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Report

State of the art accumulation tanks

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ABSTRACT

Thermal energy storage systems are often needed to decouple thermal energy production and demand. This prevents from oversizing of production equipment's and allows for using electricity in periods of lower costs [1]. In addition, thermal energy storage is very useful when working with discontinuous generation systems, such as solar energy or applications with waste heat recovery.

This report begins with a brief description of the most spread types of tanks used for domestic hot water storage. Given the interest of using accumulation together with heat pumps the use of inverter controlled and variable speed compressor order to reduce the size of the storage is studied. The main works concerning the use of inverter compressors in heat pumps and its effect on the dimensions of the tank and on the efficiency of the systems have been reviewed. Further it focuses on the use of PCMs in thermal storage tanks. The available literature on PCMs for thermal storage tanks has also been reviewed and the main ideas drawn are summarized in the last part of this report.

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1 INTRODUCTION

Thermal energy storage systems are often needed to decouple thermal energy production and demand. This prevents from oversizing the production equipment and allows using electricity in those periods of lower costs [1]. In addition, thermal energy storage is very useful when working with discontinuous generation systems, such as solar energy or applications with waste heat recovery.

This report focuses on the use of PCMs in thermal storage tank, and it begins with a brief description of the most spread types of tanks used for such purpose. It also reviews the main works concerning the use of inverter and variable speed compressors in heat pumps and its effect on the dimensions of the tank and on the efficiency of the systems. The available literature on PCMs for thermal storage tanks has also been reviewed and the main ideas drawn are summarized in the last part of this report.

2 TYPES OF TANKS

This chapter shows a classification of the most common types of tanks, and points out some of the most typical considerations that must be taken into account to minimize the thermal energy losses and corrosion. The majority of the information stated in this chapter was obtained from the work of Rico Ortega [1].

2.1 Introduction and classification of storage tanks

Tanks are normally classified into two groups, attending to where the domestic hot water is produced.

- Tanks with heat exchangers inside. DHW is directly produced in the tank where it is stored (double walled storage tank, Figure 1a; storage tank with helical coil, Figure 1b).
- Tanks that store water heated somewhere else in the system and use this water to produce DHW, normally instantaneously (tank and external heat exchanger, Figure 1c).

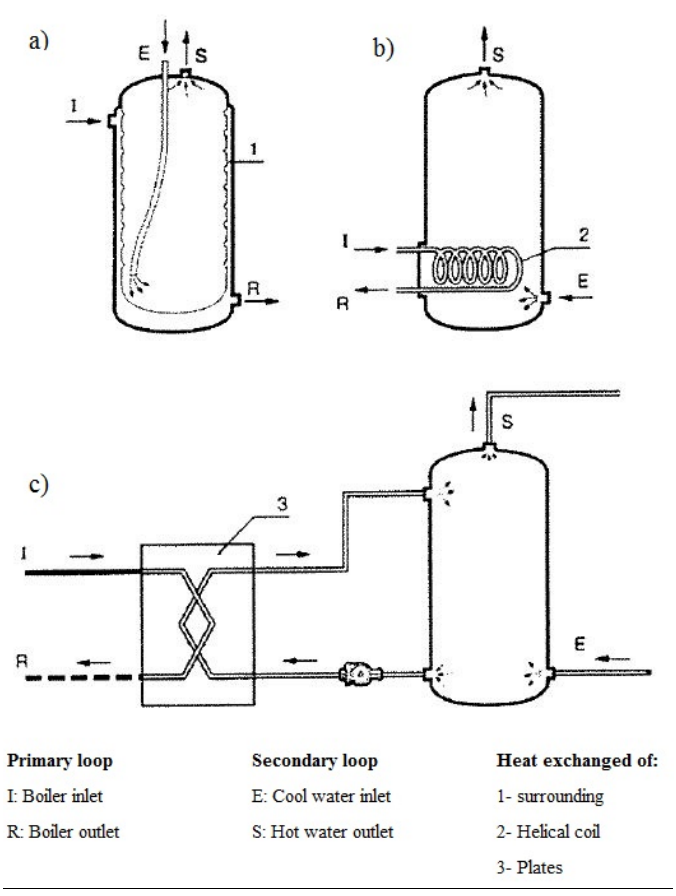

Figure 1 ***(a) Double walled storage tank; (b) storage tank with helical coil; (c) storage tank without inner heat exchanger*** **[1]**

The structure of storage tanks belonging to the first group depends on the heat exchanger used. Double-wall storage tanks (Figure 1a) are constructed with one storage tank inside the other. The inter-space between walls is connected to the primary loop, and the water from the generator circulates through it. Primary water transfers heat to the water stored in the inner tank through the inner wall. Typically, the temperature of the water in the primary loop is 80 ºC, and the storage temperature of the DHW is 60 ºC (20 minutes are normally needed in order to achieve this temperature). This type of store is usually used for domestic purposes, with storage volumes between 50 and 500 litres. The inlet of the primary loop must be on the top of the tank ensuring flow from the top to the bottom of the tank, both in vertical or horizontal tanks (Figure 2). When possible, vertical storage tank arrangement is recommended in order to enhance water stratification.

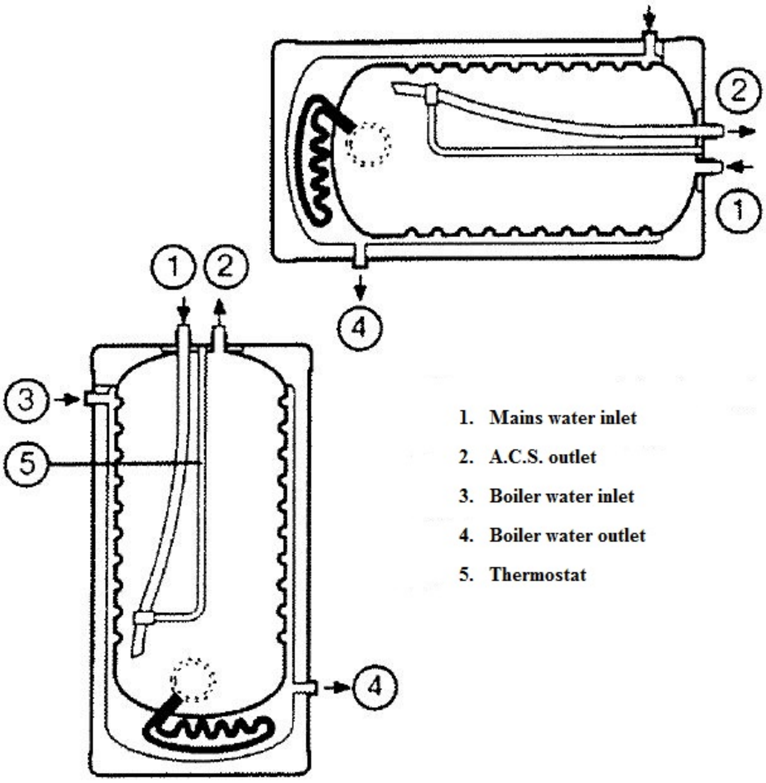

Figure 2 Double walled storage tank with electric heater [1]

Helical coil heat exchangers (Figure 1b) are also typically used inside storage tanks, as they lead to high heating rates (larger heat exchanging surfaces are achieved). The helical coil must be placed as close to the bottom of the tank as possible, to heat the complete tank and prevent from the appearance of legionella in the colder layers. Electric heaters can also be used, as seen in Figure 2.

Thermal storage systems with external heat exchanger are indirect systems that use the heat stored inside the tanks to heat DHW through a heat exchanger placed outside the tank. Typically, plate heat exchangers are used for such purpose.

2.2 Considerations

2.2.1 Insulation

A correct insulation of the tank is essential to minimise heat losses to the environment. Small volume storage tanks (up to 500 litres, for common storage for 2 or 3 families approximately), are usually insulated by the manufacturer injecting high density expanded polyurethane (CFC free) inside a double wall. Higher volume tanks are insulated in situ using elastomeric foam (or other insulating material) sheets. A minimum insulation thickness of 30 mm is required in those tanks with a heat loss surface lower than 2 m^2, and it must be 50 mm when the surface is higher than 2 m^2.

The minimum insulation thickness of indoor hot water pipes depends on the diameter of the pipes and the temperature of the water. Pipes up to 50 mm require 20 mm of insulation thickness, and larger pipes 30 mm. This insulation should be increased in 20 mm in case of outdoor pipes.

2.2.2 Corrosion

Metallic parts in continuous contact with water suffer from electrochemical corrosion and incrustations. The risks increase with the water temperature, an important factor both in DHW and space heating hydronic systems.

The difference between them is that hydronic systems are closed loops; corrosion and incrustations occur during the initial period, but after it the material is protected given that the free oxygen in the space heating water is eliminated rapidly in the oxidation process, forming a protection layer (incrustations work also as a protection layer). However, DHW loops use open loops of city water, which renovates continuously, and brings new chlorine, oxygen, slats, gasses, solids, etc. Therefore, corrosion and incrustation effects are cumulative and contribute to the progressive deterioration of the components of the installation. Corrosion destroys the metal, and incrustations reduce the flowing section and produce noise. Incrustations also reduce heat transfer, and the existence of slimes may reduce the capacity of the storage tanks. In conclusion, the necessity of taking appropriate measures to prevent corrosion and incrustations is proven.

In primary loops, which work with water that is not going to be directly consumed by humans, solutions with inhibitors of corrosion, softeners, etc. can be adopted to modify the aggressive characteristics of water.

In consumption loops, the use of substances and the concentration of these substances are limited. Choosing suitable materials for the type of water used, a careful manufacturing and installation, or using cathodic protection are some recommended solutions.

The more significant parameters of water, concerning corrosion and incrustations are hardness of water (content in Ca and Mg soluble salts) and chloride concentrations (generally the water used is not acid).

2.2.3 Materials and protection

Galvanized steel: Employed in pipes and in the manufacturing of storage tanks, mostly in industrial and centralized applications given that the galvanization is done following the standard and with water temperatures that do not exceed 60 ºC.

Galvanized steel pipes can be used under the following conditions: only with water which will result in a protective layer, with installed filters, respecting the order of installation (concerning copper piping and dielectric connection), employing tubes which follow the standard, follow a correct start-up process, etc.

In storage tanks, the protection which gives better results is Impressed Cathodic Current Protection (a correct distribution of the current is needed). However, it is preferable to use external heat exchangers (indirect systems), which allow the proper protection, supervision and maintenance tasks.

Copper: Has well-known anticorrosion and bacteria growth inhibition properties. It is very resisting to most types of water. It is desirable, however, that the formation of protective layers occurs. Soft water can cause soft attacks due to free CO_2.

Cooper is widely employed in domestic applications. An increasing risk of corrosion may occur due to the entrance of iron oxide particles from other parts of the installation. When these particles deposit on the inner surface of the tube, they may promote corrosion of the copper due to differential aeration and even the perforation of the pipe.

The recommendations concerning order of installation, water filters and installation start-up, previously mentioned for galvanized steel pipes, are equally suitable for copper. The inner wall in double-wall storage tanks is sometimes manufactured in copper with a reinforcement layer of steel. If the rest of the installation is in copper, no problems associated with galvanic pair should occur.

Stainless Steel: Stainless steel has a passive layer that protects against water with pH between 4 and 10 (no additional protective layers are needed). It is a sensitive material to water with high concentrations of chlorides, so the working limits recommended by the manufacturer must be followed. This material is not frequently used in pipes due to its high price. The installation needs to be carefully done, as for all the other materials.

Stainless steel is an excellent material for the manufacturing of storage tanks, both from corrosion resistance and hygienic point of view. Ferritic, austenitic and chrome-nickel-molybdenum stabilized with titanium steels are used. The best behavior concerning corrosion is seen in the last one.

Vitrified: Vitrified coating is applied to the inner surface of the steel tank in order to increase corrosion resistance and improve hygienic properties. It consists of two varnish layers vitrified in a furnace at 900 ºC. A good adhesion and the absence of pores and discontinuities are needed for an effective layer. However, in order to reduce the risk associated to the existence of micropores, a magnesium sacrificial anode is used. The consumption of the anode leads to the blocking of the micropores with Mg compounds. Despite that, this solution leads to the appearance of slimes, which dirty and cause problems inside the tank.

The solution rate of the magnesium anode depends on the conductivity of the water. This must be taken into account in order to renew it. There are anodes available in the market that warns the user or installer when replacement is needed. When the water conductivity does not allow the use of the anode, it will be substituted by Impressed Cathodic Current Protection, a system where anodes are connected to a DC power source, helping to prevent galvanic corrosion.

Other coatings: Elastic resistant coatings (Polyamide for temperatures lower than 85 ºC).

Plastic: Due to its corrosion resistance, plastic is becoming more and more the basic material for pipe manufacturing and any kind of installations. However, it must be taken into account that at the hot water temperatures, the walls of the pipes are not impermeable to atmospheric O_2. Oxygen diffusion implies a risk of corrosion on the metallic surfaces of the installation. Therefore, tubes with layers which prevent diffusion should be used.

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3 Use of inverter

3.1 Introduction

Controlling the capacity of compressors, pumps and ventilators in heat pumps adds degrees of freedom for the system of control. In addition heat production control leads to an increase in energy efficiency. When the heat pump can be controlled more accurately than on-off, the heat production can be controlled and a reduction on the size of the storage tank may follow.

Buffer tanks are normally needed with on-off heat pumps, in order to prevent the compressor from turning on and turning off continuously. The process with such systems starts when the compressor is turned on and the heat pump heats or cools the fluid contained in the buffer tank. When a certain temperature is reached in the tank, the compressor is turned off. This hot or cold fluid can be used, and the compressor will only be turned on again when needed.

In contrast with this, variable speed compressors in heat pumps allow matching the heating or cooling demand and production. This makes buffer tanks less necessary when working with such compressors, meaning smaller accumulation sizes or sometimes even the removal of storage what affects in the total cost of the installation, as well as on the space required for it.

The energy efficiency of heat pumps with variable speed compressors increases when working with variable loads, particularly during partial loads. Less supplementary heat and evaporator defrost are needed with such systems. Nevertheless, suitable control strategies and variable speed circulating pumps should be used to prevent the heat pump performance from decreasing. An improper design of such heat pumps leads to longer operation times than with on/off heat pumps and to higher electricity consumptions [1].

3.2 Analysis of the use of inverter in heat pumps

The complete thermodynamic potential of heat pumps is only reached if a suitable control strategy is developed and fitted for each and every installation. These considerations are studied by Madani [2]. This work describes the development of a ground source heat pump computer model, which covers the heat pump itself, the building, the heat source, a tank and the climate. Through it, existing and new control strategies for heat pump systems are analysed.

The dynamic interaction between the components of a heat pump complicates the prediction of the consequences of changing a parameter on the whole system. Moreover, the heat pump itself is affected simultaneously by the climatic conditions, the building (light or heavy), the heat source (air or ground), the heating distribution system (radiant soil, radiators or fan-coils), the storage tank (if needed), the user, etc. It is essential to take all the components and their interactions in consideration when different strategies of control are compared.

Jakobsen [3] states that including variable speed compressors, pumps and fans increases the degrees of freedom of refrigeration systems, allowing the optimisation of their performance through a suitable control. Small adjustments in the control strategy have important effects on the system. Continuing his research, Jakobsen [4] proposes a method to minimize the energy loss in a refrigeration system by regulation the speed of the compressor.

In Diz et al. [5] three commercial air source heat pumps with inverter technology were analysed. This work concludes that inverter driven heat pumps are able to reach the DHW set temperature (55 ºC in this work) with lower energy consumption the support electric heaters than on/off heat pumps. Therefore, the efficiency of those systems with inverter technology is higher when heating the storage tanks. Moreover, this work points out that the control strategy of the air source heat pumps with inverter technology depends on the manufacturer. Some companies prioritize efficiency during the heating process, meanwhile others minimize the heating time (which decreases the efficiency of the process). In Diz et al. [6] an experimental analysis focused on the storage tanks provided by the heat pumps aforementioned. This work points out inverter technology allows increasing the energy available in tanks with support electric heaters at the end of heating process without water consumption. This improvement was also observed during a similar study with water discharge processes (Diz et al. [7]).

3.3 Comparison use of inverter vs on-off-control

Madani et al. [8] analyze two heat pumps with different types of control (on/off vs variable speed compressor). This work concludes that the system with variable speed compressor is more efficient than on/off system when the heat pumps are dimensioned to cover 55% of the peak demand. On the other hand, when systems are designed to cover more than 65% of peak demand the efficiency is similar.

Lee [9] compared the development of geothermal heat pumps, both with variable speed compressors and on-off compressors, using simulations for three different climates (sub-tropical, temperate and continental) and three control modes (no part-load control, part-load control for the cooling operation mode and part-load control for both cooling and heating). The author concludes that part-load control, and particularly the mode developed for both heating and cooling, leads to reductions in the electricity consumed by the compressor. He also states that the borehole length may be shortened using part-load controls. Both the diminutions of the energy consumption and of the borehole length have an important effect on the cost of the installation and compensate the cost of the inverters. Payback periods were importantly reduced through part-load control modes.

3.4 Conclusion

The use of variable speed compressors in heat pumps is interesting from many points in view. Firstly, because it is possible to match energy demand and production almost instantaneously, and this allows eliminating from the installation buffer tanks, which have important costs and are a problem when the space is limited. In addition, heat pumps with variable speed compressors are more efficient during partial load operation than heat pumps without it, and a decrease of the energy consumption can be achieved. Nevertheless, suitable control strategies and variable speed circulating pumps should be used to prevent the heat pump performance from decreasing.

3.5 References

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4 PHASE CHANGE MATERIALS IN ACCUMULATION TANKS

4.1 Introduction

The use of PCMs allows a higher density of thermal energy storage than systems based on sensible thermal storage only, and therefore the reduction of size of the storage tank. According to Sharma et al. [1] the thermal density storage of PCM systems is between 5 and 14 times higher than in sensible storage systems. This is useful in buildings, especially in cities, where there is usually no possibility of creating spaces for thermal storage tanks. Moreover, Phase change materials (PCM) systems lead to more constant and stable temperatures during the process of thermal energy charge and discharge.

PCMs are often classified, attending to their composition, in three big groups, as shown in Figure 3 [2].

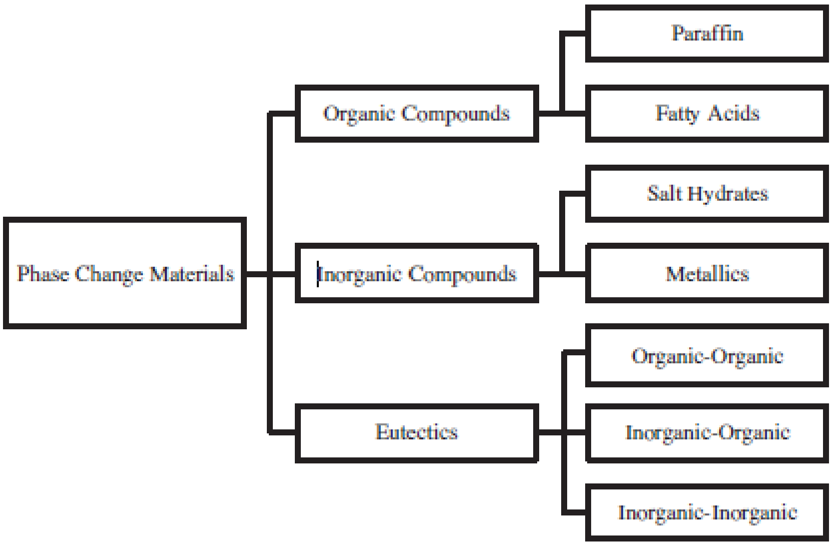


Figure 3. Classification of PCMs [2]

Advantages and disadvantages of each type are explained bellow.

The melting process for organic compounds is homogeneous and they have properties that favour nucleation. Moreover, they are not corrosive, and compatible with the materials normally used. The main disadvantage of these compounds is their low thermal conductivity.

Inorganic compounds have higher thermal energy storage capacity per volume unit than organic compounds, and also higher thermal conductivity. The melting process is not very homogeneous, which leads to different components. These components stay independent during solidification if no nucleation agents or stabilizers are used. Moreover, nucleation of the solid crystals is hard to achieve. This causes the subcooling of the liquid. Finally, inorganic compounds are corrosive with some metal and incompatible with most of the materials used in the manufacturing of tanks. Thermophysical properties of organic and inorganic compounds are summarized in Table 1 [3].

Table 1. Properties or organic and inorganic compounds [3]

Comparison of organic and inorganic materials for heat storage

Organics	Inorganics
Advantages	Advantages
No corrosives	Greater phase change enthalpy
Low or none undercooling	
Chemical and thermal stability	
Disadvantages	Disadvantages
Lower phase change enthalpy	Undercooling
Low thermal conductivity	Corrosion
Inflammability	Phase separation
	Phase segregation, lack of thermal stability

Eutectics are materials of two or more component, which melt and freeze congruently and form crystals of the component. The melting and freezing of these materials is nearly always without segregation [1,4].

The characteristics of the PCM employed need to be taken into account when selecting the material of the tanks and other equipment put into contact with them. Solutions are needed to enhance the thermal conductivity of PCMs, particularly of those with very low values of this property.

Each PCM has its own characteristics and singularities. For the selection of a PCM, [2,4] four basic aspects have to be identified: thermodynamic properties, kinetic properties, chemical properties, health issues and economic issues. Abhat [5] summarises the ideal characteristics of a PCM for each of these aspects (Table 2).

Table 2. PCM selection criteria [5]

Thermodynamic properties	(1) Melting temperature in desired range (2) High latent heat of fusion per unit volume (3) High thermal conductivity (4) High specific heat and high density (5) Small volume changes on phase transformation and small vapor pressure at operating temperatures to reduce the containment problems (6) Congruent melting
Kinetic properties	(1) High nucleation rate to avoid super cooling (2) High rate of crystal growth to meet demands of heat recovery from the storage system
Chemical properties	(1) Complete reversible freezing/melting cycle (2) Chemical stability (3) No degradation after a large number of freezing/ melting cycle (4) No corrosiveness (5) No toxic, no flammable and no explosive material
Economic properties	(1) Effective cost (2) Large-scale availabilities

Table 3 encloses the main characteristics of the substances mostly employed as PCMs [6].

Table 3. Properties of the most common types of PCMs [6]

Properties	Organic paraffin compound	Organic non paraffin compound	Organic sugar alcohol	Inorganic salt hydrate	Inorganic metallics	Eutectic organic	Eutectic inorganic
Corrosives	No[a]	No	No[a]	Low level	–	–	–
Toxic	No	Low level	No	Slightly[b]	–	–	–
Phase segregation	No[c]	No	–	Yes[a,c]	Yes[a]	No[d]	No[d]
Compatibility with container material	Yes except plastic[d]	–	–	With plastic[d]	No	–	–
Chemical stability	good[a]	–	–	No when heated[e]	–	–	–
Fire hazard	Yes	Yes	Yes	–	–	–	–
Volume change during solidification	10%	–	10 %[e]	10 %[a]	–	–	–
Phase change enthalpy per unit (mass/volume)	Low	Low	High	High	High	–	–
Vapor pressure	Low	–	–	Low	Low	–	–
Supercooling	No or low[b]	No ,little[b]	Yes[e]	Yes[a]	Yes	–	–
Thermal stability	Good[c]	–	–	Lack[a]	Lack[a]	–	–
Thermal conductivity	Low[d]	Low	Low	High	High	High	High
Cost	Low[e]	High	–	Low	–	–	–
Abundant	Yes	–	–	–	–	–	–
Application in thermal energy storage	Widely used[e]	Widely used[e]	–	Extensively used[b]	Not seriously used[b]	–	–

Zalba et al. [3] developed an extensive review of the compounds that can be used as PCMs. This review includes organic and inorganic compounds, as well as eutectic mixtures, fat acids, and PCMs available in the market. In addition, it encloses for each material its phase change temperature, latent heat, thermal conductivity and density. Similar values are shown in Sharma et al. [1].

Oró et al. [4] presented a review focused on existing and of-the-shelf compounds for cooling storage purposes. From [3, 4] it can be drawn that there are compounds for a very important range of temperatures.

The PCM phase change temperature must coincide with the desired storage temperature, and it will depend on the application. For air conditioning installations, with temperatures between -5 ºC and 10 ºC, the main available options of thermal energy storage with phase change are ice, hydrated salts, ice slurry or paraffin [7]. Zhai et al. [8] presented a review on the performance of PCMs in storage tanks for air conditioning.

Paraffin advantages are its non-toxicity, low price and compatibility with typical materials. It has also been proved that paraffin maintains a good stability for more than 5000 cycles. The main inconveniences of paraffin are its low thermal conductivity and high flammability [7]. He and Setterwall [9] analysed the thermal storage with a paraffin wax known as “Technical grade paraffin wax” (Rubitherm RT5 [10]), which has a melting point of 7 ºC and latent heat of 158.3 kJ/kg. The authors observed a homogeneous melting process, an appropriate nucleation (no subcooling prior to crystallization) and a good stability during an important number of cycles. The contraction due to phase change, 6.32%, cannot be neglected.

Concerning hydrated salts, their main limitation is it instability when heated, since at high temperature they degrade and they lose part of their water content. Furthermore, some salts are not compatible with the installation materials, have a low thermal conductivity (between 0.4 and 0.7 W/m·K) and need a high subcooling degree in order to initiate crystallization.

When choosing the phase change temperature of a PCM for the storage of DHW and heating water, the typical design temperature should be between 50 and 60 ºC. The eutectic mixture stearic acid – palmitic acid is within this range (phase change temperature 52.3 ºC and latent heat 181.7 kJ/kg) and has been proposed by Baran and Sari [11]. In Agyenim and Hewitt [12] the proposed compound is RT58 [10], with a phase change range of 53-59 ºC. The main results achieved are commented farther ahead in the text.

Several solutions have been developed in order to increase the thermal conductivity of PCMs (which is actually low). The insertion of PCM in a metal, the use of solid high conductivity metal particles, the encapsulation in macro and micro packages, the use PCM-graphite (or other material) compounds, and the use finned tubes are some examples of these solutions.

Nakaso [13] analysed the use of high conductivity carbon fiver materials to increase heat transfer, and concluded that it increased with a low volume. Figure 4 shows the fibres used in the work.

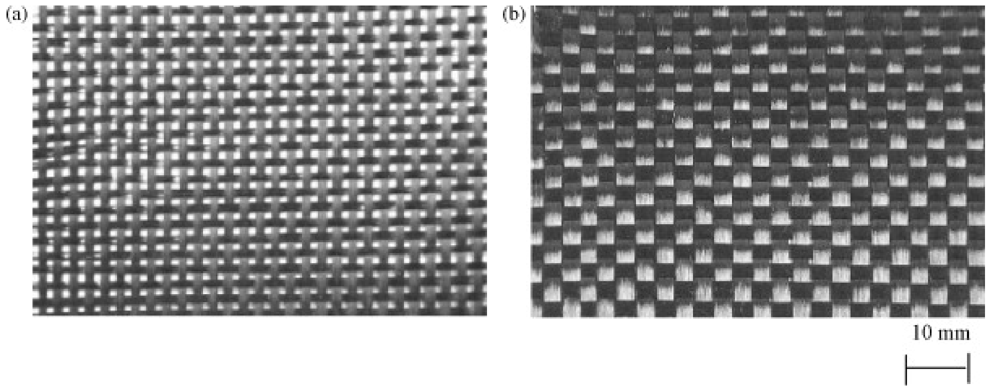


Figure 4. Carbon fiber for the increase of heat transfer with low conductivity PCMs [13]

A similar solution is carbon fiber “brushes”, shown in Figure 5, that were studied by Hamada and Fukai [14]. They also obtained an increase of the energy stored by this material and observed that an enhancement of 15% was achieved for the thermal conductivity.

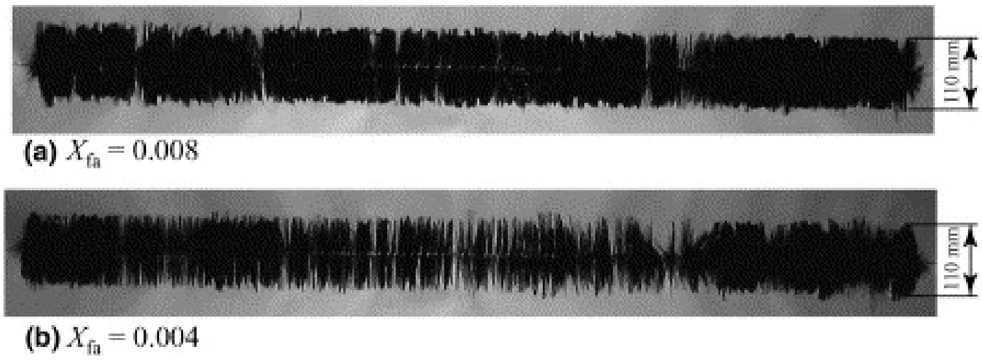


Figure 5. Carbon fiver "brushes" [14]

In [15], Hamada et. al. compare the behaviour of "brushes" with a solution that consists of carbon fivers shavings. Both solutions lead to an enhancement of the heat transfer, but "brushes" present higher overall heat transfer coefficients than shavings.

4.2 Types of storage systems

A large amount of studies have been developed in order to analyze different heat exchanger geometries for the storage of thermal energy with PCMs, as shown below. Al-Abidi et al [6] studied up to 5 heat exchanger geometries, but propose the shell-and-tube heat exchanger as the most promising technology. PCMs have been used both in the shell side and inside the tubes. Other geometries employed up-to-date are helical coils, serpentines, double tubes, fin-and-tubes and plate heat exchangers.

In [16], Trp presents a work where a thermal storage system based on shell-and-tube is analyzed (Figure 6). The author developed a mathematical model to simulate the process of thermal charge and discharge of a shell-and-tube storage system with Rubitherm RT 30 paraffin in the shell side and water through the tubes, which is validated with experimental data. In Trp et al.[17], the developed mathematical model was used to evaluate the effect of the heat exchange fluid conditions and the storage system geometry. They concluded that the selection of the operating conditions and geometric parameters depends on the required heat transfer rate and the time in which the energy has to be stored or delivered.

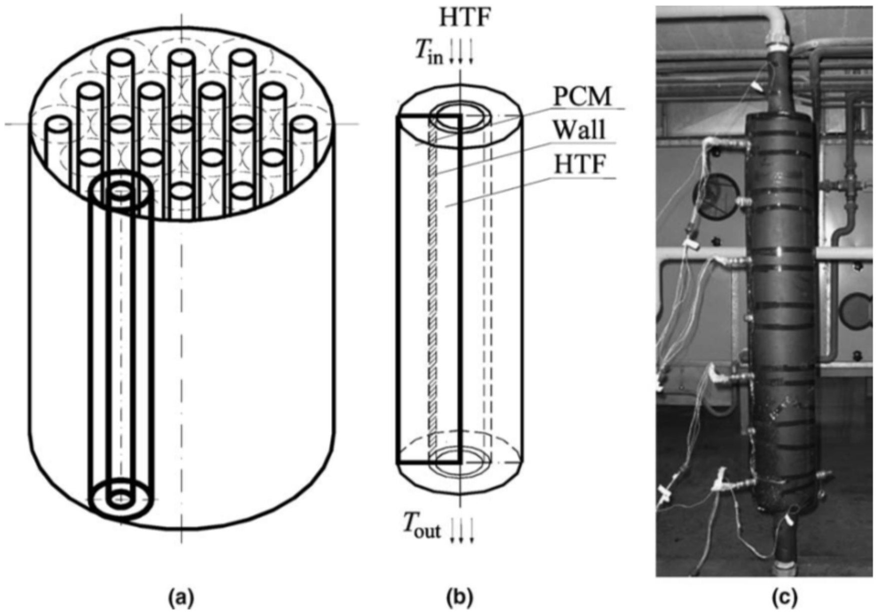


Figure 6. Shell-and-tube storage system [16, 17]

A study with the same geometry was carried out by Esen et al. [18]. They analysed the situation where the PCM is in the shell side and the heat exchange fluid from the solar collector inside the tubes, and the situation where the PCM is inside the tubes and the heat exchange fluid inside the shell side. In this study they optimized the geometry for both working modes and the authors concluded that the thermal storage is much faster when the PCM is inside the shell and the heat exchange fluid flows inside the tubes.

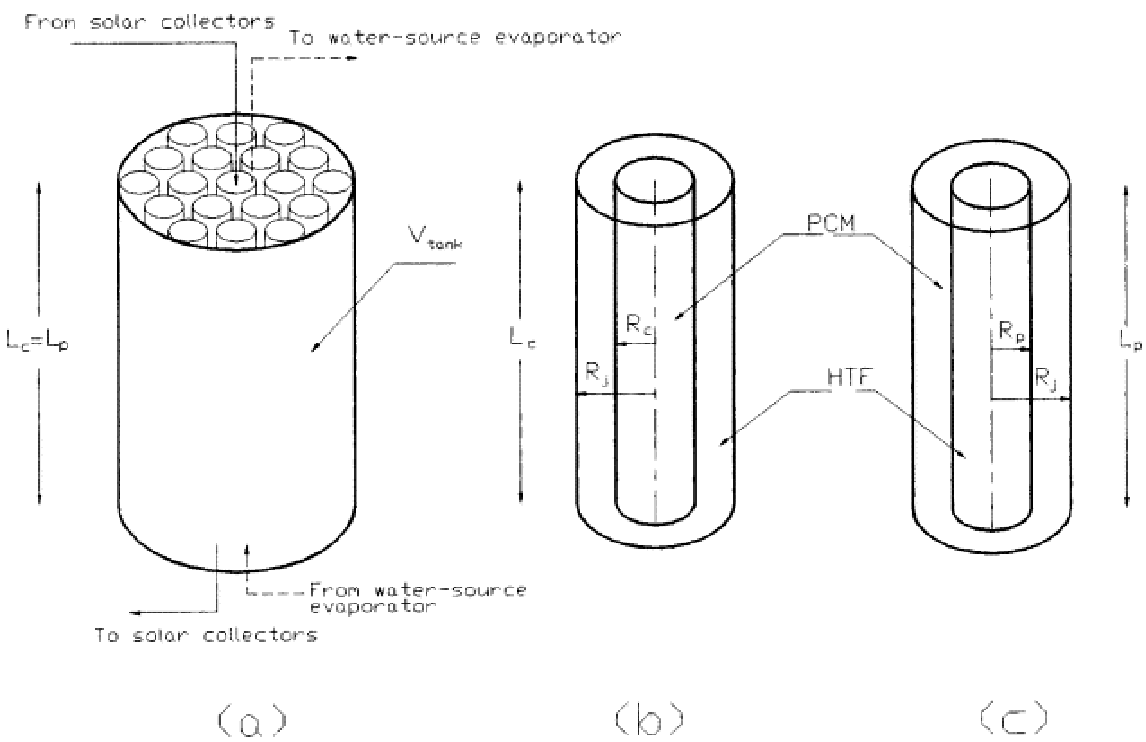


Figure 7 Modelled and analyzed systems in [18]

Tay et al. [19] proposed a new system based on a storage tank with vertical tubes "dynamic melting". It consists of the recirculation of part of the already melted PCM to enhance the phase change process. In Figure 8, an image of the prototype built is shown. This design worked with tubes where the melting of PCM (a hydrated salt with a phase change temperature of -11 ºC) starts. When the liquid phase appears, the already melted salt is recirculated in order to accelerate the rest of the melting process. The average efficiency increased between 33 and 89% for high temperature differences and between 58 and 82% for smaller gradients. This enhancement is equivalent to that achievable with finned tubes.

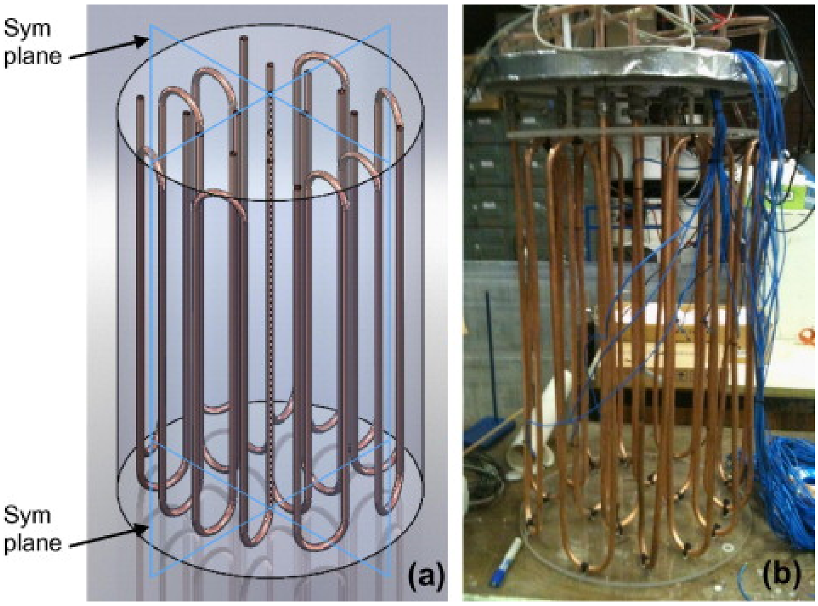


Figure 8 Test rig used by Tay et al. [19]

The use of PCMs can be limited to certain areas of the tanks, as seen in Figure 9 [20]. The main conclusion of this work is that the use of PCM in DHW systems in solar applications may not prove to be substantially beneficial, according to their numerical study, as the improvement observed during the day period caused by PCMs to store the solar energy was compensated by the losses undergone by the storage tank during the night.

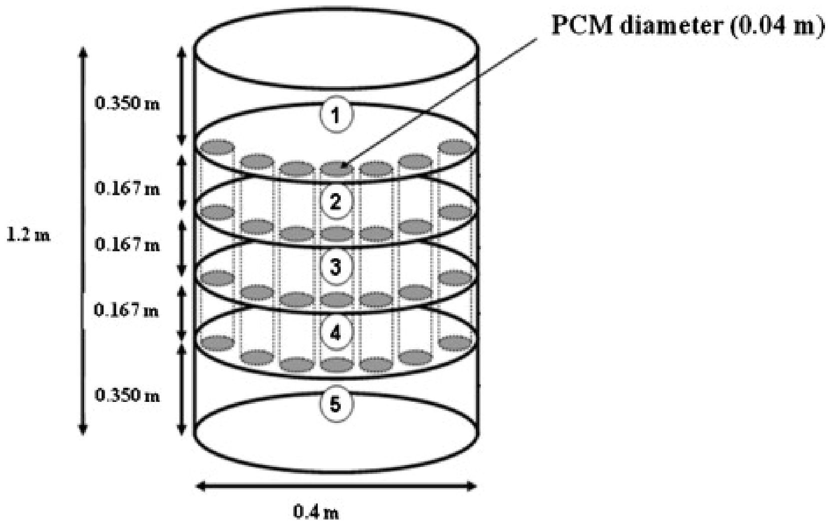


Figure 9 Model studied by Kouskou et al. [20]

As already pointed out, the use of fins is a solution to the low thermal conductivity of PCMs. Tay et al. [21] analyzed the behavior with two types of fins, annular and "spine" and they compared the results with those for plain tube. They concluded that the annular configuration exchanges more heat and faster, due to the higher heat exchanger surface. Compared with plain tube, an increase of the heat transfer between 20 and 40% and a reduction in phase change time of 25% were achieved with annular fin configuration.

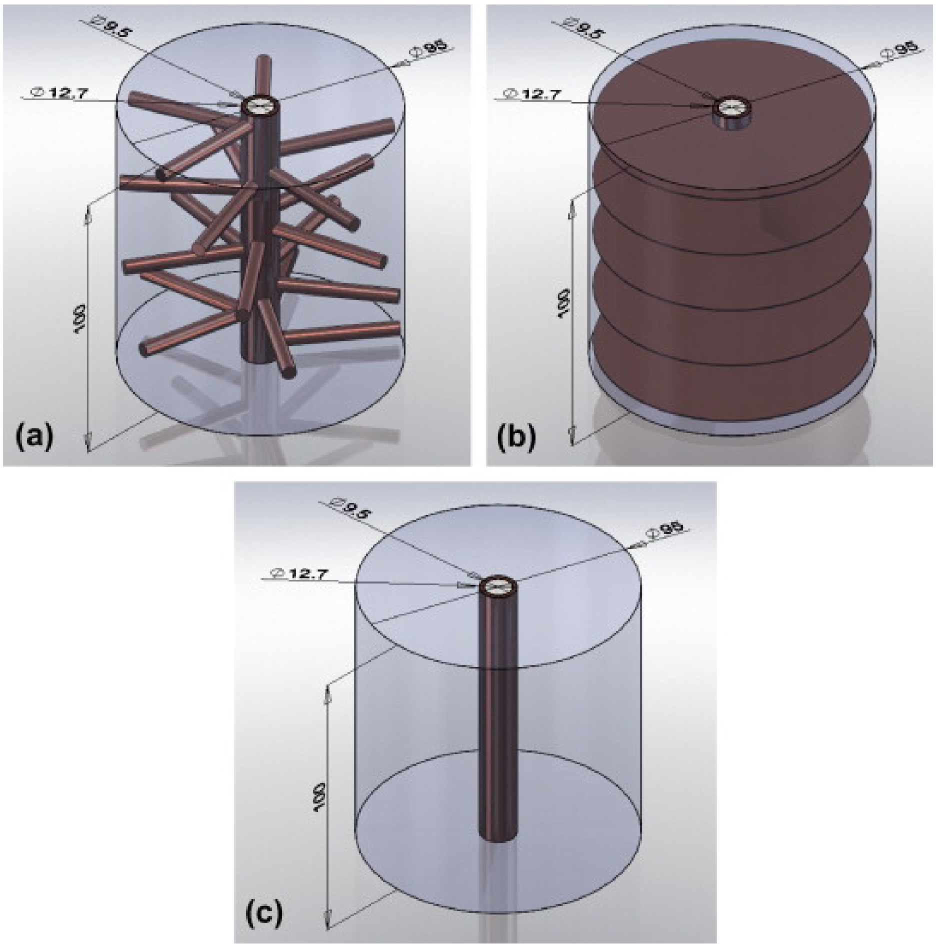


Figure 10. Geometries considered by Tay et al. [21]

Continuing with the effect of adding fins, Gil et al. [22] studied two identic tanks, for the storage of thermal energy at high temperature (solar applications), as seen in Figure 11. The only difference between tanks is that one had 196 square shaped fins homogeneously distributed meanwhile the second had none. The use of fins led to a heat transfer enhancement of the 20%.

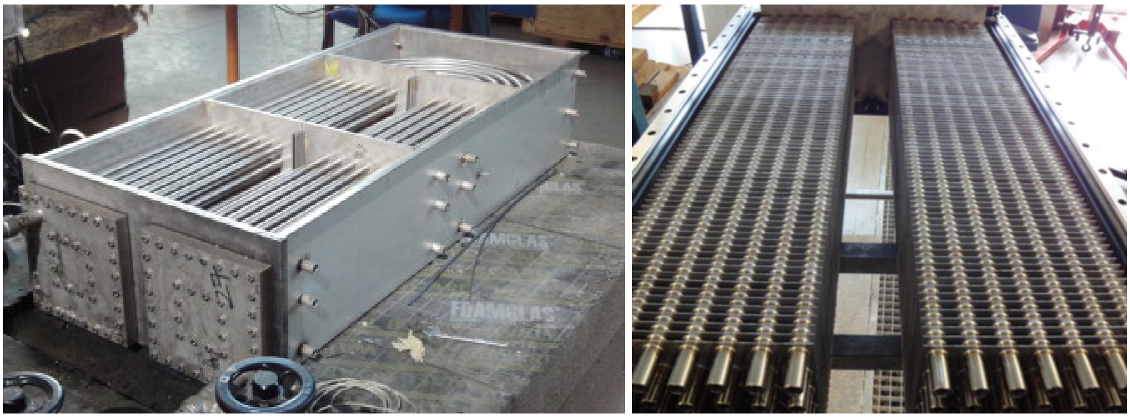


Figure 11. Tanks studied in [22]; left: without fins; right: with square shaped fins

Another work concerning solutions with fins is Agyenim and Hewitt [12], where they proposed the use of a cylindrical tank of 375 mm of diameter and 1.2 m long, with a finned copper tube of 65 mm of diameter (Figure 12). The fins used were longitudinal fins (1100 mm long, 120 mm wide and 1 mm thick). The tube was filled with 93 kg of RT 58 [10]. The results show a quadratic relationship between heat transfer coefficient and the inlet HTF (Heat transfer fluid) temperature within the investigated temperature range (62-77 °C). The improvement by integrating a PCM storage system to an air source heat pump to meet 100% residential heating energy load for common buildings in UK causes a size reduction of the storage system by up to 30%. This system was thought to optimize the performance of a heat pump installation, to make the best of those periods of the day when the energy is cheaper.

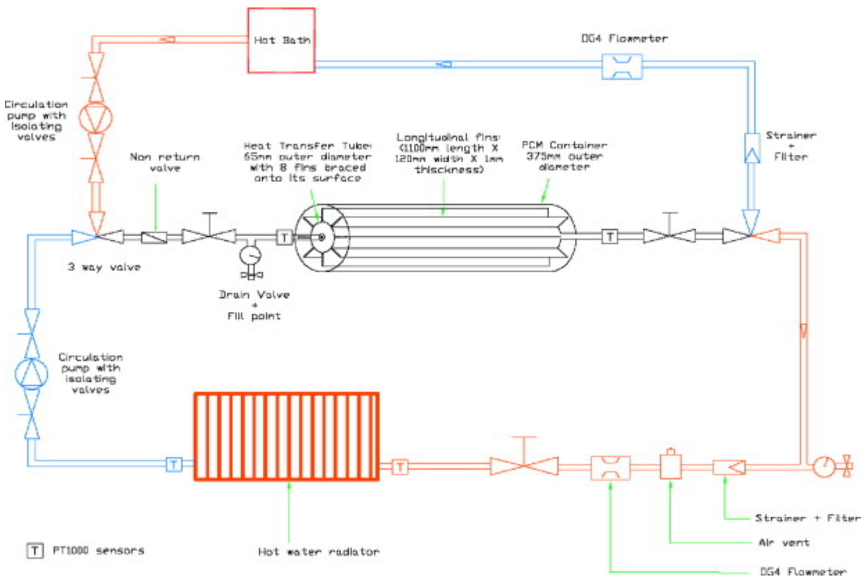


Figure 12. Sketch of the installation from [12]

Murray and Groulx [23] also studied a system with longitudinal fins in a tank with two vertical tubes (4 fins per each tube), as shown in Figure 13. One tube was used for the thermal energy charge process and the other for the discharge. One of the contributions of this work is that the dodecanoic acid can be used as PCM, as it has been shown to been safe, inexpensive, and has a melting temperature in a range suitable for its use in solar DHW applications. Moreover, this work showed that increasing the heat transfer fluid flow rate during the PCM charging process resulted in significantly faster melting, while increasing the flow rate during discharging had no effect on the time needed to discharge the LHESS (latent heat energy storage system).

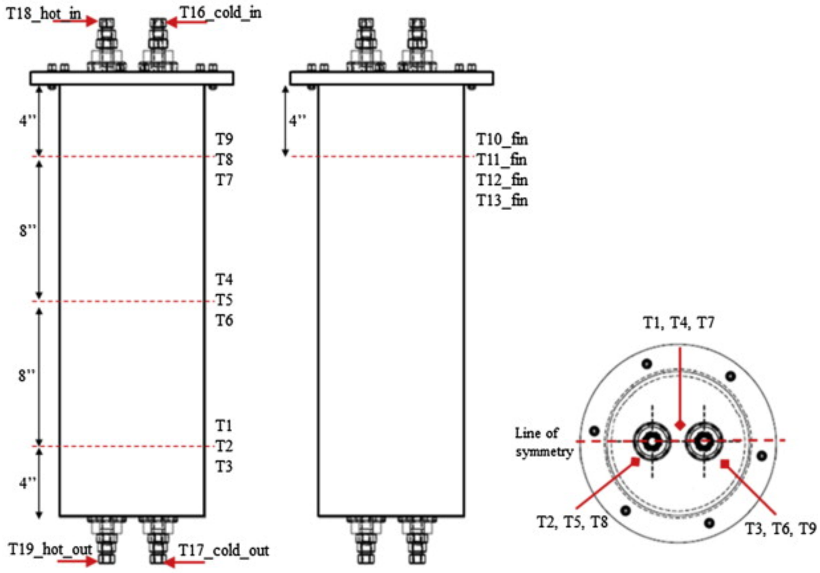


Figure 13. System proposed in [23] with longitudinal fins

The use of metallic packing materials with PCMs is also proposed in the literature, in order to enhance heat transfer and to solve the problem of low thermal conductivity of PCMs. In [24], three different heat transfer enhancement methods are analyzed: longitudinal fins on a vertical cylinder filled with paraffin, lessing rings (Figure 14) inside a cylinder with paraffin inside it, and vapour bubble generation inside a cylinder with paraffin. The conclusion from this work is that the first two techniques lead to a considerable increase of heat transfer, both from the reduction of the thermal energy charge time point of view and from the stored energy quality point of view (results in Figure 15). These metallic pieces do not have influence in the quality of the water of accumulation since they can also be encapsulated.

Figure 14. Lessing rings from [24]

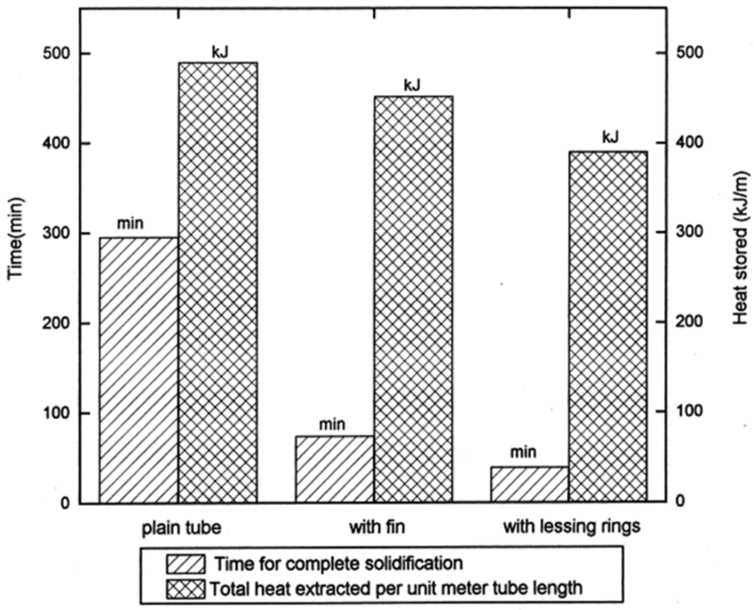


Figure 15. Results obtained in [24]

Banaszek et al. [25] analyzed thermal storage with a spiral vertical heat exchanger (Figure 16). This kind of heat exchangers is widely used in chemical and food industries. These heat exchangers are very compact, with large heat exchange surface, easy to seal, with a minimum heat exchange length where the fluid suffers no perturbation, and tend to have high heat transfer coefficients due to the centrifuge forces suffered by the fluid. Its use with PCMs requires only the substitution of one of the fluids for a PCM. In [25] a paraffin wax PPW-20 was used as PCM. The phase change temperature of this material is not constant (for a temperature between 45 ºC and 60 ºC requires an enthalpy increase of 173 ± 5 kJ/kg). This study analysed the heat exchange between this PCM and air.

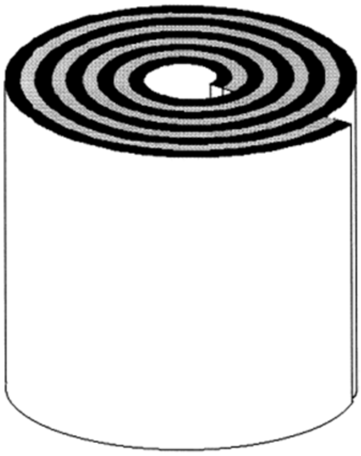


Figure 16. Spiral cylindrical heat exchanger [25]

Concerning helical coils, Torregrosa-Jaime et al. [7] studied the cooling storage in a tank with helical coil and paraffin RT 8 from Rubitherm (phase change temperature between 4 and 8 ºC). The tank was made of plastic and the helical coil consisted of 34 loops, with 17 turns per loop and a total length of 70 m (Figure 17). The tube was made with polyethylene tube (without fins) of 1.8 cm of external diameter and a pitch of 2.3 cm [26]. The paraffin was chosen attending to its high stability with time. During the accumulation process, a solid layer occurred around the helical coil wall, and it was observed that this layer deteriorated heat transfer. Caused by this and by the low thermal conductivity of the paraffin, the authors observed that up to 31% of the tank remained unalterable.

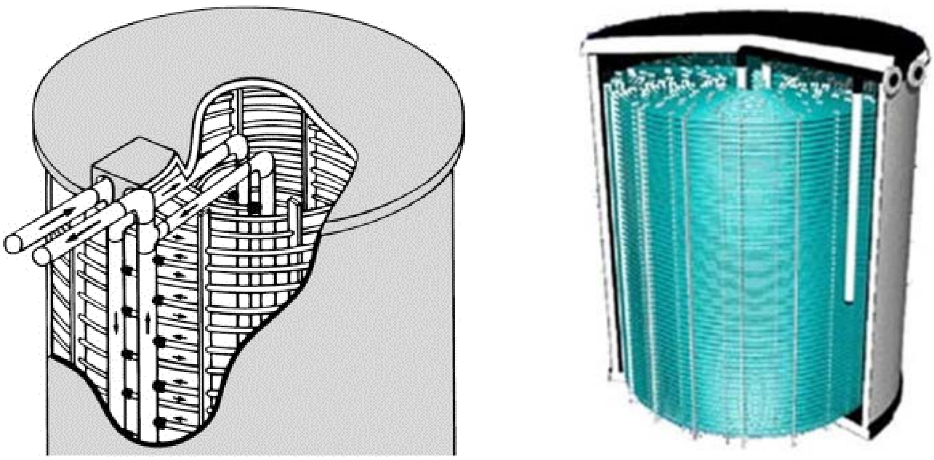


Figure 17. Tank with helical coil [7, 26]

Öztürk [27] analysed the thermal energy storage in a horizontal steel tank of 1.7 m of diameter and 5.2 m of length (volume 11.6 m^3), filled with 6000 kg, approximately, of paraffin. The heat exchanger in the tank was a helical coil Figure 19. Through the coil flowed hot air from solar panels.

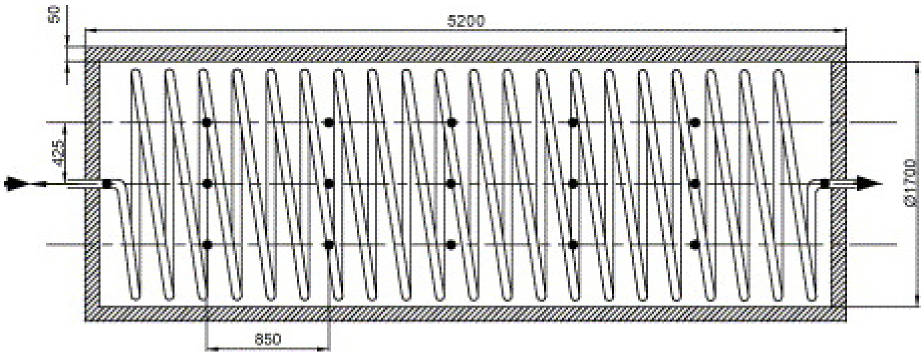


Figure 18. Horizontal tank with helical coil [27]

Five small heat exchangers are studied by Medrano in [28], working as latent heat storage systems with Rubitherm RT 35, and water as the heat exchange fluid. This PCM was chosen since the storage temperature desired was between 35 and 40 ºC. The heat exchangers analyzed were three double tube heat exchangers (plain double tube with PCM in the annulus, copper finned double tube with PCM in the annulus, and double tube with a graphite base to enhance heat transfer), a fin-and-tube heat exchanger and a plate heat exchanger. From this analysis the authors concluded that the double tubes and plate heat exchangers are not suitable for thermal energy storage; in double tubes due to the reduced heat exchange surface and in plate heat exchangers due the reduced storage capacity. The fin-and-tube heat exchanger had a larger storage capacity and seems more suitable for real installations.

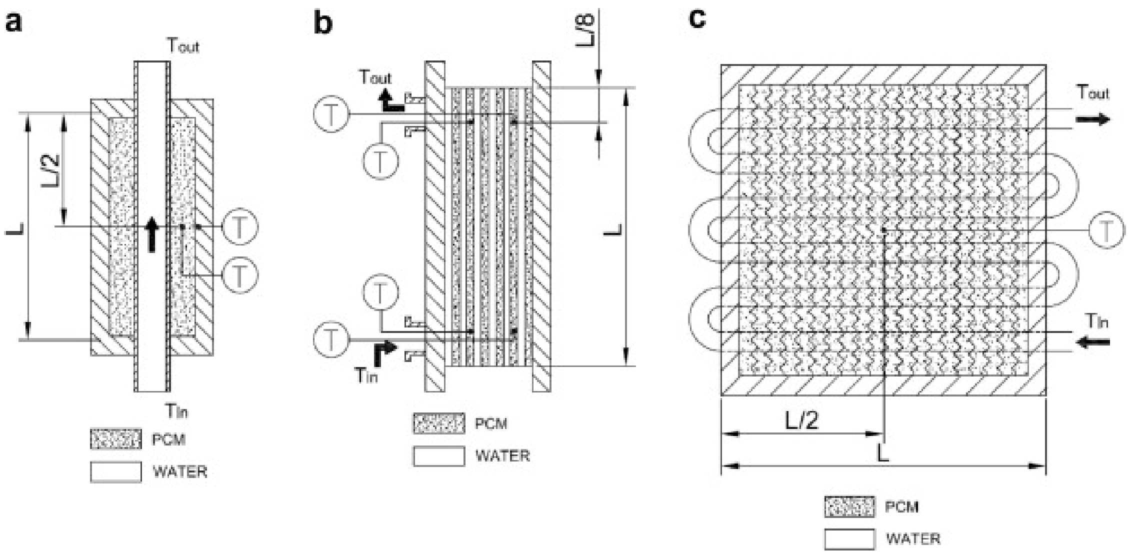


Figure 19. Sketch of the three types of heat exchangers used in [28]

Another compact system for thermal energy storage, consisting of parallel plates of PCM, separated by a rectangular channel, is presented and analysed in [29, 30]. Figure 20 is a representation of the computational model developed by the authors for the study. Both works employ the same model to obtain empirical correlations which optimize the energy storage unit. The aim of this storage unit is reducing the domestic electric energy consumption during peak period loads. The effect of several design and operating conditions on the thermal behaviour of the unit was studied through a parametric analysis. The authors of these works also state that the average output heat load during the recovery period is strongly dependent on the minimum operating temperature, on the thermal diffusivity of the liquid phase, on the thickness of the PCM layer and on the flow rate and temperature at the inlet of the heat transfer fluid.

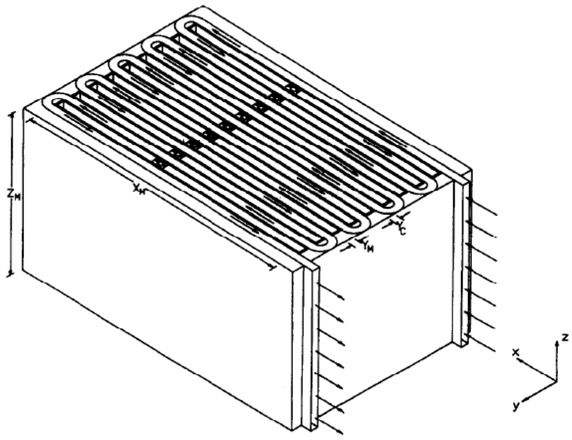


Figure 20. Thermal energy storage system with rectangular cavities [29, 30]

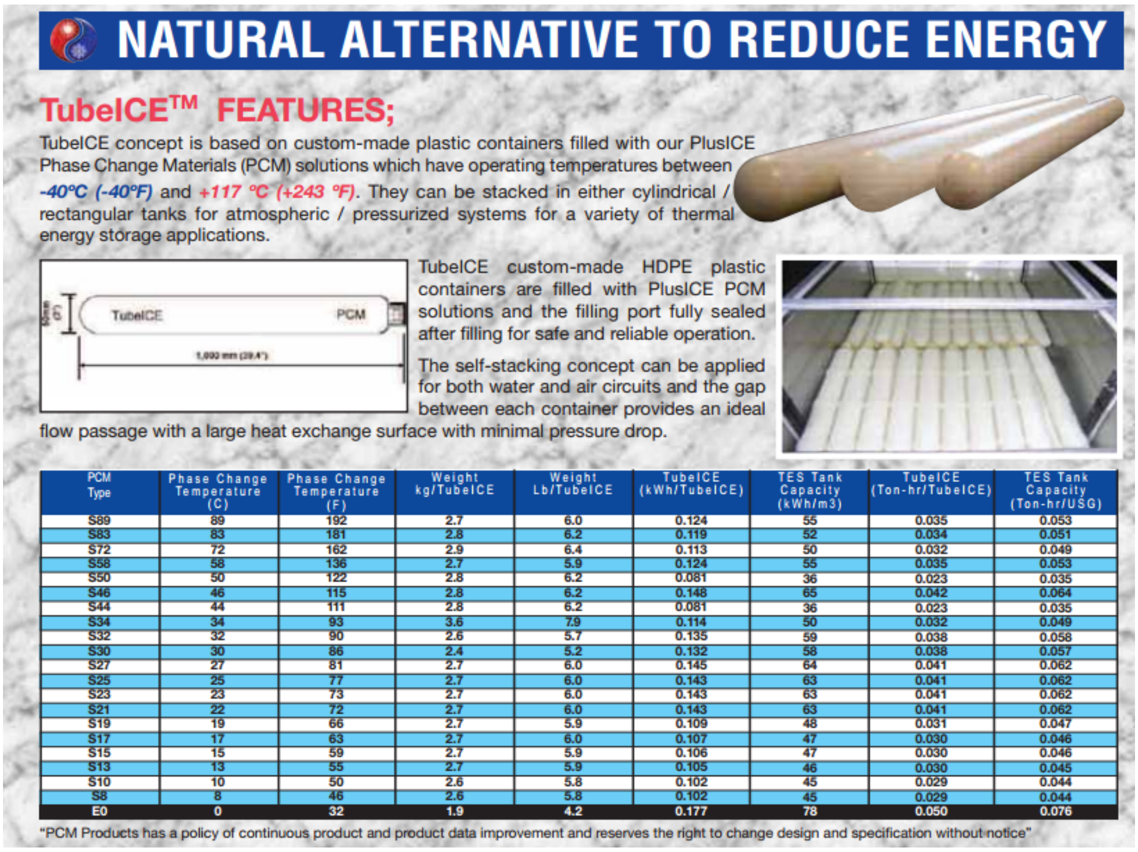
Table 4 encloses all the commercially available tanks for PCMs (up to 2007) from the companies Cristopia [31] and EPS [32].

Table 4. Commercially available tank models for PCMs (2007)

Table 12. Commercially manufactured phase change storage tanks

Volume (m^3)	External diameter (mm)	Total length (mm)	External surface area for insulation (m^2)	Connections inlet/outlet (mm)	Number of cradles	Empty weight (kg)	Heat transfer fluid volume (m^3)
Cristopia Energy Systems (Cristopia)							
2	950	2980	10	40	2	850	0.77
5	1250	4280	18	50	2	1250	1.94
10	1600	5240	29	80	2	1990	3.88
15	1900	5610	37	100	2	2900	5.82
20	1900	7400	47	125	3	3700	7.77
30	2200	8285	61	150	3	4700	11.64
50	2500	10,640	89	175	4	6900	19.40
70	3000	10,425	106	200	4	7300	27.16
100	3000	14,770	147	250	6	12,700	38.80
Environmental Process Systems Limited (EPS Ltd.)							
5	1250	3750		50			
10	1600	4500		80			
25	2000	8000		125			
50	2500	10,000		150			
75	3000	10,600		200			
100	3000	11,100		250			

Another possibility for the use of PCMs is encapsulation. Depending on the size of encapsulation, it can be distinguished between microencapsulation (from less than 1 mm to 300 μm) and macroencapsulation (larger than 1 mm). Microcapsules are normally made of natural and synthetic polymers. Macrocapsules normally consist of spherical containers, but there are also other geometries such as cylindrical or rectangular bars [31, 33]. The recommended materials for encapsulations, attending to compatibility with typical PCMs for low temperatures, are stainless steel, propylene, polyolefin [32]. Off-the-shelf examples are exposed in Figure 21.



PCM Type	Phase Change Temperature (C)	Phase Change Temperature (F)	Weight kg/TubeICE	Weight Lb/TubeICE	TubeICE (kWh/TubeICE)	TES Tank Capacity (kWh/m3)	TubeICE (Ton-hr/TubeICE)	TES Tank Capacity (Ton-hr/USG)
S89	89	192	2.7	6.0	0.124	55	0.035	0.053
S83	83	181	2.8	6.2	0.119	52	0.034	0.051
S72	72	162	2.9	6.4	0.113	50	0.032	0.049
S58	58	136	2.7	5.9	0.124	55	0.035	0.053
S50	50	122	2.8	6.2	0.081	36	0.023	0.035
S46	46	115	2.8	6.2	0.148	65	0.042	0.064
S44	44	111	2.8	6.2	0.081	36	0.023	0.035
S34	34	93	3.6	7.9	0.114	50	0.032	0.049
S32	32	90	2.6	5.7	0.135	59	0.038	0.058
S30	30	86	2.4	5.2	0.132	58	0.038	0.057
S27	27	81	2.7	6.0	0.145	64	0.041	0.062
S25	25	77	2.7	6.0	0.143	63	0.041	0.062
S23	23	73	2.7	6.0	0.143	63	0.041	0.062
S21	22	72	2.7	6.0	0.143	63	0.041	0.062
S19	19	66	2.7	5.9	0.109	48	0.031	0.047
S17	17	63	2.7	6.0	0.107	47	0.030	0.046
S15	15	59	2.7	5.9	0.106	47	0.030	0.046
S13	13	55	2.7	5.9	0.105	46	0.030	0.045
S10	10	50	2.6	5.8	0.102	45	0.029	0.044
S8	8	46	2.6	5.8	0.102	45	0.029	0.044
E0	0	32	1.9	4.2	0.177	78	0.050	0.076

"PCM Products has a policy of continuous product and product data improvement and reserves the right to change design and specification without notice"

Figure 21. Example of PCM bars available in the market [34]

Typical diameters for the spherical macrocapsules are between 75 and 100 mm, depending on the manufacturer [32,33], and the durability of the capsules is, in some cases, over 10000 cycles (over 20 years). The encapsulation breakage can cause health problems, so avoiding having the domestic hot water in direct contact with PCM capsules is something to be taken into account when designing an installation.

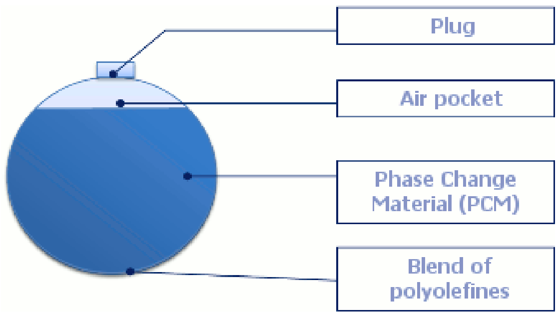


Figure 22. Sketch of the PCM capsule commercialized by Cristopia [31].

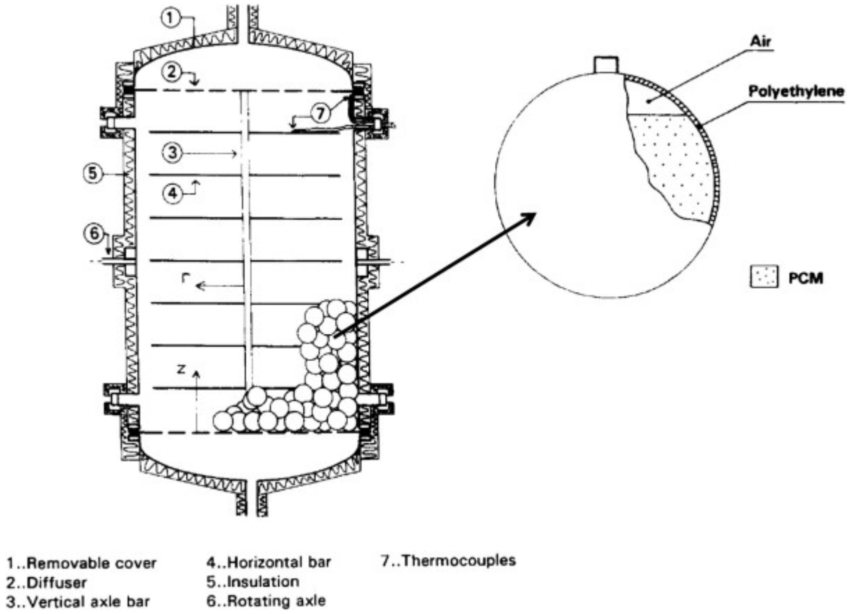


Figure 23. Thermal storage system with spherical capsules [7]

As an example, the use of PCM modules in the upper part of storage tanks allows increasing the thermal energy storage density. In addition, heat transfer occurs from the PCM modules to the stored water, increasing its temperature without an external heat source, both after partial discharges or to compensate heat losses to the environment. Mehling et al [34] proposed a solution following this line. They were able to increase the thermal energy storage density between 20 and 45% by filling 1/16 of the tank volume with PCM modules. They also maintained the temperature of the water at the upper part of the tank during a period between 50% and 200% longer. Cabeza et al. [35] also proposed this use of PCM modules, Figure 24. Taking into account that the most common storage temperature in a water tank is 55-60 ºC, the phase change temperature of the PCM was chosen in that range. In this work, the PCM chosen was sodium acetate tri-hydrated. The authors obtained an increase of the thermal energy density between 40 and 66.7%, when the temperature difference was of 1 ºC and between 6 and 16.4% when the temperature difference was 8 ºC. Ibáñez [36] describes the application of this solution to a single-family dwelling in Lledia (Spain). The authors stated that the annual solar contribution in the production of DHW increased between 4 and 8%.

In contrast, Talmsky [37] analyzes through simulation the use of PCMs in DHW systems with solar support, and obtained not so optimistic results. The main conclusion is that adding PCMs (sodium acetate tri-hydrated with graphite particles SAT-G, and paraffin RT 42 [10] in a graphite matrix RT42-G) has a negligible effect. The difference is quantified in less than 1%, and justifies that these result depends on the energy on the solar panels, and on the time of the day when the water is consumed (favorable periods and counter-productive periods). However, this work proposes that PCMs may be interesting if the tanks are designed taking into account the characteristics of such materials. Similar conclusions were drawn by Kouskou et al. [20], and they stated that the improvement on the behavior of thermal storage tanks with PCMs depends on the correct design of these systems and on the right choice of PCM material.

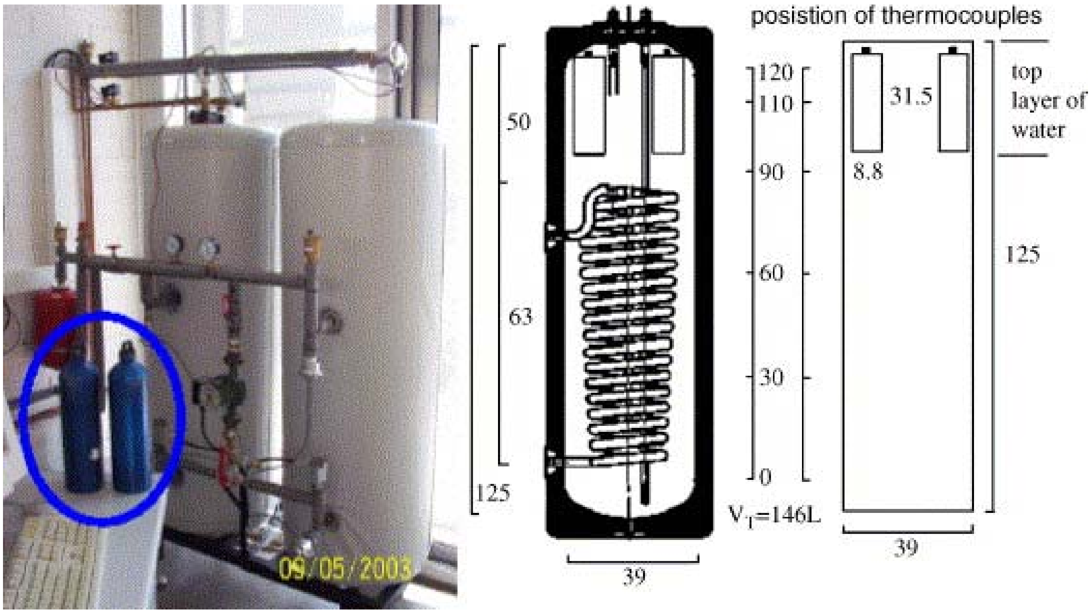


Figure 24. Water storage system with PCM modules in the upper part [35]

Conclusion PCM ,

Nowadays, different kinds of PCMs are being commercialized for a wide range of applications and temperatures, covering from several tens of degrees below 0 ºC to over 200 ºC. PCMs are usually classified into organic compounds, inorganic compounds and eutectic mixtures. However, there is not a kind of PCM that meets all applicable requirements (thermodynamic, kinetic, chemical and economical properties) for an ideal PCM. Thus, the correct selection of the PCM is still a crucial issue.

Regarding storage tanks, different geometries of heat exchangers have been proposed by many researchers. The main challenge of these systems is improving heat transfer which is limited by the formation of a solid film around the heat exchange surfaces. Therefore, different solutions have been proposed such as fins, metallic inserts, carbon fibers and carbon brushes.

In conclusion, phase change materials are a promising technology but still under development. The continuous development of PCMs with increasingly efficient properties and the improvement in the design of heat exchange systems will lead to important reductions in the size of storage tanks and to the design of even more efficient systems.

4.3 TCMs: Thermochemical materials

Thermochemical materials are thermal energy storage systems based on a reversible chemical reaction, which is energy demanding in one direction and energy yielding in the reverse direction. TCMs, just as PCMs, allow separating the charge process of thermal energy accumulators to the discharge process. Unlike PCMs, TCMs (thermochemical materials) store energy chemically, so no charge is lost over time.

Figure 25 shows the difference of space needed to accumulate the same energy with sensible accumulation (water), latent accumulation (PCM) and thermochemical accumulation (TCM) [38].

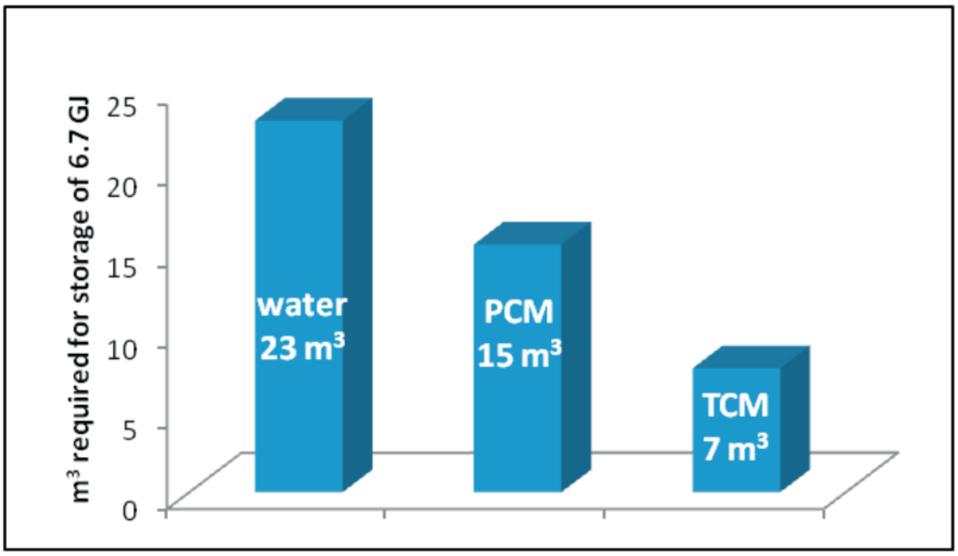


Figure 25. Storage volume decrease with PCMs and TCMs [38]

The most typical TCMs are salt hydrates in which thermal energy is stored by drying the salt hydrate and storing the dry salt and the water separately [38].

Ard-Jan de Jong [39], performed a study of the applicability of TCMs for heating production and on the design parameters for such systems. The studied reactor, shown in Figure 26, could accumulate 1kWh 5 minutes working with a power of 12 kW. The contribution for the reactor power in this case is limited by the size of the tubes. However, it should be possible to scale the system up to capacity needed.

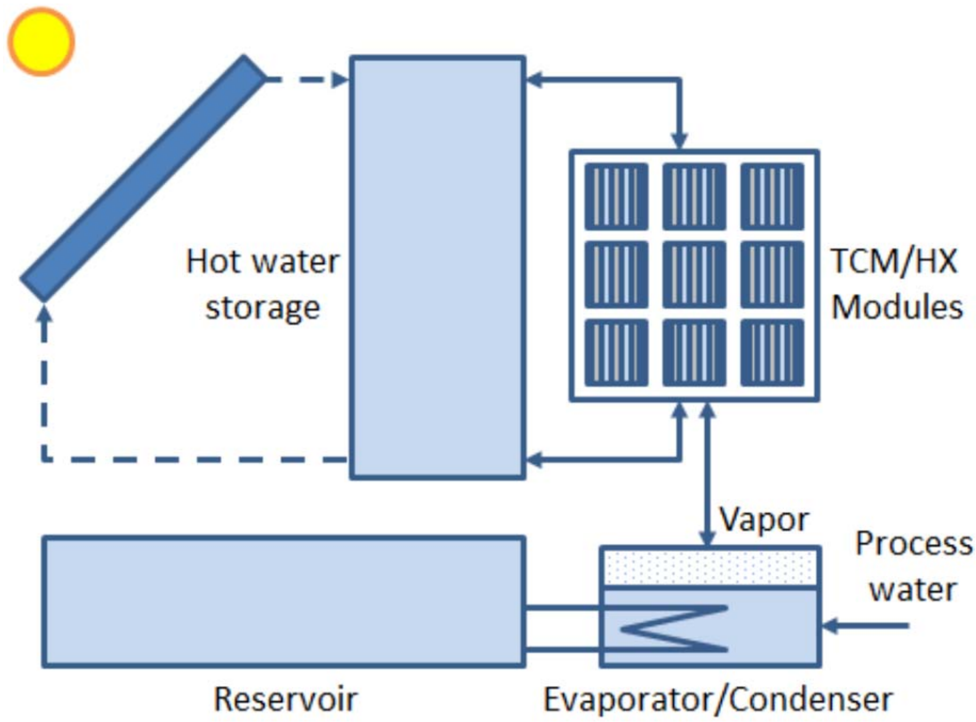
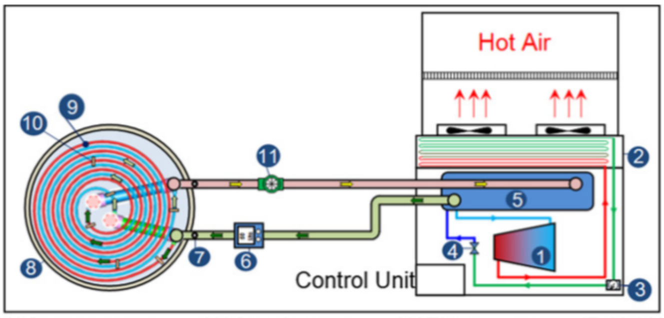


Figure 26. Installation studied [39]

4.4 Use of inverter with PCM

Looking for an improvement in the performance of the installation, using PCM in the accumulator together with frequency control of the compressor arises as an interesting possibility.

Ekren [40] conducted a study to determine the performance of a system using a variable speed refrigeration system in latent heat thermal energy storage. A schematic diagram of the experimental setup is given in Figure 27.



(1)Compressor, (2)Condenser, (3)Flow meter(R404A), (4)Expansion valve, (5)Evaporator, (6)Flow meter(Brine), (7)Pt-100, (8)Storage Tank, (9)Coil, (10)Measurement Cards, (11)Pump

Figure 27. Schematic diagram of the installation studied in [40]

To test the installation, Ekren [40] proposed a series of tests in order to determine the best control parameter of the system, for which he proposes 4 different cases. These control cases are: (i) control with evaporation temperature, (ii) control with ethylene glycol temperature at the outlet section of evaporator, (iii) control with suction pressure of the compressor and (iv) on/off control. The result of the study is that the best COP was achieved for the control strategy (ii).

Benli [41,42] studies a heating system geothermal heat pump with latent heat storage tank (PCM) to estimate the performance of thermal energy storage. The heating system consists mainly of a ground heat exchanger, a heat pump, a cylindrical thermal storage tank latent heat, units of measurement and a space heating of greenhouses. The heat pump COP ranged from 2.3 to 3.8 and the global COP installation ranged between 2 and 3.5. The installation diagram is shown in Figure 28.

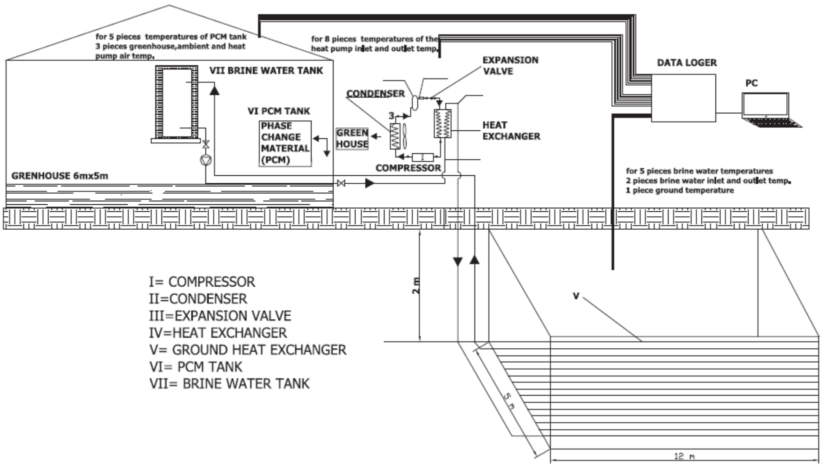


Figure 28. Installation diagram [41,42]

4.5 Conclusions

An extensive review has been conducted concerning the use of PCMs in thermal storage tanks, focusing on both commercial equipment and experimental prototypes. PCMs have been used inside tanks, being heated or cooled, depending on the application, by means of different kinds of systems. Encapsulated PCMs inside the tanks are also common and have been studied in several works. Both solutions have advantages and disadvantages, and using one or another depends on the application.

Concerning the method used for heating or cooling the PCM, many geometries of heat exchangers have been studied. Shell-and-tube geometry is the most spread geometry. However, helical coils in tanks are also available in the market nowadays. Different methodologies are also described in order to heat or cool the PCMs, such as the alternative flow of fluids for charging and discharging the thermal energy in the PCMs, or the use of two heat exchangers.

A common issue of PCM systems is the reduction of heat transfer that occurs due to the formation of a solid film around the heat exchange surfaces. Many solutions are proposed in the literature to minimize this problem, such as employing fins of different geometries or introducing high conductivity elements in the tanks. Among those elements, metallic inserts, carbon fibers and carbon brushes can be pointed out. Heat transfer may also be enhanced increasing the heat exchange surface available in the tanks.

A wide range of compounds can be used as PCMs, but they are normally classified into organic compounds, inorganic compounds and eutectic compounds. Each kind of compound has advantages and disadvantages concerning criteria such as latent heat, thermal conductivity, safety, physical-chemical stability or price.

The main characteristic during the selection process of a PCM is the phase change temperature (or temperature range), which depends on the application and on the source that provides the thermal energy. Heat pumps, used for heating or cooling, have a quite limited temperature range, as the working temperatures have a great effect on their COP. This fact limits as well the types of PCMs that can be used with heat pumps.

However, using PCMs in tanks with heat pumps has a potential advantage over other thermal storage fluids. Due to the higher density of thermal energy storage of PCMs, the temperature at which energy is accumulated can be decreased (heating applications) or increased (cooling applications). The storage temperature diminution also leads a reduction in the environmental losses. In conclusion, the COP of the heat pump and the efficiency of the installation increase.

In addition, this higher thermal energy storage density of PCMs may lead to a reduction of the number of start and stop cycles of the compressor, which are the processes at which its electricity consumption is maximum. This effect is even more important if combined with inverter technology and variable speed compressors.

Another advantage of using PCMs is that it is possible to reduce the size of the tank due to this higher thermal energy storage density. Therefore, the size of heat pump-tank systems can be reduced, which is important from a commercial point of view.

Inverter driven heat pumps can adapt the heating or cooling production temperature to the phase change temperature of the PCM, maintaining their COP in an acceptable range, a great advantage if compared to on-off heat pumps.

Finally, TCMs (thermochemical materials) appear as a feasible alternative to PCMs, and should be also taken into account in the future for thermal energy storage.

4.6 Further work

This state of the art is the basis of a project that has the main objective of choosing and applying appropriate PCMs for the thermal energy storage in inverter driven heat pumps.

The first part of the project will be the selection of PCMs for the range of temperatures normally found when working with heat pumps. For DHW applications, the chosen PCMs will have a phase change temperature around 45 ºC. For heating applications, the temperatures considered will be around 35 ºC and around 45 ºC, and for cooling applications, around 7 ºC and 15 ºC.

A second part of the future work will be testing the selected PCMs in storage tanks, focusing on DHW tanks. The main objective is to combine PCMs and storage tanks particularly designed for PCMs to minimize the storage tank size, which is crucial from a commercial point of view.

4.7 References

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