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Bibliography on PCM Thermal Energy Storage Solar Water Heating Systems

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Abstract: Phase change materials (PCM) in thermal energy storage (TES) are a revolutionary technology for improving solar water heating (SWH) performance because of their substantial heat capacity even during the phase change process and their potential TES at a nearly constant temperature. There have been reports on studies of different types of materials used as PCM and TES for SWH systems with varying efficiency and performance. Thus far, this study has focussed on identifying TES materials, use in SWH technology. Then, compare the thermophysical properties of some TES materials from literature database sources also uncovers the different encapsulation techniques, used for TES materials in SWH systems. The methodology employed in this research is a quantified literature bibliography, citing relevant literature from the science database. Based on the analysis of relevant literature, paraffins, salt hydrates, and fatty acids are the most commonly used PCMs. The latent heat capacity of the three PCMs are relatively high. Paraffins are non-corrosive and non-toxic substances that can be obtained at a wide variety of temperatures. Salt hydrates prone to segregation and supercooling but they have higher thermal conductivity and density than the other materials. Paraffins and fatty acids were usually quite stable than salt hydrates. Physical methods, chemical methods, and physical-chemical techniques are the three types of microencapsulation PCM techniques available. PCMs may be used to capture and gather solar energy, ensuring that hot water is accessible throughout the day. In residential, commercial, and industrial applications, microencapsulated PCM is required in SWH systems.

Keywords: Phase Change Material, Thermal Energy Storage, Solar Water Heating, Encapsulation Techniques, Thermophysical Properties

1. Introduction

Thermal energy storage (TES) is a type of energy storage that stores energy for later uses in heating or cooling. It is a technology that allows to transport and storage of heat energy as well as energy from ice, cold air, or water. It is a material that acquires energy when the temperature rises and loses it as the temperature falls. Using this property allows you to employ a variety of materials with varying thermal properties to produce a variety of results, which can lead to a variety of TES applications such as heating and cooling. TES when used in thermal systems, can help to balance energy demand and supply on a daily, weekly, and even seasonal basis. For instance, off-peak nighttime energy might be used to

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produce hot or cold storage that could be used to power systems during the day. Peak demand, energy consumption, carbon dioxide emissions, and costs may all be reduced using TES, while total energy system efficiency is improved [1].

The concept behind TES is to change how people create the massive quantity of heating and cooling capacity that consumes so much conventional energy from the grid. The problem is that fossil fuels such as coal, oil, and natural gas provide the majority of energy demand, which are restricted and contribute to severe pollution and climate change [2]. Solar water heating (SWH) systems are the most prevalent use for TES. Thermochemical, sensible, and latent heat storage are three types of TES that rely on the change of internal energy inside the storage medium [3]. Latent heat storage is more efficient than sensible heat storage because it offers a considerably higher energy density with a smaller temperature difference between storing and releasing heat [4]. We live in an energy-rich world, yet harnessing and storing it is challenging. Phase change materials (PCM), also known as latent heat storage (LHS) materials, are excellent for applications that need the storage and release of thermal energy. PCMs are materials that can absorb, store, and release a lot of energy by forming and breaking molecular interactions [5]. However, the low thermal conductivity of PCM, results in poor heat transfer rate. The leakages of PCM in the container is a prevailing problem. To address these issues, encapsulations of PCM has been effectively studied with minimal progress. There are different microencapsulation techniques used in the micro or macro encapsulation of PCM-TES integrated SWH systems. And indebt study on this encapsulation techniques and applications in SWH is performed in this current study.

This study carries out the assessment of thermal energy storage with solar water heating systems using a literature bibliography. The other aims are to identify thermal energy storage materials, use in solar water heating technology, to compare thermophysical properties of some thermal energy storage materials from literature database sources and lastly, to identify different encapsulation techniques and materials, use for thermal energy storage materials in solar water heating systems.

2. Materials and Methods

2.1 Materials

Literature reviews are used to quantify the assessment of PCM-TES integrated SWH systems. Review on past and current literatures is divided into three (3) main segments which are: (a) Thermal energy storage, (b) Phase change materials, and (c) Solar water heating. The searched resources used in this study are from science and engineering journals such as material engineering, mechanical engineering, material science, nanotechnology, renewable energy, and solar energy journals.

2.2 Methods

The methodology employed in this research is quantified literature bibliography, citing relevance literatures from science-database. Estimated two hundred and fifty references was be studied for the review assessment. The studied references are itemized in tabular forms. The references used in this study are relevant citations from past and present studies and limited to 2015 to 2021 year of publications. The bibliography references used were two hundred and fifty in number.

3. Results and Discussion

The reviews on TES, SWH system, PCM applications, TES microencapsulation, TES integration techniques with SWH, and applications of SWH integrated with PCM-TES systems.

3.1 Summary studies on types of PCM

There are various types of PCM which are paraffin, fatty acids, alcohol, esters, salt, salt hydrates, metallic compound, and metal alloy. However, paraffin (organic), salt hydrates (inorganic), and fatty acids (organic) are the most commonly utilised PCMs in TES applications as shown in Figure 1 below.

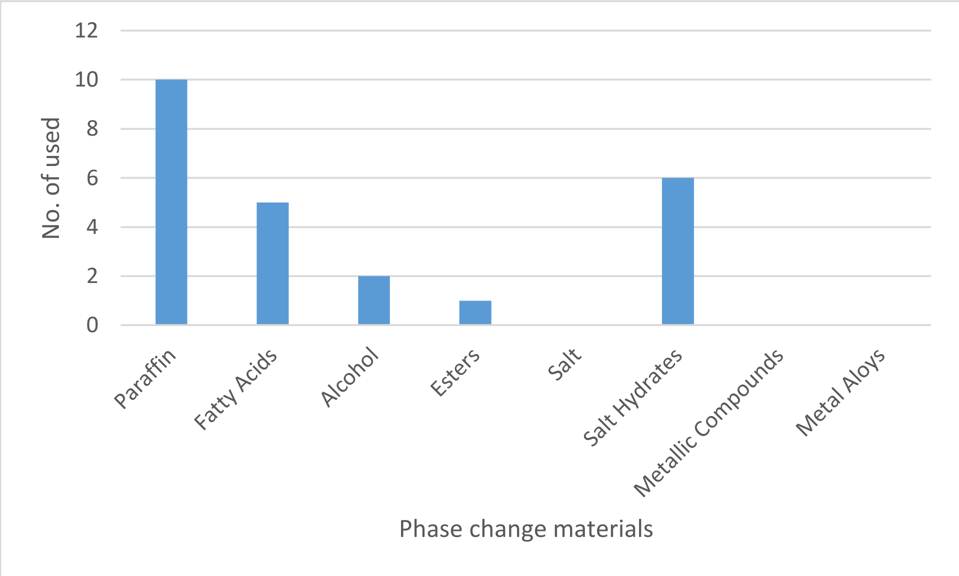

Figure 1: Phase change materials

3.2 Summary studies on PCM applications to SWH

Figure 2 shows the distribution of the literature concerning the cited reports collected. The data shows that review articles make up around 30% of the total number of publications; it should be noted that the review articles are focused on the overall applications of PCM in SWH. Furthermore, experimental studies, which make up the majority, are primarily concerned with the development and evaluation of PCM in the laboratory, with research in real-world conditions. Additionally, numerical simulation is defined in 15% of the publications.

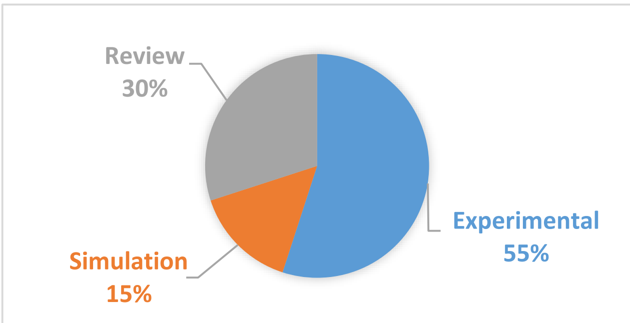

Figure 2: Distribution of the literatures used PCM in SWH

3.3 Summary studies on types of TES systems

Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Heat Storage (THS) are the three types of TES. SHS is well-documented. LHS using phase change materials (PCMs), which primarily use the liquid-solid transition to store latent heat, allows for a smaller, more efficient, and hence more cost-effective system. Despite its appealing potential for long-term energy storage, THS is still in the early stages of laboratory and pilot research. Some research has been done on combining various PCMs to create a sensible storage type system with increased effective heat capacity. Because of its high energy storage density, THS often outperforms SHS and LHS in terms of energy storage performance efficiency. Heat storage at room temperature and long-term energy storage because the products can be cooled and stored at room temperature without energy losses because heat can be stored indefinitely in chemical bonds, the convenience of transport since solid materials can be transported over long distances, constant restitution temperature providing constant heat source. Exothermic processes, after all, take place at sufficiently high temperatures to create electricity under constant circumstances and hence provide constant power.

3.4 Summary studies on TES applications to SWH systems

Figure 3 shows the distribution of the literature to the cited reports collected. The data shows that review articles make up the majority, it primarily focused on the overall TES applications to SWH. Furthermore, experimental studies, which make up around 40% of the total number of publications, are concerned with the development and evaluation of TES in the laboratory, with research in real outdoor conditions. Additionally, numerical simulation is defined in 15% of the publications.

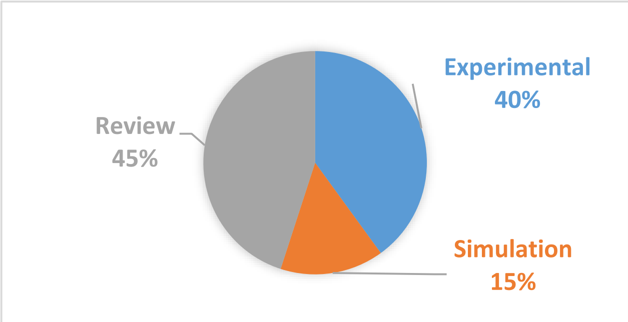

Figure 3: Distribution of the literatures used TES in SWH

3.5 Summary studies on SWH systems

SWH systems are well known and effective structures that transfer sunlight into heat for water heating using a solar thermal collector. SWHs are often applied for residential and some industrial applications. A sun-facing collector heats a working fluid, which is then stored for later use. A SWH system consists of a flat plate solar collector, a storage tank, and connecting pipes. SWH system's efficiency is mostly determined by well-designed solar collectors and proper operation mechanisms.

3.6 Summary studies on SWH applications

Based on Figure 4 above that shows the application of SWH worldwide, between 2009 and 2020, the global capacity of SWH systems started increasing, owing to new legislation that aided sales. Solar collectors, which are commonly found on a building's roof, transform the solar energy into heat, which is then used to heat water. The installed capacity increased every year from 203 to 482 gigawatts thermal until 2018. The global SWH capacity increased to 501 gigawatts thermal capacity in 2020.

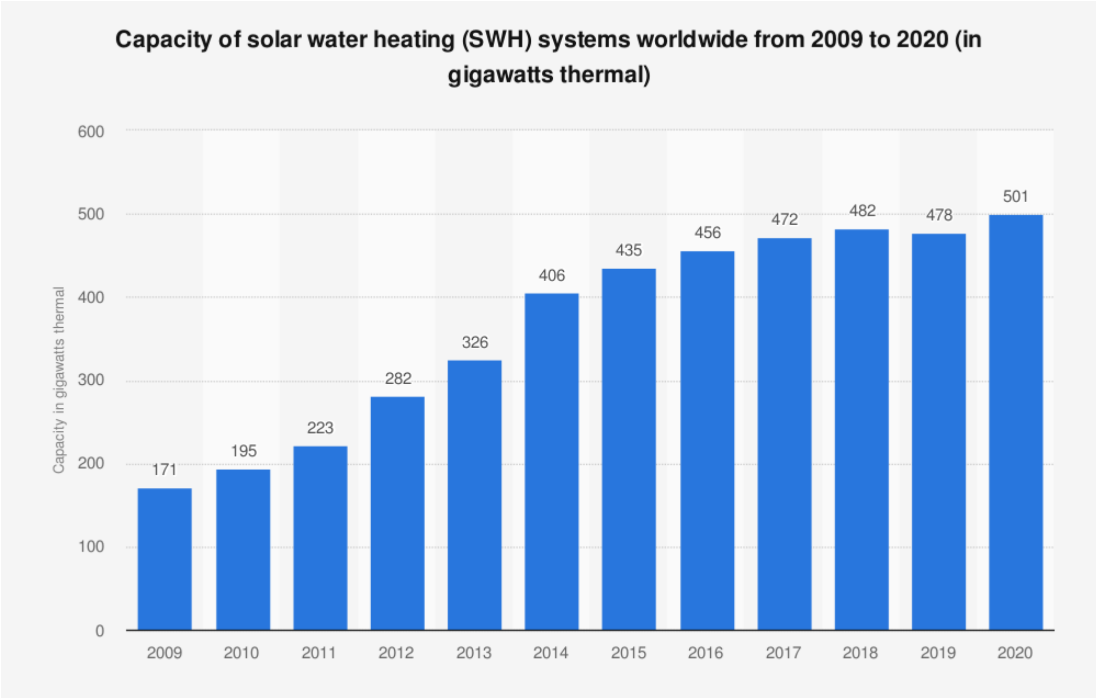

Figure 4: Applications of SWH worldwide [6]

3.7 Summary studies on PCM microencapsulation techniques

Microencapsulation of PCM techniques can be classified into three categories according to the synthesis mechanism which are physical methods, chemical methods, and physical-chemical methods. The formation of microcapsule shells through physical methods is limited to physical processes such as drying, dehydration, and adhesion. The commonly used are spray-drying and solvent evaporation. In situ polymerization, interfacial polymerization, suspension polymerization, and emulsion polymerization are the most common chemical methods. The physical-chemical method combines physical and chemical processes to get a result. To obtain microencapsulation, physical processes such as phase separation, heating, and cooling are combined with chemical processes such as hydrolysis, cross-linking, and condensation. The most representative and commonly used are coacervation and the sol-gel method.

3.8 Summary studies on PCM microencapsulation applications with SWH

Figure 5 shows the distribution of the literature concerning the cited reports collected. The data shows that review articles make up the majority, it primarily focused on the overall applications of PCM microencapsulation to SWH. Furthermore, experimental studies, which make up the second majority around 45% of the total number of publications, are concerned with the development and evaluation of microencapsulation PCM in the laboratory, with research in real conditions. Additionally, numerical simulation is defined in only 5% of the publications.

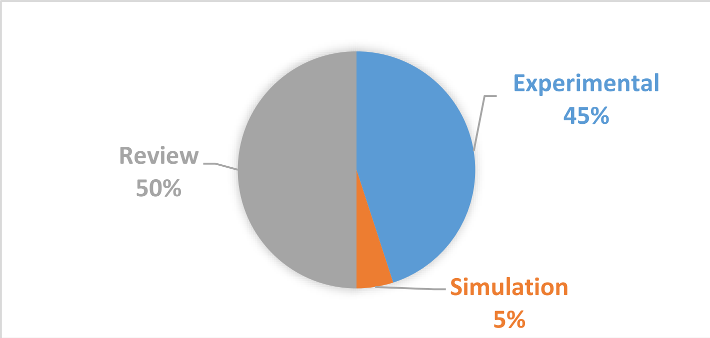

Figure 5: Distribution of the literatures used microencapsulated PCM

3.9 Summary studies on TES integration with SWH

Figure 7 above shows a few benefits of integration TES to SWH systems based on the data collected. They can reduce the overall capital costs and operations and maintenance costs of heating or cooling. TES has the ability to improve energy efficiency while also lowering carbon footprint and greenhouse gas emissions. In addition, by smoothing out any possible supply and demand imbalances as well as system temperature variations, TES can assist enhance overall system stability, performance, and demand response.

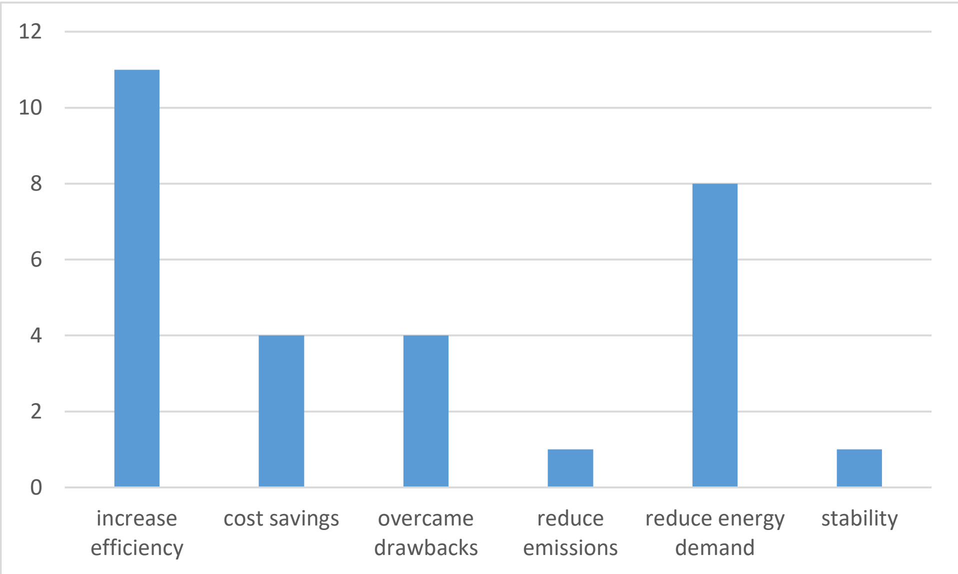

Figure 4.7: Benefits integration of TES

3.10 Summary studies on TES physical and mechanical properties for SWH

Thermal properties such as melting temperature, latent heat of fusion, thermal conductivity, and the solid and liquid density are the first things to analyze. The melting temperature should be matched to the required operating temperature, such as outdoor design temperature when selecting PCMs incorporated into SWH systems. The latent heat of fusion per unit mass should be as high as possible, allowing for the utilization of a smaller material container and a lower amount of material to store the needed amount of energy. High thermal conductivity is advantageous since it determines heat transfer during fusion or solidification and aids the pace of heat charge and discharge. A high density is preferable so that materials take up less space. The PCMs should fully melt, resulting in a homogenous liquid and solid phase. Furthermore, to minimize containment issues, small volume changes during phase transition and low vapour pressure at the working temperature are both selection criteria.

Comparison for the thermal properties of the PCMs based on the data collected illustrated in Table 1 below.

Table 1: Thermal properties of the common PCMs

Properties	Types of PCMs		
	Paraffin	**Fatty Acids**	**Salt Hydrates**
Melting Temperature	Low	High	High
Latent Heat of Fusion	High	High	High
Thermal Conductivity	Low	Low	High
Density	Low	Low	High
Volume Changes	Large	Large	Small
Vapour Pressure	Low	Low	Low
Thermal Stability	Good	Good	Lack
Segregation and Supercooling	No	No	Yes
Corrosive	No	Yes	Yes

3.11 Summary studies on techno-economics of SWH

The techno-economics in SWH can prevent the emission of tones of CO_2 per year and some other harmful pollutants. It is also very economic with a payback period of 3 to 4 years with the help of the government subsidies. SWH systems also have the flexibility to be operated on auxiliary power in low ambient conditions or bad climatic conditions. It is an attractive option for energy, cost savings and also maintenance of eco-balance. Widespread utilisation of SWH can reduce a major portion of the predictable energy being used for heating water in households, industries, commercial, and other institutional establishments.

3.12 Summary studies on SWH for thermal comfort in building

Thermal comfort in the building can be achieved through the sustainable design of SWH systems. Advantages of this systems are endless amounts of energy, no CO_2 emissions during operation of the systems, it also used less energy to heat water which is caused to cost savings, its reduced consumption of fossil fuels and also this systems work efficiently even in winter which brings thermal comfort in the building.

4. Conclusion

Based on the analysis of relevant literature, there are various types of PCMs which are paraffin, fatty acids, alcohol, esters, salt, salt hydrates, metallic compound, and metal alloy. However, paraffin, salt hydrates, and fatty acids are the most commonly used PCMs. The latent heat capacity of the three PCMs is relatively high. Paraffin are non-corrosive, non-toxic, reliable, and cheap substances that can be obtained at a wide variety of temperatures. Despite that, fatty acids and salts hydrates are corrosive. Salt hydrates tend to have segregation and supercooling than the other materials but providing nucleating agents will avoid the problems. The thermal conductivity and density of salt hydrates were higher than paraffin and fatty acids. However, adding carbon additives or fillers will increase the thermal conductivity of paraffin or fatty acids. Because paraffin and fatty acids are passive, they do not require any additional energy and are usually quite stable from a chemical standpoint when in a very longer crystallisation-melting cycle that will contribute to the most efficient TES rather than salt hydrates. Improving the thermophysical properties of PCMs in a TES system is necessary for energy storage and release efficiency. Encapsulation, the inclusion of highly thermally conductive materials such as carbon-based nanomaterials, metallic or inorganic nanoparticles, and the production of form-stable PCM can all help improve thermal properties. Physical methods, chemical methods, and physical-chemical techniques are the three types of microencapsulation PCM techniques available. Spray-drying and solvent evaporation are two popular physical techniques. The most popular chemical methods are in situ polymerization, interfacial polymerization, suspension polymerization, and emulsion polymerization. In physical-chemical techniques, coacervation and the sol-gel method are the most typical and widely utilized. PCMs may be used to capture and gather solar energy, ensuring that hot water is accessible throughout the day. In residential, commercial, and industrial applications, microencapsulated PCM is required in SWH systems.

Several recommendations for the system performance are made for future study. It is advised that current information be incorporated to offer better facilities to end-users to deliver better and more cost-effective PCM performance in energy storage applications. Improvements in the performance and efficiency of thermal systems using TES, as well as improved materials, storage arrangements, and operational techniques, will almost certainly be explored in the future, particularly where they are essential to industry. The thermophysical properties of PCMs are essential for the advancement of TES technology. Even though numerous researchers have created and examined a range of high temperature phase change thermal storage materials, the amount of data available is still insufficient. Researchers must concentrate on fundamental parameter measurements to provide a complete database of thermophysical properties for the selection of appropriate materials. Future studies should concentrate on strategies to improve and optimize PCM heat transmission. To deliver significant and beneficial societal benefits in sustainable living, more research into the development of efficient and cost-effective PCMs with minimal aging effects for solar TES applications is required.

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