change material locations, phase change unit form, and other aspects of the phase change unit. While choosing a PCM, for instance, one has to take into account two characteristics like latent heat and phase transition temperature.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest.

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