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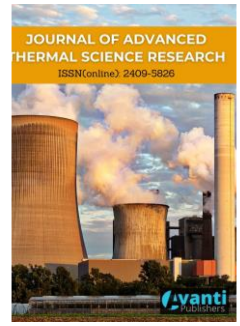

Laboratory Configurations for PCM-TES Materials: A Review

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ABSTRACT

The global energy crisis and the negative impact on the environment of the existing technologies have constrained researchers to capture several types of waste energy using different technologies and materials. For heat, energy harvesting technologies include a major source, the sun, and as an effective storage media, phase change materials. The current review covers experimental laboratory configurations used for thermal energy storage (TES), mainly with phase change materials as working fluids. The required characteristics of PCM-TES materials are covered. Geometric configurations, starting with simple shell-and-tube heat exchanger (HX), other multiple constructive alternatives, plate HX, and also modular HX or fixed and fluidized beds systems are overviewed in order to concentrate on heat transfer characteristics important for TES systems operation and optimization. Emphasis falls on important constructive characteristics for thermal performance, such as the heat charge and discharge rates, within specific temperature ranges, depending on the type of TES fluid used, the energy storage capacity, or density. The advantages and disadvantages of each constructive piece of equipment are critically reviewed. Some comparisons among designs are also included, with an accent on beneficial alterations to improve thermal features.

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1. Introduction

Every year, the environment is polluted with greenhouse gasses such as carbon dioxide, produced by the combustion of fossil fuels (such as coal, natural gasses, & oil) for energy, industry, and transportation. Pollution is in continuous growth. Gas emissions also negatively impact the environment. Changing the climate (global warming) is just one of the effects of greenhouse gas pollution.

To reduce pollution and fossil fuel consumption, to develop new technologies in energy production, and to meet to a close level the continuously increasing energy demand of the modern society, scientists have investigated renewable and clean energy sources (e.g., solar wind and hydro energies, ocean waves, tidal energy, and biogas). These sources had a major role in restoring the balance in nature by reducing pollution, reducing the use of natural resources, and fulfilling energy demands [1]. Keeping the balance between fluctuating resources, utilizing unused energy, reducing energy consumption, and integrating more renewable energy are some of the goals that scientists want to achieve by using thermal energy storage devices [2].

TES technologies have the potential to be an important factor in increasing the use of renewable sources in energy systems and also provide the flexibility to integrate non-conventional energy sources so that they can be applied as a solution to the problems listed above, for both domestic use and industrial processes [3]. The energy can be absorbed and stored within the system for hours, days, weeks, or months, allowing for night/day or seasonal supply and requirements disparities to be solved.

Nevertheless, TES systems have several benefits, including increased efficiency and dependability, improved economics, lower investment costs, and less pollution (e.g., greenhouse gasses) [3]. The storage medium can be located in spaces of various types, including tanks, ponds, caverns, and underground aquifers [4]. However, the need for more diverse energy storage systems suitable for diverse applications is high, and thus, new materials within novel configurations are still designed and investigated.

Generally speaking, all TES systems exploiting different forms of energy have a strong transient characteristic, and lately, there has been growing research interest in addressing this aspect, especially the so-called rate issue, i.e., the rate at which the energy is charged and discharged, in different PCM-TES systems [5]. These comprise a diversity of materials with special physico-thermal properties such as high thermal conductivity, high heat capacity, and low viscosity that are used more or less efficiently within many configurations. Despite the high number of studies, most of them use one type of TES material with well-described, sometimes enhanced properties [5-9] and also its behavior in one single configuration, with reports on the increased heat transfer coefficients and thus, heat transfer fluxes [10-12]. Comparisons among these designs are hard to make since the material properties can be very different and are affected by different factors. For example, in the case of dispersed nanoparticles or nanoemulsions, parameters influencing the nanofluids microstructure, including surfactant type, dispersed solid/liquid type and their concentrations, molar ratio of dispersed liquid to surfactant, temperature [13,14], and factors such as the number of repeated charge/discharge cycles, make the evaluation difficult.

Additionally, the operation of a certain heat exchanging configuration can be influenced by its geometrical characteristics because the same fluids can behave differently within dissimilar spaces and, thus, determine distinctive operating parameters. As a result, comparing and evaluating the performance of different device designs using various TES fluids is a difficult undertaking. Novel studies should address these differences in thermal storage performance, depending on the energy necessities, and new methodologies should be developed and completed in accordance with the thermal requirements of an energy-storing system.

Thus, this current review concentrates on several significant heat transfer laboratory configurations used to test different types of thermal energy materials in order to provide improved benefits, but also the disadvantages related to the investigated configuration. In addition, it addresses some favorable improvements from one design to another and the key parameters essential to be controlled for each system.

2. PCM-TES Systems

2.1. TES Materials

Heat can be stored as sensitive heat, latent heat, chemical heat, or a combination of these, the enumerated forms corresponding to increasing amounts of accumulated energy. Thorough reviews on each class of materials are available [15].

Among TES materials, a large variety called generically PCMs, based on phase change heat transfer, has been intensely investigated, and new such systems are explored and assessed even at present [16-27]. These materials undergo a phase transformation during the accumulation/release of energy, and in this process, a large amount of thermal energy is stored. A temperature difference is necessary to conduct the heat through PCMs, which means that some of the energy will be stored as sensitive energy in the latent heat system (LHS) [28].

In applications, the most used phase change material transition is solid-liquid. The charging process implies liquefaction of the solid material, discharging, and solidifying of the TES material [29]. A solid-liquid system implies small volume changes (less than 10 %), does not require air-tight sealing, implies a simple design, and is cost-effective, especially for small-scale applications [30].

Another two-phase conversion can be liquid–gas or solid-solid [15; 31]. Liquid–gas transition system has the highest energy storage density. It needs, however, an air-tight sealed, and strong-walled vessel, which requires large volume changes, and thus, the cost increases considerably. Solid–solid transition systems present the smallest energy storage density and are frequently very pricy. Therefore, these systems are not used for energy storage [15].

The energy stored can be calculated with the equations below [32].

$$Q_s = \int_{t_i}^{t_m} m \cdot C_p \cdot dt + m \cdot f \cdot \Delta q + \int_{t_m}^{t_f} m \cdot C_p \cdot dt \tag{1}$$

$$Q_s = m \cdot [C_{ps} \cdot (t_m - t_i) + f \cdot \Delta q + C_{pl} \cdot (t_f - t_m)] \tag{2}$$

where Q_s – the storage capacity, in J; t_m – the melting temperature, in ◦C; m – the mass of PCM material, t_i – the initial temperature; t_f – the final temperature; C_{ps} - the average specific heat of the solid phase, C_{pl} - the average specific heat of the liquid phase, f - the melt fraction, Δq - the latent heat of fusion.

The LHS systems should fulfill several requirements:

- Physical and technical requirements: low-density variation and small volume change; high energy density; small or no subcooling; no phase segregation; low vapor temperature; chemical and physical stability; Compatible with other materials;
- Thermal requirements: suitable PCMs temperature fitted to application; large PCMs enthalpy (DH) and specific heat (Cp); high thermal conductivity; cycling and thermal stability;
- Non-technical requirements: high availability; low cost; non - toxic; recyclable; safety; harmless for the environment [29; 33-35].

Miro *et al*. [35] created a new methodology for selecting the phase change material according to some of the requirements presented above.

Phase change materials have been classified as organic, namely paraffins, fatty acids, alcohols, esters [36-42] and non-paraffinic materials (e.g., fatty acids), inorganic comprising salt hydrates and metallics, also, polymers (PEG) [43-46] or eutectics, i.e., a combination of organic and inorganic materials. Nanoemulsions, defined usually as immiscible liquid-liquid nano-dispersed systems, are an emerging class of materials, intensely studied in the last decade, suitable for resolving the imbalance mentioned above between energy supply and demand. Furthermore, these PCM slurries combine the high latent heat capacity of the PCM with the good flow ability of the carrier fluid and, thus, enable higher heat transfer rates in comparison to pure PCMs due to the large surface-to-volume ratio of the continuous phase [47]. Among the most studied nanoemulsions, one can mention paraffins-in-water, beeswax-in-water, and water-in-polyalphaolefin [48-53]. Microencapsulated PCM dispersions within the water are another type of efficient TES materials, and numerous studies concentrate on the thermal characteristics and system efficiency [54].

2.2. TES Systems

A TES system is described by a series of characteristics, such as:

- Storage period – the time that energy is stored (hours, days, months, years);
- Storage capacity (kWh/kg, kWh/m^3) – depends on the medium and the size of the system, the storage material, and boundary conditions;
- Power (W/kg, W/m^3) – how fast the energy stored can be charged and discharged;
- Efficiency – the ratio between the energy that the user needs and the energy necessary to load TES devices;
- Cost – the price related to the storage technologies implementation and exploitation (total expenses for the TES equipment investment and operation related to the number of storage/discharge cycles) [2;3].

The following three components are included in a phase change based thermal energy storage device (PCM-TES), namely, a phase change material (PCM) with a melting temperature within the storage application's operating range, a storage container for the PCM, and a highly thermally conductive surface that separates the PCM from the heat transfer fluid (HTF).

During the charging period, the HTF circulates through the flowing space and transfers heat to the cold nanomaterial in the form of sensible heat and latent heat if the PCM is in a subcooled solid state and melting afterward. In the beginning, conduction prevails, followed by convection if enough material is liquified [55-57]. In the discharging process, the PCM releases heat to the HTF. However, as the solidifying process proceeds and the conduction thermal resistance increases, the thermal rate decreases [58,59].

A variety of PCM-TES devices were designed and tested in order to investigate different types of phase change materials and the operation parameters for charging/discharging cycles.

These designs range from simple shell-and-tube and triplex tube arrangements to modular or fixed/ fluidized bed configurations. In some geometries, PCM is encased in the annular space or rectangular or spherical modules, while the HTF flows inside the circular tube(s) or passes across the PCM modules. There are, however, few studies that compare the performance of these various designs. In addition, unlike traditional heat exchangers, where heat is exchanged between two steady-state fluids, in PCM-TES systems, heat is exchanged between a steady flow of HTF and a stationary mass of PCM undergoing a phase change process.

2.3. TES Laboratory Configurations

Some relevant heat transfer systems for thermal storage are presented below, and important measured parameters are discussed.

2.3.1. Circular Pipes/Tubes

For the flow of different PCMs in channels and circular tubes, in laminar or turbulent flows, presented succinctly in Table **1**, increased heat transfer coefficients were reported compared to the basic fluid coefficient. Most of the tested fluids were miscellaneous types of nanoemulsions in order to assess whether they are suitable as thermal storage fluids [60-64].

Table 1: Channel-type laboratory configurations for TES materials testing

Set-up Experimental Configuration	Convection Type	Observations	Reference
Channels	Laminar/turbulent of 10.1% bees wax NE	Improved heat transfer coefficients, the largest value of 935 W/m2K at 1.2 GPM flowrate; valid Sieder-Tate correlation	[60]
Circular tubes	Turbulent n-decane/water NE	15% increase in Nusselt number	[61]
Minichannels	Transition, turbulent water-in-PAO NE	70% increased heat transfer coefficient	[62, 63]
Circular tubes	Laminar flow of microencapsulated PCM	Increased Nusselt numbers depending on MPCM concentration	[64]

The channel configuration helps determine if a newly tested material, usually a nano-dispersed fluid, has heat transfer coefficients higher than those of the continuum fluid. However, a TES system can have different geometrical configurations, and thus, channel data cannot convey reliable information related to the TES system's operational characteristics.

Different types of heat exchangers have been investigated. Depending on their geometric and constructive features, they proved to be more or less effective in storing and releasing thermal energy at certain rates.

2.3.2. Coil-in-Pipe Design

Using a coil inside a cylindrical shell or a rectangular box is meant to increase the heat transfer area compared to a pipe-in-pipe configuration. Several studies used this type of configuration, with different shaped coils [65; 67-69], synthesized in Table **2**:

Table 2: Coil-in-pipe/tank designed laboratory configurations for TES materials testing

Set-up experimental configuration	Heat transfer fluid	Observations	Reference
Coil-in-tank	Paraffinic emulsion	34% higher energy density than the regular water tank	[65]
Flat spiral tube HX	Commercial paraffin RT35	Vertical configuration is most efficient in heat storage, with a stored energy fraction >0.99; over 3500 W heat flux, at a constant temperature	[66]
A multi-pass coil in a tank	Dodecanoic acid	The largest averaged energy storage rate is 325 W	[67]

A coil in tank TES design, using as working fluid a paraffinic emulsion on the one hand and water on the other, has been analyzed to assess the efficiency of the heat transfer process and the stored energy for each case [65]. The density of the energy stored in the case of the PCM tank was found to be 34% higher than the water tank for the exact temperature of the storage fluid. Comparisons of some parameters, such as the global heat transfer coefficient, the ratio of heat transfer area versus the tank volume, and the stored energy density to other TES systems from the literature, indicated that the PCM emulsion system is a promising solution for thermal storage.

Ardahaie [66] investigated a new type of flat spiral tube heat exchanger (FSTHX) for thermal charge and discharge using PCM paraffin RT35 via thermal solar collectors, presented in Figure **1**. Nine different geometric coil configurations (with changes in coil number of each flat spiral tube plane, HX shell's tilt angle, and distribution of flat spiral tube planes throughout the shell), together with variations in HTF mass flow rate and its inlet temperature, were studied both experimentally and numerically. A certain vertical configuration was characterized by the absence of conductive heat transmission at the last stages of the melting process, as well as stronger natural convection, which contributed to the improved performance of FSTH. Following the dominance of natural convection, the rate of PCM melting has increased. Therefore, the rate of charging has also increased. Compared to vertical systems, the heat transfer rate in horizontal systems was faster until halfway through the melting process. Additionally, the high difference between inlet and outlet temperatures attained in FSTHX compared to traditional shell-and-tube HX proved the substantial efficiency of the first configuration.

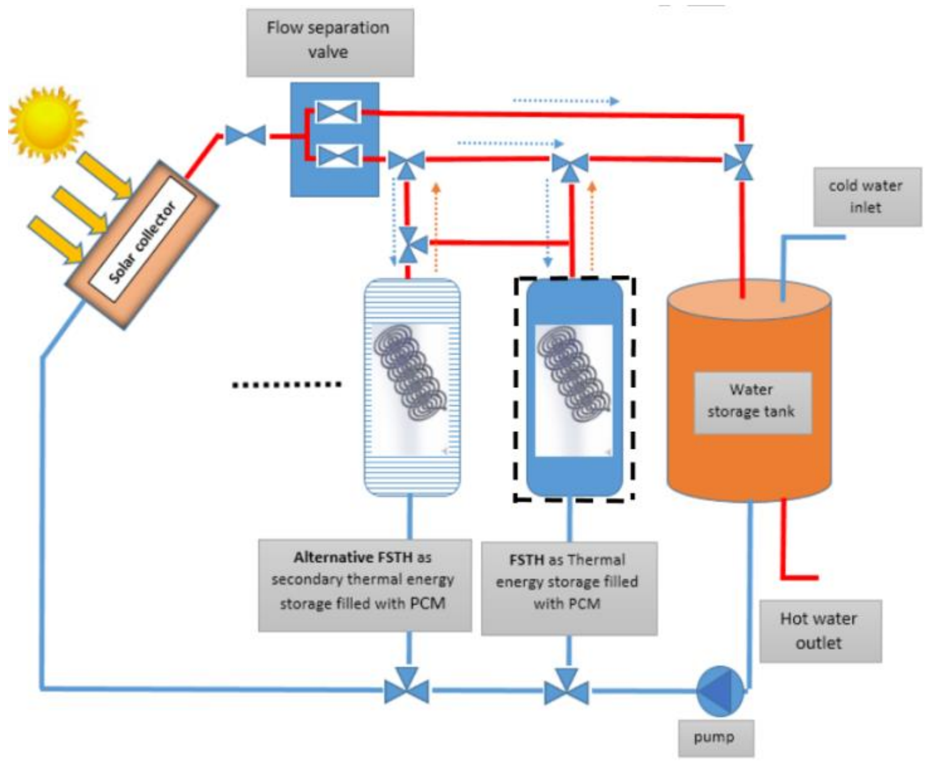

Figure 1: PCM-based flat spiral heat exchanger scheme for solar heat storage [66]

2.3.2.1. The Multi-Pass Coil in Box Design

A horizontal multi-pass coil with 1-, 2- and respectively, 3-coils - as represented in Figure **2** -, containing dodecanoic acid as phase change material, placed in a rectangular box, was experimentally investigated by Patil [67]. The heat transfer rate increases as the number of coils inside the device grows, resulting in a shorter experiment completion time. The heat transfer rate is highly affected by the HTF temperature but not by its flow rate and very little influenced by the PCM's initial temperature. Additionally, during the charging stage, the rate was higher than throughout the discharging step.

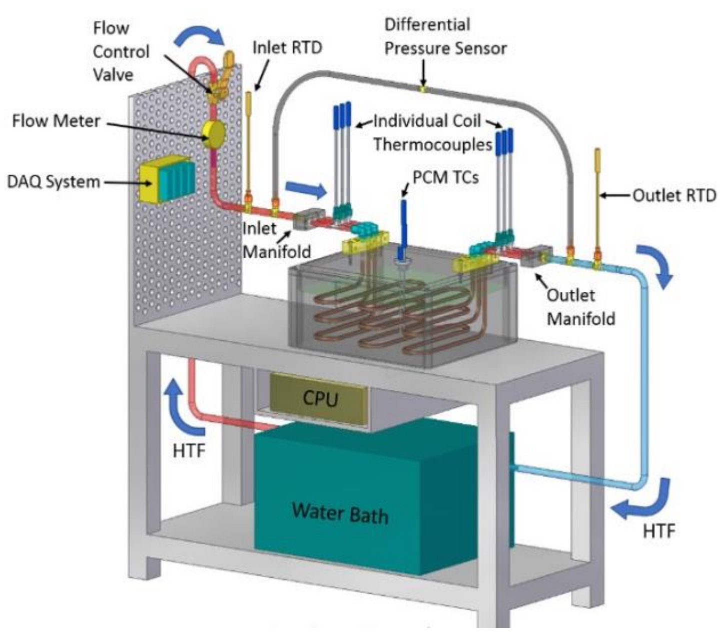

Figure 2: Experimental setup with three horizontal multipass coil heat exchangers [67].

Comparisons between the last two presented coil-in-tank designs indicate an order of magnitude difference in heat transfer rate, suggesting that, depending on the intended application necessities, both configurations can be used. However, a quantified assessment of the two setups is challenging to make since no established standards are available. Still, the investigated tank-coil configurations suggest that proper coil layout design inside the tank can significantly improve thermal storage characteristics.

2.3.3. Shell-and-Tube Configurations

The shell-and-tube configuration is simple and easy to use. Usually, the TES fluid flows through the inner tube to diminish the heat losses, while the heat transfer fluid circulates through the annular space between the tubes. Several studies were dedicated to this type of configuration, with reported improved heat transfer characteristics for the multiple tubes and shell configurations [68-77], as presented succinctly in Table **3**:

Table 3: Shell-and-tube designed laboratory configurations for TES materials testing

Set-up Experimental Configuration	Heat Transfer Fluid	Observations	Reference
Slanted shell-and-tube	Paraffinic emulsion	Decrease in the melting time by 30%;	[68]
Flat spiral tube HX	Commercial paraffin RT50	Increased melting efficiency to 88.4% during melting	[73]
Several tubes-in-shell	Erythritol/Commercial paraffin RT35/ water	Enhanced heat transfer rate/ ≥40% increase in HX performance	[70,76,77]
Eccentric horizontal shell-and-tube	Paraffin RT50	More uniform melting, improved heat rate/ at 0.75 eccentricity, 64% reduced melting time	[74,75]
Improved shell-and-tube configuration	N-eicosane in elliptical inner tube/ Paraffin waxes as multiple PCM/ Erythritol in HX with finned surfaces	Vertical HX with increased melting rate +decreased solidification rate/More uniform heat transfer/ 2-2.5kW for optimal fin design	[80-82]

Akgun [68] placed the PCM in the annular space and the HTF in the inner pipe. The system was slanted with a 5-degree inclination angle to facilitate heat transfer during the melting and freezing processes. The experimental data indicated an overall melting time decrease of approximately 30%, which was also recorded when an increase in the HTF's inlet temperature was applied. Additionally, if lower energy consumption was desired, a smaller HTF's mass flow rate was supposed to be used.

Hosseini *et al*. [75] studied experimentally and numerically the positive effects of increasing the inlet temperature of the heat transfer fluid (HTF) inside a shell-and-tube heat exchanger on the charging and discharging processes of the paraffin RT50. The theoretical efficiency in melting and solidifying processes rose from 81.1% to 88.4% and 79.7% to 81.4%, respectively.

Agyenim and co-workers [70] studied and compared different systems, namely the one tube and shell and, respectively, four-tube and shell configurations, containing PCM Erythritol, a medium temperature PCM, with a melting point of 117.7^{o}C. The PCM horizontal external tube with an inner diameter of 146.4 mm sheltered one tube of 54 mm diameter or four equally-spaced tubes of 28 mm diameter. Based on isothermal contour plots and on temperature time variation, it was established that the axial gradients in each configuration, during phase change, were respectively 2.5 and 3.5% out of the radial gradient, indicating a two-dimensional heat transfer in the phase change material side. During charging, despite the significant subcooling, the multitube system enhanced the heat transfer rate and provided an output temperature adequate for powering a $LiBr/H_2O$ absorption cooling system.

Later, another longitudinally finned one-tube and shell system included in a two loops charging-discharging system was investigated, using paraffin RT58, with a melting point of 60^{o}C [71]. Complete melting could be obtained only in the upper section of the tube. The charge and discharge rates of energy averaged only 0.6 kW and 0.2 kW, respectively, while an increase in the HTF inlet temperature from 60.9^{o}C to 65.9^{o}C rendered an improvement in the heat transfer coefficient by as much as 70% for charging and 11.3% for the heat release process [71]. Interestingly enough, the same authors reported in another study the complete melting of Erythritol in a similar longitudinal finned system [70] which was compared with a circular finned system with a no fins control system, for an imposed 8 hours charging time. The arrangement with longitudinal fins provided the best charge performance with insignificant subcooling during discharge.

Kousha *et al*. [76] have investigated the influence of a number of inner tubes on the melting/solidification processes of RT35 in a shell-and-tube heat exchanger experimentally and found, as expected, an increase in the HX performance by 43% for the melting stage and respectively 50%, for solidification step, when the number of tubes is increased at four tubes instead of one tube, due to the increased heat transfer area between the two fluids. Also, when the tube number rose, an increase in the rate of heat transfer was recorded, simultaneously with a decrease in the average Nusselt number due to the PCM melt flow slowed by upper HTF tubes.

Another study using a shell-and-tube setup focused on the domestic hot water (DHW) supply based on a PCM storage material encapsulated in 57 PVC vertical tubes (of 0.75 m length and 0.04 m interior diameter), as shown in Figure **3**. The principle of this method is based on water heating and PCMs melting during night. The cylinder was heated at the bottom with a 3 KW electrical heater, controlled by a thermostat. Hot water came out from the top, and cold water entered from the base of the cylinder. Despite the limited amount of water in the system, the PCM provided a higher water discharge capacity and the request coverage increased from 40% to 55% [77].

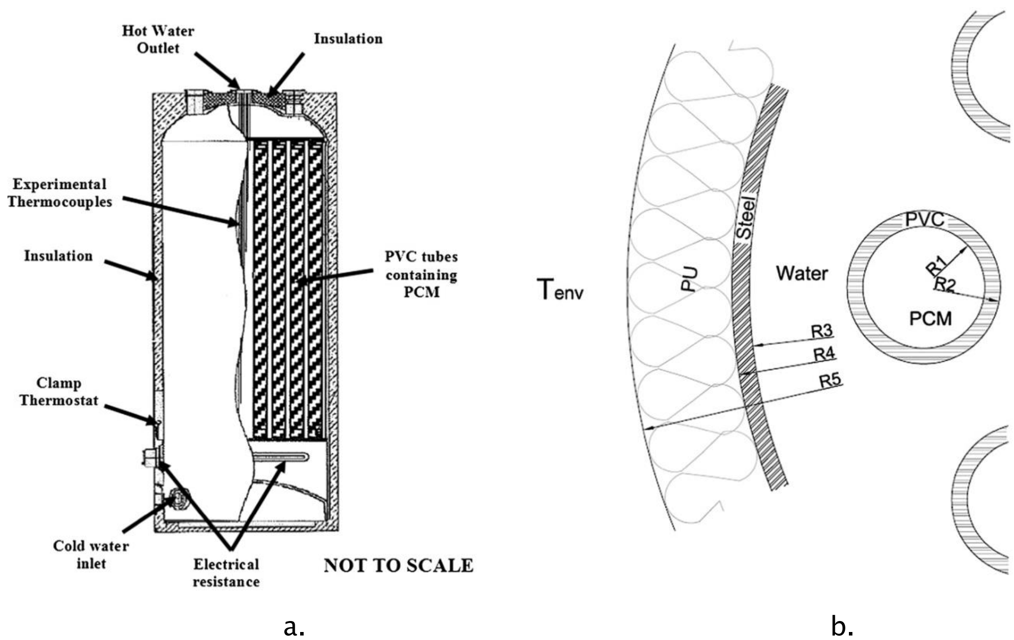

Figure 3: a) Hot water cylinder with inner tubes with PCMs; b) The modeled system [77].

Based on the observation that the melting process in the annular space of a shell-and-tube HX occurs mainly in the upper section, some researchers tried to resolve this problem and designed eccentric horizontal shell-and-tube type PCM-TES in which the inner tube is moved downward from the center axis of its outer shell [74; 75]. For an outer tube of 110 mm diameter and an interior copper tube of 28.5 mm, the region in which the natural convection dominated was observed to increase, resulting in higher heat transfer rates during the charging process compared to the concentric shell-and-tube PCM-TES design. For example, an eccentricity of 30 mm resulted in about a 67% decrease in the total melting time with respect to the concentric case [50]. The improvement was, however, reported only for the charging step. These results were also confirmed numerically in a study using transient three-dimensional heat transfer analysis in a shell-and-tube HX containing PCM paraffin RT50, based on the enthalpy porosity method [75]. When increasing downward eccentricity to 0.25, 0.5, and 0.75, the natural convection was enhanced, and the melting time was reduced by 33, 57, and 64 %, respectively. Because of the shorter melting time for an eccentricity of 0.75, the PCM was not exposed to the HTF's heat for a long time, and thus, it did not receive a significant amount of heat which, at the end of the melting process, resulted in a lower average temperature than the other cases. Thus, the total amount of stored heat is the lowest for the highest value among all the eccentricities. An increase in Stefan number (i.e., the inlet HTF temperature) from 0.54 to 0.8 induced a decrease by 27% in the melting time, while increases in HTF Reynolds number (i.e., its flow rate) did not have any significant impact on melting time.

2.3.3.1. Shell-and Tube Orientation

The vertical orientation of shell-and-tube devices has been studied by Seddegh [78], who reported that complete charging and discharging strongly depend on the shell-to-tube radius ratio and the HTF temperature, while it is almost independent of the HTF flow rate. A lower ratio gives a lower storage capacity but a larger charging and discharging rate. By balancing the discharging time and stored energy capacity, the best shell-to-tube radius ratio was around 5.4 for the studied systems.

It has been reported that the latent heat system (LHS) devices with horizontally oriented HTF tubes provide better thermal augmentation than those with vertically oriented HTF tubes, especially under load situations [79]. Additionally, in both horizontal and vertical systems, the hot HTF inlet temperature significantly impacted heat transmission. The HTF flow rate, on the other hand, did not affect the charging and discharging processes in the LHTES units.

2.3.3.2. Shell-and-Tube Design with Elliptical Inner Tube

Besides circular inner tubes in a shell-and-tube HX, elliptical shapes, as presented in Figure **4**, were also investigated to assess transfer rates during the loading and to release thermal energy cycles [80]. A vertical HTF carrying elliptical tube rendered an increased melting rate of the PCM-TES device compared to a regular circular tube. Nevertheless, it decreased the overall solidification rate. In the case of a horizontal elliptical tube, no improvements in the melting rate were observed, and the solidification performance of the device was reduced.

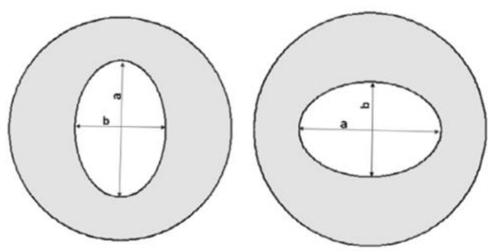

Figure 4: Shell-and-tube configuration with vertically and horizontally-oriented elliptical inner tube.

One of the major disadvantages of regular shell-and-tube exchangers is that regions within the PCM space cannot be efficiently melted. Thus, the total melting time is increased. Single or multi-tube configurations in the shell-and-tube HX become more suitable from the thermal storage perspective if the changes in the PCM region are distributed as evenly as possible so that melting and solidifying during the charging/discharging stages take place at an increased rate.

To achieve this goal, different techniques were proposed, such as using multiple PCMs, and adding fins or nanoparticles to accelerate the melting within those areas.

2.3.3.3. Multiple PCM in Shell-and-Tube Configuration

Since the HTF continually exchanges heat with the surrounding PCM while flowing through the inner tubes of a shell-and-tube PCM-TES device, its driving temperature difference steadily diminishes across the length of the inner tube during this process. As a result, near the inner tubes exit, the HTF exchanges less heat with the PCM than near the entering point. One solution proposed in order to get a more uniform heat transfer along the inner tube during charging was the usage of multiple PCMs, kept side by side in an order corresponding to the decreasing melting temperature PCM, such that the lowest melting temperature material is located right at the exit [81]. The same arrangement is also suitable for the discharging stage to ensure a faster thermal response, provided that the HTF flow direction is changed. The air-paraffins mixture shell-and-tube latent thermal energy storage unit's heat transfer rate depends, according to the numerical results of the enthalpy model, on the PCM's fractions and their melting temperatures.

2.3.4. Finned Surfaces

Mostly, fins are used on the side of the lowest thermal conductivity fluid in order to increase the heat transfer area and, subsequently, the heat transfer rate [80-90]. It is one of the common methods used to enhance the apparent thermal conductivity of a PCM.

Different types of fins, such as longitudinal, circular/annular, plate, or pin-shaped, have been used in experimental studies [83,84]. Longitudinal fins or circular fins used in shell-and-tube configurations were more effective for heat enhancement than pin fins [58]. The low construction costs, simplicity, and easy fabrication make them extremely versatile in many applications.

Rabienataj [80] reported, based on numerical calculations, that an increase in the number of fins in the annular gap of a shell-and-tube system from 4 to 20 renders a decrease in solidification time by 28% and 85%, respectively, in comparison to a no-fin configuration. However, the increase is not as efficient for melting as it is for solidification due to the suppressed natural convection in the melting PCM.

The performance and storage capacity of the heat accumulator is influenced by geometrical properties of fins such as pitch, height, and thickness, and thus, care should be taken in their selection. In order to optimize these geometric parameters, a heat accumulator consisting of alternating coolant channels and PCM channels, with brazed fins, as in Figure **5**, was designed and investigated experimentally and numerically [82]. A model was developed to simulate various configurations of the heat storage system. Based on heat transfer rate and heat storage capacity, the simulation results were used to establish ideal options.

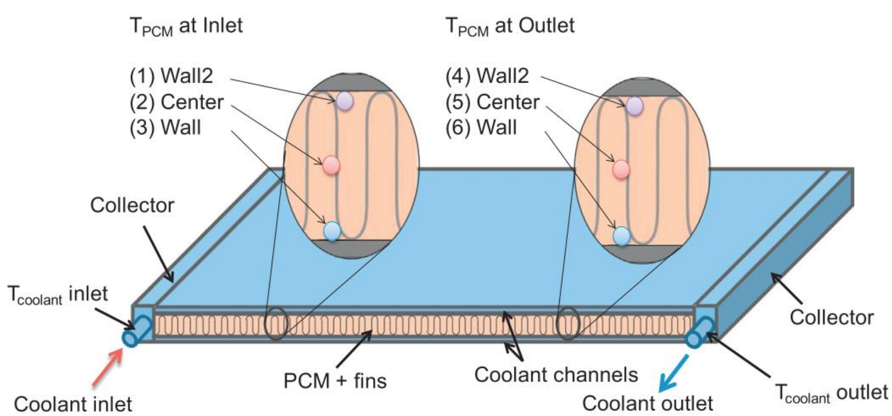

Figure 5: Schematic of a heat accumulator with brazed fins [82].

The model can readily be adapted to applications with similar geometries and materials. The findings show an optimal fin height for a satisfactory heat transfer rate of 2-2.5 kW, depending, however, on flow conditions.

Gürtürk [84] designed and investigated a new type of longitudinal fins, scale-shaped, inside the rectangular shell and circular tube HX. He then compared experimentally and numerically the melting and solidification characteristics within the same geometry having other types of fins. An increase of 60% in the melting process was attained when the longitudinal and the scale-shaped fins were used, and 65% when short fins placed in the upper and lower sides of the tube were tested. The fin shape was reported as having no significant influence in the case of the solidification process, probably due to the effects of the PCM overcooling.

Abdulateef [83] has used a triplex tube heat exchanger (TTHX), presented in Figure **5**, consisting of the inner, middle, and outer tubes of 76.2 mm, 381 mm, and 500 mm diameters, respectively, and 3 m lengths with longitudinal and triangular fins to charge thermal energy using a water-PCM- water fluid system.

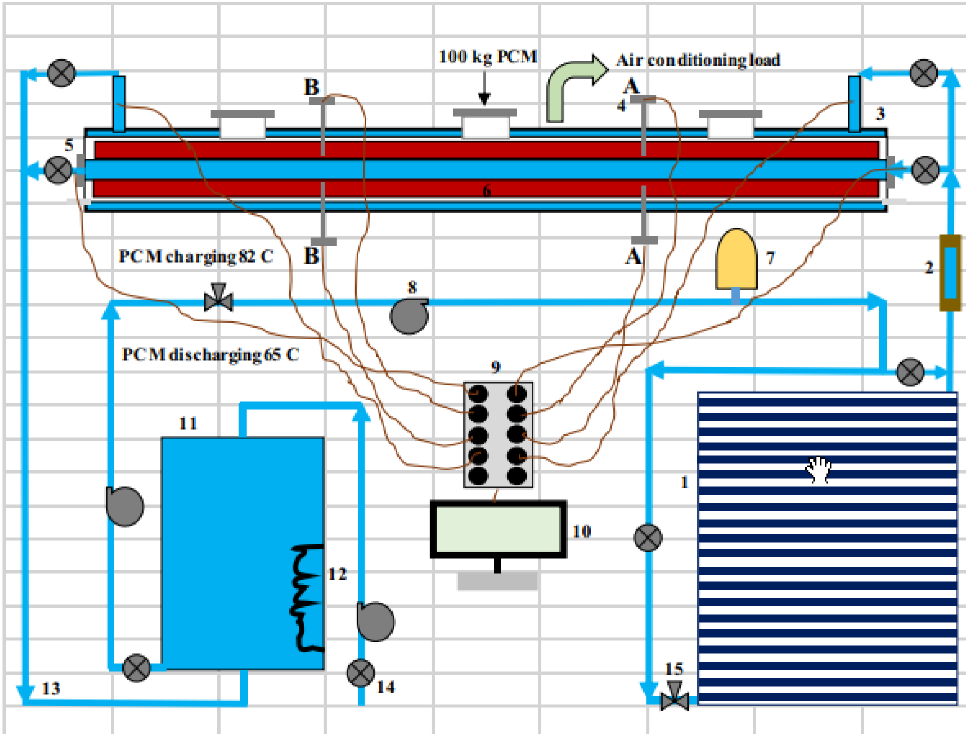

Figure 5: Triplex tube heat exchanger [83].

Another experimental and numerical study also used a triplex configuration, however, with a finned hexagonal-shaped inner tube containing PCM water with TiO_2-graphene oxide hybrid nanoparticles placed inside a double shell [85]. Besides the reported 12% increased solidification rate with a simultaneous increase in particle concentration and application fins in the latent heat thermal energy storage system, no comparison to a regular circular-shaped finned tube was made.

As expected, finned surfaces providing larger heat transfer areas offer improved performance in a transient regime of charging/discharging TES systems. However, the size of the fins and their spatial distribution with respect to the HX inner geometry strongly influence the system's thermal operation parameters. A unitary approach to allow for easy comparison among different fin shapes and arrangements is also missing.

2.3.5. Plate-Type Heat Exchanger

Saeed *et al*. [87] studied an energy storage system consisting of a plate-type heat exchanger. Water was the working fluid, and a PCM material was the energy storage medium. The heat exchanger's thermal parameters, such as heat transfer coefficient, effectiveness, efficiency, heat storage rate, total energy storage capacity, and the storage period, were studied by the authors. The compact parallel plate design (2 layers of overlapping aluminum sheet, which provides a large heat exchange surface) demonstrated better performance compared to conventional storage systems, with an efficiency of 83.1 % at an average power output of 4795 W. This configuration helps to reduce the costs in infrastructure, equipment, and maintenance/operations related to conventional ones.

2.3.6. PCM Modules and Shell

Several researchers have designed PCM modules of different shapes enclosed in larger tanks containing an HTF [91-96]. Modular systems are simple to set up and can be quickly adapted to suit the application's storage requirements by adjusting the number of modules in the system [94]. This PCM-TES architecture can be successfully utilized in applications that employ air as the HTF and are mentioned in Table **4**:

Table 4: Shell-and-tube designed laboratory configurations for TES materials testing

Set-up Experimental Configuration	Heat Transfer Fluid	Observations	Reference
Slabs in a rectangular box	Hydrated salt (PlusICE S15)	Thicker slabs provided better thermal characteristics	[91]
Cylindrical modules in a cylindrical tank	Commercial paraffin RT28HC	70% heat storage increase	[92]
U-tubes in a rectangular unit	Paraffin-copper foam	Improved heat storage rate	[95]

One study [91] concentrated on the thermal charging and discharging rates, using a rectangular box aligned with slabs of two different thicknesses, 35 mm and 17 mm, respectively, encapsulating the same phase change material. Temperature profiles, heat transfer rates, and energy stored or released were compared for both arrangements. For a fixed box volume, using thicker slabs was more efficient in terms of longer discharging periods and higher storage capacity.

Koselj [92] used 67 cylindrical modules containing paraffin (RT28HC), symmetrically arranged inside a cylindrical tank, to increase the energy density of the water's thermal storage. Paraffin represented 15% of the total tank volume and increased heat storage by 70% over a conventional heat storage tank containing only water. The design was, thus, assessed as suitable for TES applications. However, no optimization of the size or position of the modules, the PCM quantity, and the initial and final temperature for an efficient operation was performed.

Another developed design investigated a configuration consisting of several U-tubes in a rectangular latent heat storage unit. The unit was filled with modified paraffin-copper foam composite, which is one of the efficient methods to ensure a more uniform temperature distribution due to its contribution to an increased PCM thermal conductivity [95]. It was found that the heat storage rate was significantly improved when the copper foam was used, compared with the case when only PCM was utilized, with the highest percentage of 49.3% obtained for the lowest HTF temperature of 65 ^{o}C. In total, the U-tube rectangular unit was reported to have a relatively high heat storage rate of 200 W compared to other systems, for example, simple shell-and-tube latent heat storage unit, with reported heat storage rates of up to 100W [52].

PCM encapsulation modules in a shell seem to be a more versatile configuration, with increased thermal storage characteristics compared to other designs. However, information related to their shape and size, as well as the optimal PCM quantity for the most efficient heat transfer between the HTF and PCM, have not been reported. Also, the minimal thermal storage temperature difference required for the PCM material to completely melt/solidify should be investigated further.

2.3.7. Packed Bed or Fluidized Bed Systems

Packed bed and fluidized bed systems designed as PCM-TES devices can be used successfully due to the high ratio of contact area between the HTF, either gas or liquid, and PCM fluid to its volume, resulting in a high heat transfer rate during TES operation.

PCM is encapsulated in small spheres in the form of a commercially available composite material GR50 and GR80, with a mean particle size of 1.64 mm and 1.58 mm, respectively. It is configured in a packed bed, inside of a container, where an HTF, namely air, flows through the remaining free gaps, which have also been investigated in terms of temperature-time profiles and stored energy. The experimental data matched the numerical results obtained based on a one-dimensional time-dependent two-phase model and indicated higher energy stored levels than data obtained using sand within the same system [97].

Another study [98] also used PCM-filled spheres inside a container and established that the reduction of their diameter resulted in an increase in the heat transfer rate between the PCM and HTF due to the surface/volume ratio increase. Also, the more the decrease in the capsules diameters and the smaller the inlet temperature, the more significant the heat rate enhancement. Similar findings related to the size of PCM capsules and, additionally, the beneficial, increasing HTF inlet temperature on the efficiency of the PCM-TES system were reported by other researchers [99]. When the storage unit is connected to a solar collector, it was found that the mass flow rate significantly affects the heat extraction rate from the collector and, thus, the charging rate of the TES system.

For thermal energy storage in fluidized beds of PCM (paraffin) bound within a secondary supporting structure of SiO_2, mixed with sand in the form of a commercially available PC 50 composite, an experimental study established [100, 101] its increased thermal efficiency in comparison to that of a fluidized sand bed and fixed sand and PCM bed. After the solidification time, the PCM also had a higher recovery efficiency for both beds. It was concluded that an increase in the bed height results in higher efficiency despite the longer time necessary to attain a certain temperature. However, using a higher flow rate can solve this inconvenience. Once the charging process ends, similar values of efficiencies are obtained, no matter the flow rate used. High gas flow rates also diminish the charging efficiency. Approximately 15 complete cycling test runs indicated a stable PCM.

2.3.8. Other Configurations

Sajawal [102] used three configurations in order to establish the best thermal storage capacity of a solar air heater: firstly, with no PCM, secondly, with semi-circular finned tubes (SFT), filled with one type of paraffin as PCM, RT44HC, having a higher melting point, in the upper pass of a double solar air heater (DPSAH) and thirdly, with circular finned tubes containing two types of paraffin, RT44HC and RT18HC having a lower melting point, inside the finned tubes, in upper and lower passes, respectively to render an enhanced thermal storage capacity of the solar air heater (SAH). The PCM designs are presented in Figure **6**. The recorded thermal efficiencies for the three configurations were respectively 53.2%, 68.4%, and 71.9%.

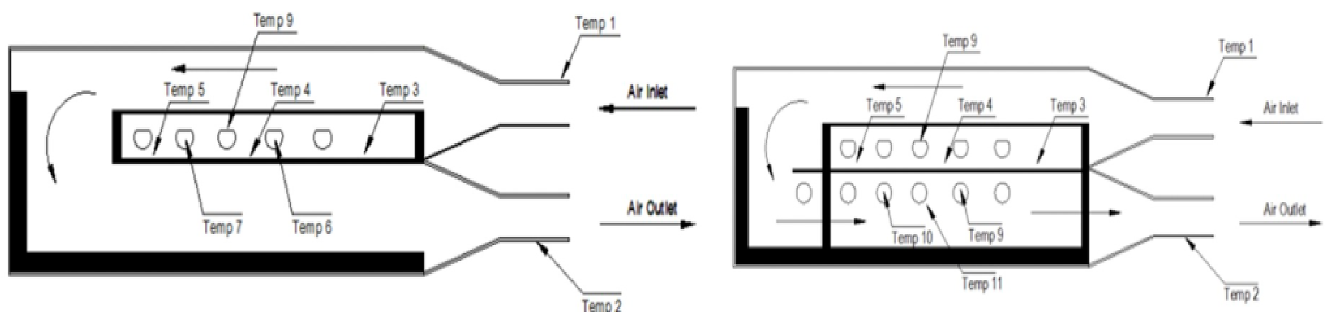

Figure 6: Configuration with one and respectively two PCM in a solar air heater [102].

It can be concluded that the design in terms of the PCM used and its properties, the space geometry, and any small alterations/improvements affect the performance of the TES system. Thus, experimental data and modeling are mandatory for the efficient operation and optimization of such a system.

Many of the TES mentioned above heat exchangers have dead volumes; some of them were reported to reach as much as 31% out of the HX total heat transfer space [103]. This should be reduced as much as possible during both the charging and discharging steps [104].

3. Methods Used to Evaluate the Effectiveness of PCM Systems

Designing an efficient PCM-TES system for a specific application is all the more difficult, given the lack of configuration methodologies and standards. Unlike the classical heat exchangers, where heat is transferred between two fluids in a steady state regime, the PCM-TES devices contain an HTF in steady convection and a PCM mass, stationary at the beginning and flowing towards the end of the melting stage. Thus, the heat transfer becomes transient and difficult to characterize [105, 106].

Some researchers tried to establish correlations among relevant operation parameters for PCM-TES systems. For example, [107] an equation containing dimensionless Fourier and Stefan numbers was proposed to determine the melt-fraction for a PCM in a 2D rectangular enclosure, based on numerical analysis or another study [108] developed for PCM wallboards, used in building cooling, a correlation between charging time expressed as Fourier number (Fo) and the PCM board thickness included in the Biot number (Bi). Based on dimensional analysis, other equations were developed for 2D geometries with different boundary conditions, like constant temperature or constant heat flux, some of them including an aspect ratio parameter [109-112]. Similar correlations were developed for cylindrical or spherical shapes containing phase change materials, comprising Grashof and Rayleigh numbers, relevant for natural convection [107; 113-116] or even considering the Reynolds number for the HTF [117, 118]. The superheat or subcooling effects were sometimes considered dimensionless numbers [119, 120].

These types of correlations are extremely useful in storage system design, having different geometries. However, they do not allow for a reliable estimation of the effectiveness of a PCM-TES system. Extrapolating methods applied in heat exchanger operation, some researchers have applied the effectiveness-NTU method to some PCM-HXs in order to quantify their performance [121, 122,123].

The TES systems using PCM slurries are characterized by smaller heat transfer coefficients and, thus, higher charging periods.

For many presented systems, only stored energy density is presented without being reported to the entire TES system. A more efficient comparison among different TES systems was suggested by Delgado [65] in the form of one term *UA/V*, where *U* is the global heat transfer coefficient, *A* is the heat transfer area, and *V* is the system volume. This parameter may provide a more uniform characterization of the system's thermal power versus its volume. Based on available literature data, it was concluded that some TES systems have the best thermal response [124]. However, with the lowest energy density due to a low PCM capacity content. Larger storage capacities were reported by other researchers who used materials with higher heat capacity values [125, 126].

4. Conclusions

This review has covered different laboratory configurations, mainly using phase change materials, since these have received the most significant attention in the last years to design more efficient thermal energy storage units. Several geometries from very basic to more complex heat exchangers/bed configurations have been overviewed, including the main factors affecting their operation such as the inlet/outlet fluids temperatures, the geometric features (e.g., diameter, winding step, number of coils, tilt angle, presence of fins), HTF flow rate and also, the characteristic working parameters, such as the accumulated energy density, the melting/solidifying time influencing the storing/discharging heat rates. The paper highlights the steps in TES unit design to grasp better the main improvements made until now and to open the way towards new ideas in approaching these designs. Experimental setups are virtually endless; however, it is clear that no guidelines or standards for TES systems' comparison are available at present, most probably due to the strong transitory nature of the heat exchange process inside PCM-TES devices and also to the large variety of PCMs used for a wide range of applications. Therefore, choosing the most effective PCM-TES design and creating a suitable-sized one for a particular application are complex tasks.

Unitary methodologies and parameters necessary to compare different TES units' efficiency are missing. Novel parameters should be defined based on variables such as the global heat transfer coefficient, the heat transfer rate, the energy density, the heat transfer area over the enclosure volume, and the melting/solidification time in order to create a common base, relevant to different TES configurations efficiency assessment.

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