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Report

State- of-the-Art - Thermal Energy Storage Accumulation Tanks

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ABSTRACT

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

This report begins provides a brief description of the most commonly used tanks for domestic hot water storage. Given the interest of using accumulation together with heat pumps the use variable speed drive (VSD) compressors order to impact on reduce storage size has been studied. The use of VSD compressors in heat pumps and its effect on the dimensions of the tank and on the system efficiency has been reviewed. The application of PCMs in thermal storage tanks has also been studied. The available literature on PCMs for thermal storage tanks has been reviewed and the main ideas 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 demands. This prevents expensive oversizing of the production equipment and allows utilization of low-cost electricity according to the local electricity tariff [1]. In addition, thermal energy storage is very useful when working with discontinuous generation systems, such as solar thermal energy or applications with waste heat recovery.

This report focuses on the use of Phase Changing Materials (PCMs) in thermal energy storage tanks. It provides a brief description of the most commonly used types of tanks and reviews the available literature on PCMs for thermal storage tanks. The main works concerning the use of variable speed drive (VSD) compressors in heat pumps and its effect on the dimensions of the tank and on the efficiency of the systems have also been reviewed and the main ideas drawn are summarized in the last part of this report.

2 TYPES OF TANKS

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

2.1 Introduction and classification of thermal energy storage tanks

Hot water tanks are normally classified into two groups, depending on where the domestic hot water (DHW) is produced:

- Tanks with integrated internal heat exchangers. The DHW is generated inside 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).

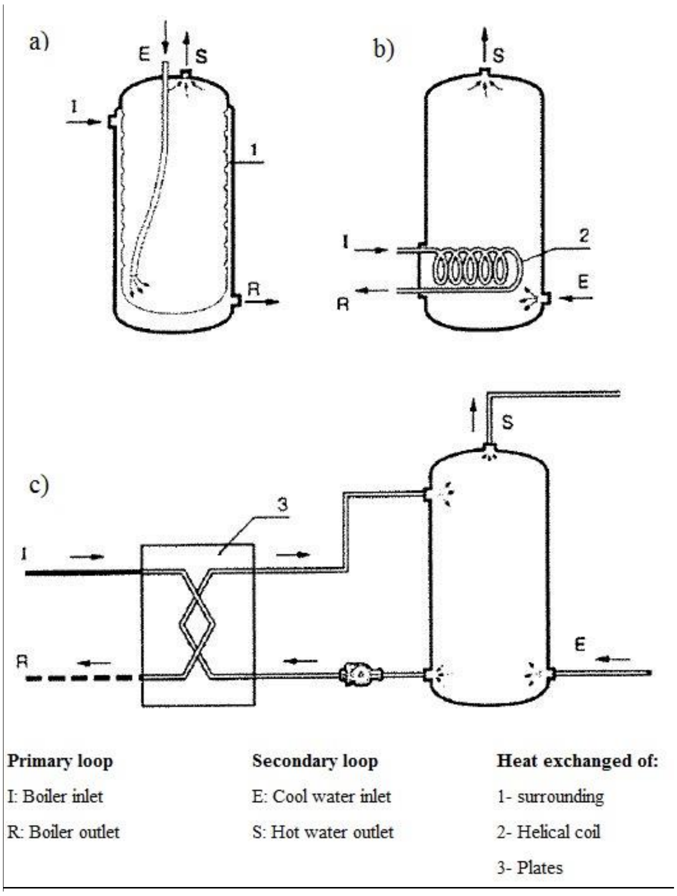


Figure 1 ***(a) Double walled storage tank; (b) storage tank with helical coil; (c) storage tank without inner heat exchanger*** **[1]**

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 the 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 (e.g. 20 minutes are needed in order to achieve the set-point temperature). This type of storage is usually applied 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 water 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.

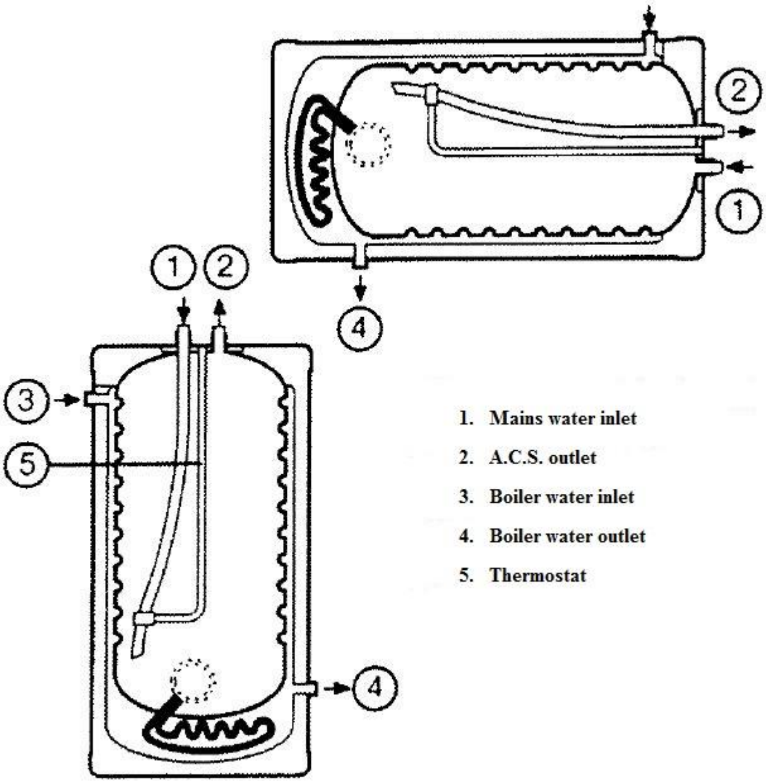


Figure 2 Double-walled DHW storage tank with electric heater – horizontal and vertical types [1]

Helical coil heat exchangers (Figure 2b) 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 legionella growth 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

Adequate 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 byinjection of high-density expanded polyurethane (PU, CFC free) inside a double wall. Large-volume tanks are insulated in situ using elastomeric foam (or other insulating material) sheets. A minimum insulation thickness of 30 mm and 50 mm is required in tanks with a heat loss surface below and above 2 m^2, respectively.

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 by 20 mm in case of outdoor pipes (National standards for insulation of DHW pipes).

2.2.2 Corrosion

Metallic parts in continuous contact with water may suffer from electrochemical corrosion and incrustations. The risk increases with the water temperature, an important factor both in DHW and hydronic heat distribution systems. The difference between them is that hydronic systems are closed loops - corrosion and incrustations occur during the initial period, but after that the material is protected given that the free oxygen in the space heating water is eliminated rapidly in the oxidation process, forming a protective layer (incrustations work also as a protective layer). On the other hand, DHW loops are connected to the municipal water network which continuously brings new chlorine, oxygen, salts, 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 area and produce noise. Incrustations also reduce the heat transfer efficiency, and the existence of slimes may reduce the capacity of the storage tanks. In conclusion, it is important to take appropriate measures to prevent corrosion and incrustations.

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

In consumption loops, the use of substances and the concentration of these substances are very limited. Selection of suitable materials for the type of water used, careful manufacturing and installation, and the application of cathodic protection are examples of recommended actions.

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

2.2.3 Materials and protection

Galvanized steel is employed in pipes and in storage tanks, mostly in industrial and centralized applications, given that the galvanization is done following standards and that the water temperature does not exceed about 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, following a correct start-up process, etc.

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

Copper has well-known anticorrosion and antibacterial properties, and resists well most types of water. It is desirable, however, that the formation of a protective layer 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. If these particles adhere to the inner surface of the tube, it may promote corrosion of the copper and even perforation of the pipe.

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

Stainless steel has a passive layer that protects against water with pH between 4 and 10 (no additional protective layers are needed). It is however sensitive to water with high concentrations of chlorides, hence the chloride limits recommended by the manufacturer must be followed. Stainless steel is not frequently used in pipes due to its high price.

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 steels stabilized with titanium are used. The last-mentioned alloy is the most resistant to corrosion.

Vitrified coating is applied to the inner surface of the steel tank in order to increase corrosion resistance and to improve hygienic properties. It consists of two varnish layers vitrified in a furnace at 900ºC. A good adhesion and the absence of pores and discontinuities are needed for an effective layer. 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 blocking of the micropores with Mg compounds. Nevertheless, this solution leads to the appearance of slimes.

The rate of solution of the magnesium anode depends on the conductivity of the water. 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) can be used for temperatures lower than 85 ºC.

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

3 PHASE CHANGE MATERIALS IN ACCUMULATION TANKS

3.1 Classification of PCMs

The use of PCMs allows a higher density of thermal energy storage than systems based on sensible thermal storage only, and therefore a reduction in the size of the storage tank. According to Sharma et al. [2] the thermal storage density 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 limited space available for thermal storage tanks. Moreover, PCM systems lead to more stable temperatures during the process of thermal energy charge and discharge.

PCMs are classified into three main categories according to their composition, as shown in Table 1. The properties of the different types of PCMs are discussed in more detail below.

Table 1 Classification of PCMs [3]

Organic compounds	Inorganic compounds	Eutectics
Paraffin Fatty acids	Salt Hydrates Metallic	Organic-organic Inorganic-Organic Inorganic- Inorganic

The melting process for organic compounds is homogeneous and they have properties that favour nucleation. Moreover, they are not corrosive, and they are compatible with the materials normally used in storage tanks. 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 however not very homogeneous, which leads to the formation of different components in the material. 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 sub-cooling of the liquid. Finally, inorganic compounds are corrosive with some metals and incompatible with most of the materials used in the manufacturing of tanks.

Eutectics are materials of two or more components, which melt and freeze congruently and form crystals of the component. The melting and freezing of these materials is nearly always without segregation, that is, the material stays homogeneous [2, 4].

Each PCM has hence its own characteristics and singularities. 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. For the selection of the correct PCM, four basic aspects have to be identified: thermodynamic properties, kinetic properties, chemical properties, health issues and economic issues[3, 4]. Al-Abidi et al [5] summarizes on their review the main characteristics of the most common substances employed as PCMs. The ideal characteristics of a PCM regarding these aspects are presented in Table 2 from [6-8].

Table 2 PCM selection criteria from [6-8]

Thermodynamic properties	Kinetic properties	Chemical properties
Range of melting within desired temperatures	High nucleation rate avoiding super cooling	Complete reversibility freezing/melting
Large latent heat	High rate of crystal growth to simplify heat recovery from storage	Stability in long term phase change behaviour
High thermal conductivity	No phase segregation	Low or no degradation
High specific heat and large density		No corrosiveness
High freezing and melting rate		Non-toxic, non-flammable, non-explosive and environmentally friendly
Small volume changes during phase change. Congruent phase change		Minimum super-cooling and without phase segregation

3.2 Types of PCMs and their applications

When selecting the proper PCM, the melting temperatures will condition the type of material to be selected, and then all the other characteristics described in Table 2 get a role. During the last 20 years different types of PCMs have been studied in research and some have already been made commercially available. The probably oldest and whose process is most known is the water- ice, used for hundreds of years and used in refrigeration. Newer materials have already passed from research to widely available, but studies about thermochemical characteristics and environmental effects have to be done before commercialization.

Zalba et al. [7] has written 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 other PCMs available in the market. In total 150 material used in research and 45 commercially available are reviewed in the paper [7] giving information regarding its phase change temperature, latent heat, thermal conductivity and density. The main applications of these studied materials are: (1) Thermal storage of solar energy (2) Passive storage in bioclimatic building/architecture (3) Cooling: use of off-peak rates and reduction of installed power, icebank (4) Heating and sanitary hot water: using off-peak rate and adapting unloading curves (5) Thermal protection of food: transport, hotel trade, ice-cream, etc. In the review, problems in long term stability of the materials and their encapsulation are discussed. Sharma et al. [2] extend this review on the investigation and analysis of the available thermal energy storage systems incorporating PCMs. The use of these is referred to heat storage applications used as a part of solar water-heating systems, solar air heating systems, solar cooking, solar green house, space heating and cooling application for buildings, off-peak electricity storage systems, and waste heat recovery systems.

Oró et al. [4] prepared a review focusing on existing and off-the-shelf compounds for cooling storage purposes (from -86 to 20 °C melting temperature). From these two review articles [4, 7] it can be concluded that there are compounds for a very wide range of temperatures. For instance, Oró and co-workers [4] found out that paraffin waxes have a melting temperature from -12 to 71 °C with a latent heat of 128–198 kJ/kg. Non-paraffin organics have a melting temperature range between -13 and 187 °C with a latent heat of 80–280 kJ/kg. The characteristics of the mixtures are mostly dependent on the weight percentages of each mixture; for instance regarding NaCl in water it is concluded that the eutectic mixture is the best mixture, as expected. Concerning hydrated salts, their main limitation is instability when heated: at high temperature they degrade and lose a part of their water content. Furthermore, some hydrated salts are not compatible with the installation materials, and they have a low thermal conductivity (between 0.4 and 0.7 W/m·K) and need a high sub cooling degree in order to initiate crystallization. This paper [4] also refers to the studies of other researchers regarding measured magnitudes and dynamics of latent heat during freezing of 14 different pre-nucleated solute aqueous systems. The value of the latent heat measured in the experiments proves to be dependent of the cooling rate. Extensive data about commercially and non-commercially available products can be found in the referred paper.

The phase change temperature of the material 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 for PCM thermal energy storage are ice, hydrated salts, ice slurry or paraffin [8]. Advantages of paraffin are its non-toxicity, low price and compatibility with typical HVAC materials. It has also been proved that paraffin maintains a good stability for more than 5000 melting-solidification cycles. The main inconveniences of paraffin are its low thermal conductivity and high flammability [8]. He and Setterwall [9] have analysed the thermal storage properties of a paraffin wax known as “Technical grade paraffin wax” (Rubitherm RT5 [10]), which has a melting point of 7 ºC and a 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 over more than 20 cycles. The contraction due to phase change is however fairly large, 6.32%.

Zhai et al. [11] has reviewed the performance of composite PCMs in storage tanks for air conditioning (chilled water at normally at 7° C thus PCM melting temperature between 5 and 10 °C) and low cooling temperature (-10 to -15 °C for pharmaceutical use for instance). Nano composite embedded in PCM to improve thermal conductivity are also studied. For the studied ones the solidification time was reduced by 12.97% in comparison to its pure form. The selection of the nanoparticle for the specific PCM was a major criterion to determine the charging and discharging rate. The density of the nano-particle must also be on the same range as the PCM. Microencapsulated PCMs are also studied [8]. The microencapsulated PCM are dispersed uniformly in a fluid, thus forming a suspension giving the advantages of increasing heat transfer areas, reducing reactivity of the PCM towards the outside environment, and controlling volumetric change between the liquid and solid phase of the PCM. The cost is still a challenge, but this paper shows the study of a scenario with high electricity tariff where the cooling load shift from daytime to night-time due to the PCM slurry storage becomes feasible and economic.

For storing DHW and water for space heating, the design temperature should be between 50 and 60 ºC. A possible PCM for this range is the eutectic mixture stearic acid – palmitic acid, with a phase change temperature of 52.3 ºC and latent heat of 181.7 kJ/kg), suggested by Baran and Sari [11]. Agyenim and Hewitt [12] have proposed RT58 [10], with a phase change temperature of 53-59 ºC. Kouskou and co-workers [13] numerically studied the use of PCMs for accumulation of solar heated DHW. On their model the PCMs occupy a part of the volume of the non-insulated tank but both bottom and top of the tank are PCM free, as seen in Figure 3 [13].The main conclusion of the study was that the use of PCM in DHW systems in solar applications may not prove to be substantially beneficial, when the selection of the PCM material (PCM melting point temperature or the PCM confinement geometry) is based on trial error. The selection of PCM bust be done on a case by case basis depending on the precise location of the DHW system installation.

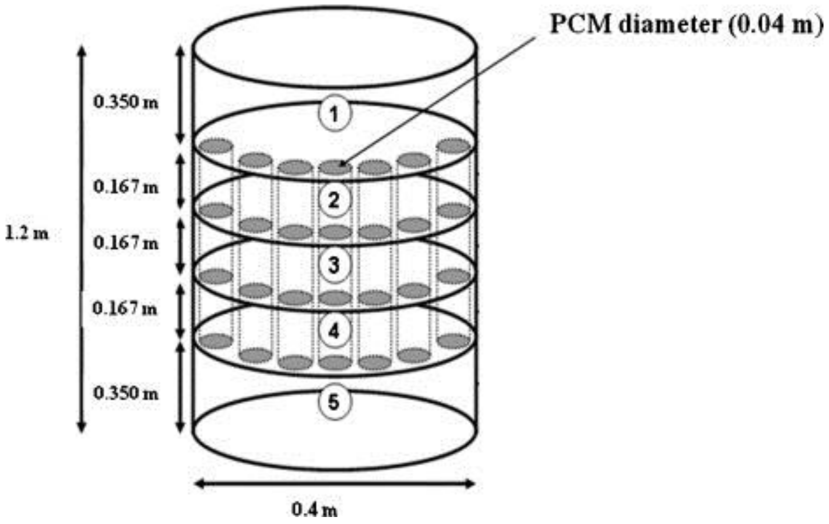


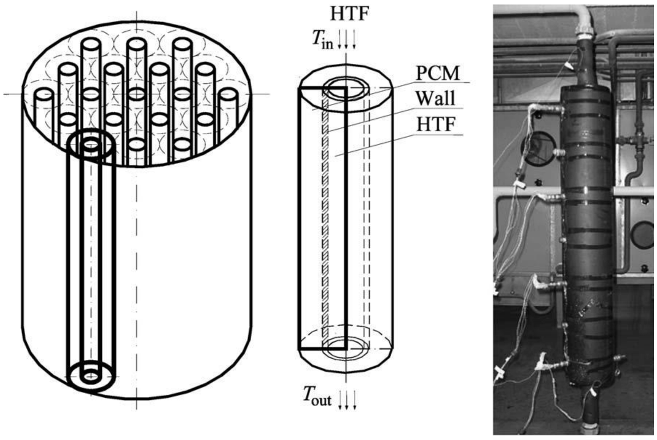
Figure 3 Model studied by Kouskou et al. [13]

4 Heat exchangers suitable as storage tanks using phase change materials

4.1 Shell and tube

A large number of studies have been carried out in order to find the best heat exchanger geometries for a thermal storage tank with PCMs. Al-Abidi et al [5] studied 5 heat exchanger geometries, and propose the shell-and-tube heat exchanger as the most promising technology. PCMs have been applied both in the shell and inside the tubes. Other geometries employed up-to-date are helical coils, serpentines, double tubes, fin-and-tubes and plate heat exchangers. In the following, studies on different PCM storage geometries are reviewed.

Trp [14] has carried out a detailed analysis of a shell-and-tube thermal storage system (Figure 4). 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 [10] in the shell side and water flowing through the tubes. The model was validated with experimental data. In Trp et al. [15], 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.



(a) (b) (c)

Figure 4. Latent energy storage system [14, 15]: (a) storage tank; (b) shell-and-tube storage unit; (c) experimental test unit.

A study on the use of PCM in combination with solar collectors with the same shell-tube geometry was carried out by Esen et al. [16] (Figure 5). They analysed both the configuration where the PCM is in the shell side and the heat exchange fluid from the solar collector inside the tubes, and the opposite. The geometry was optimized for both configurations. It was concluded that the thermal storage is much faster when the PCM is inside the shell and the heat exchange fluid flows inside the tubes.

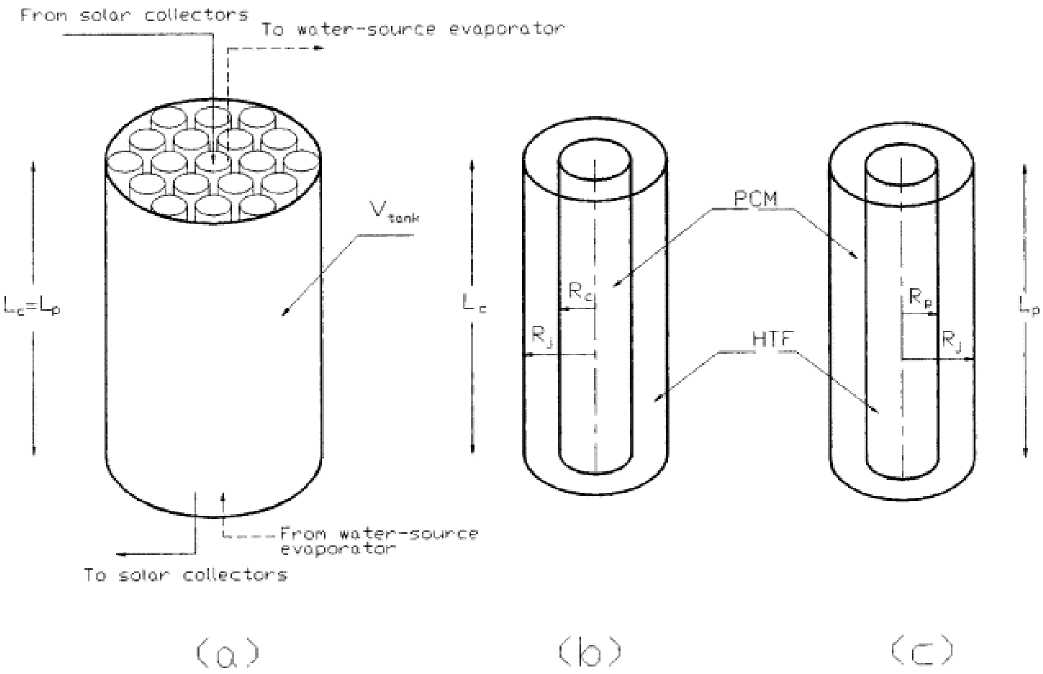


Figure 5. Shell-tube PCM combined with solar collectors[16]: (a)storage tank, (b) shell-and-tube storage unit internal PCM, (c) shell-and-tube storage unit external PCM

Tay et al. [17] proposed a storage tank with vertical tubes. The solution includes recirculation of the already melted PCM (a hydrated salt with a phase change temperature of -11 ºC) in order to enhance the phase change process. In Figure 6, a system sketch (a) as well as the prototype built (b) is shown. When the liquid phase appears, the already melted salt is recirculated in order to accelerate the rest of the melting process. This reduces the time needed for the melting process. Furthermore, the average efficiency increased between 33 and 89% for high temperature gradients, which were obtained for those tests at which the heat transfer fluid was circulated through a fan coil unit placed in a cold room, until the complete melting of the PCM was achieved.). The efficiency increased between 58 and 82% for smaller gradients, which were tests at which a water heater was used in order to heat the heat transfer fluid and melt the PCM. This enhancement is equivalent to that achievable with finned tubes.

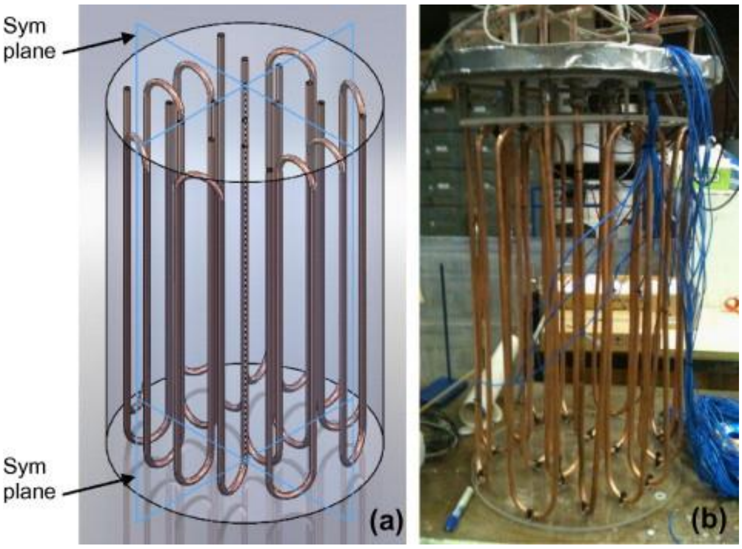


Figure 6. PCM storage with vertical tubes: (a) system configuration and (b) the test rig used by Tay et al. [17]

4.2 Finned tubes

As already pointed out, the use of finned tubes to increase the heat exchange area is a possible solution to the low thermal conductivity of PCMs. Tay et al. [18] analyzed the heat exchanger performance of two types of fins, annular and “spine”, and compared the results with the performance of a plain tube (geometries described in Figure 7). The highest heat exchange rate was obtained with the annular configuration, owing to the highest heat exchanger surface. Compared with the plain tube, an increase in the heat transfer rate between 20 and 40% and a reduction in phase change time of 25% were achieved with annular fin configuration.

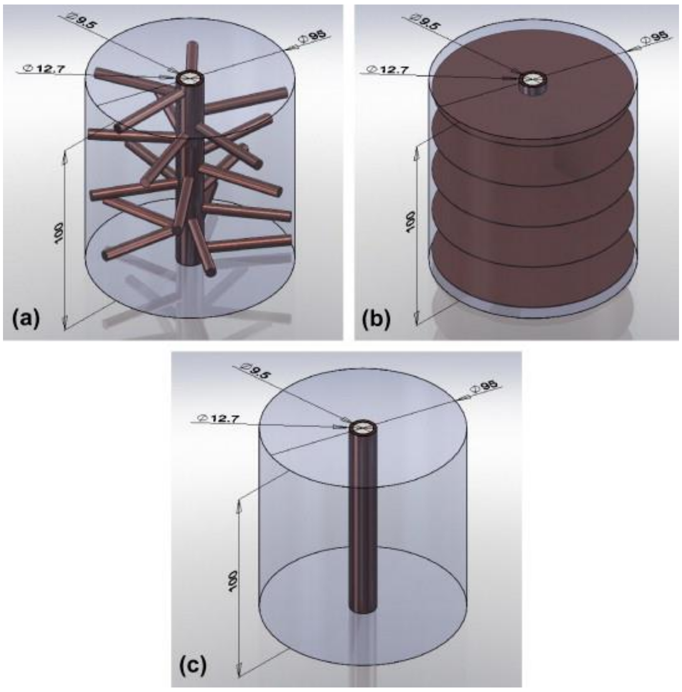


Figure 7. Geometries considered by Tay et al.: (a) spine fins, (b) annular fins and (c) plain tube [18].

The effect of adding fins has also been investigated by Gil et al. [19], who studied two almost identical tanks, shown in Figure 8, for the storage of thermal energy at high temperature (solar applications). The difference between tanks was that one of them had 196 square shaped fins homogeneously distributed while the other one had none. The use of fins led to an enhancement in the heat transfer rate of 20%.

Figure 8. Tanks studied in [22]; left: without fins and right with square shaped fins

Another work concerning solutions with fins is a study by Agyenim and Hewitt [12], where they proposed the use of a cylindrical tank of 375 mm of diameter and 1200 mm long, with a finned copper tube of 65 mm of diameter inside (Figure 9). The fins used were longitudinal (1100 mm long, 120 mm wide and 1 mm thick). The tube was filled with 93 kg of paraffin RT 58 [10]. This system solution was suggested to be integrated with an air source heat pump (Figure 12). By utilizing a PCM storage the heat pump performance can be optimized by running the heat pump in the periods of the day when the energy is cheaper, thus storing the heat in the PCM, and utilizing it in periods with high energy prices. Such a solution can enable a size reduction in the storage by up to 30% for an air source heat pump system dimensioned to meet 100% residential heating demand for a common building in UK.

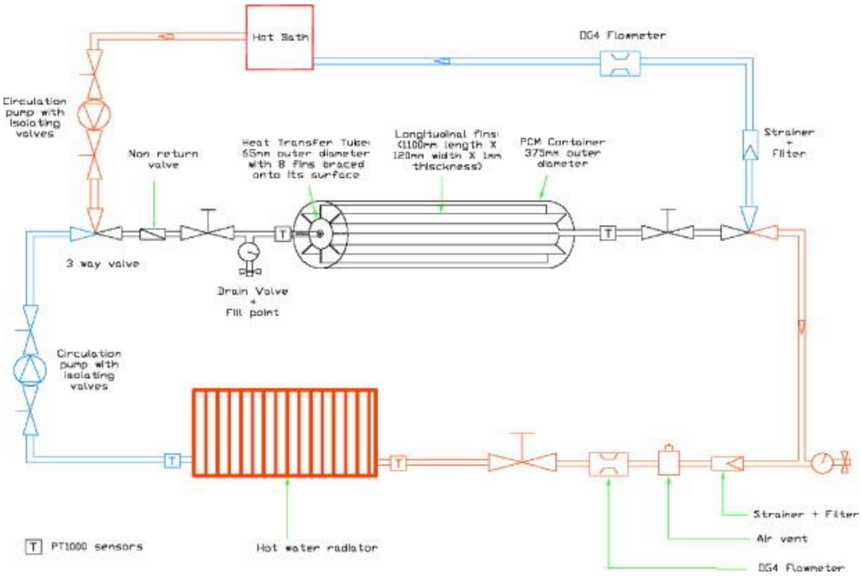


Figure 9. Hot water storage tank with PCM in a finned tube integrated to an air source heat pump heating system for a dwelling [12]

Murray and Groulx [20] have studied a storage tank with two vertical tubes with longitudinal fins (4 fins per each tube), as shown in Figure 10. One tube was used for the thermal energy charge process and the other for the discharge. The PCM used was dodecanoic acid, and in the study it was concluded that this PCM is safe, inexpensive, and has a melting temperature in a range suitable to be used 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 latent heat energy storage system.

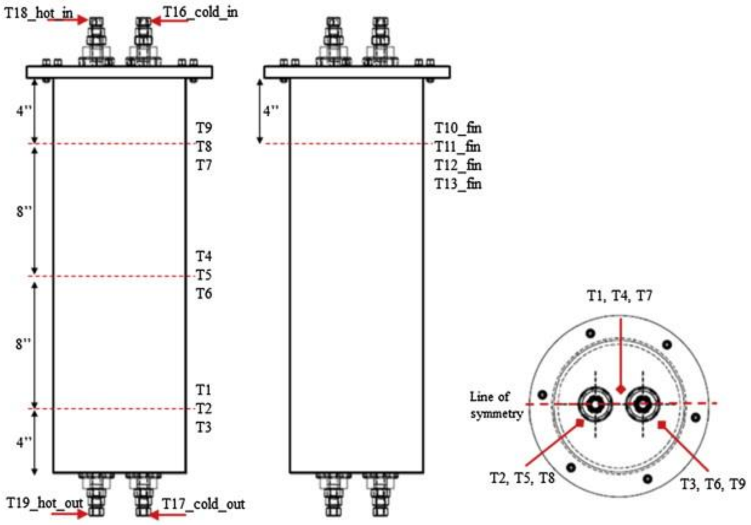


Figure 10. A storage tank with two vertical tubes with longitudinal fins [20].

4.3 Spiral vertical heat exchanger

Banaszek et al. [21] have analyzed a thermal storage with a spiral vertical heat exchanger (Figure 11). These kinds of heat exchangers are widely used in chemical and food industries. These heat exchangers are very compact and easy to seal, and have a large heat exchange surface with a minimum heat exchange length where the fluid suffers no perturbation. Furthermore, they tend to have high heat transfer coefficients due to the centrifuge forces suffered by the fluid and large heat transfer surface and easy to control fluid flow. Its use with PCMs requires only the substitution of one of the fluids with a PCM. In [21] a paraffin wax PPW-20 was used as the PCM. The phase change temperature of this material is not constant for a temperature rise between 45 ºC and 60 ºC, and an enthalpy increase of 173 ± 5 kJ/kg is required. This study analyzed the heat exchange between this PCM and air but further research is needed on the selection of the most optimal PCM and most optimal geometry of the perimetral air channels.

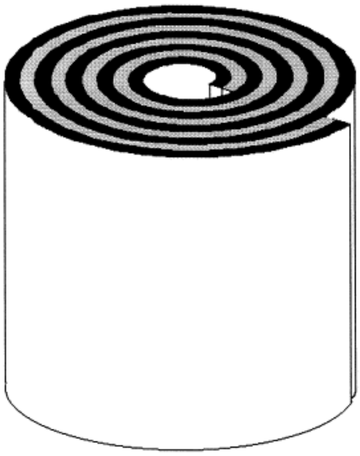


Figure 11. Spiral cylindrical heat exchanger [21]

4.4 Helical coil

Torregrosa-Jaime et al. [8] have studied the cooling storage in a tank with a 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 12). The coil was made with polyethylene tube (without fins) of 1.8 cm of external diameter and a pitch of 2.3 cm [22]. Paraffin was chosen as the PCM due to its high stability with time. During the accumulation process, a RT8 solid layer occurred around the helical coil wall, and it was observed that this layer deteriorated the 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 unaltered.

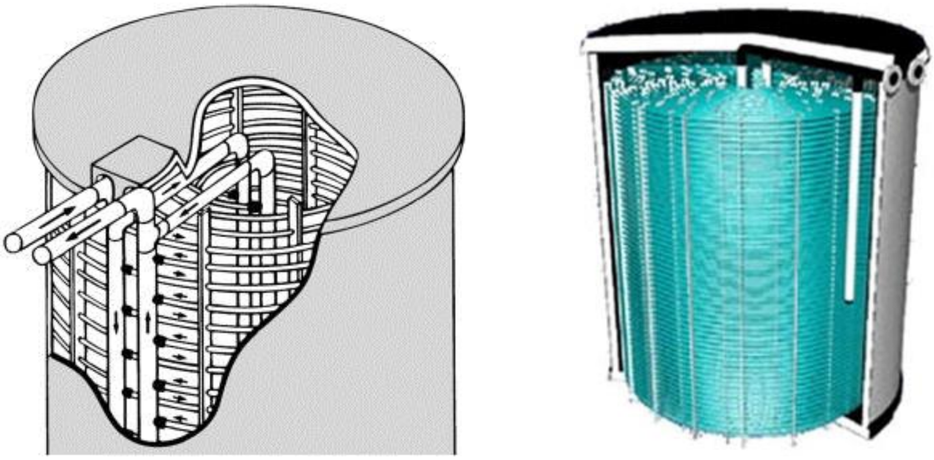


Figure 12. Tank with helical coil [7, 26]

Öztürk [23] has 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 approximately 6000 kg of paraffin. The heat exchanger in the tank was a helical coil (Figure 13). The system was utilized to store heat from solar collectors, with air as the heat exchange fluid.

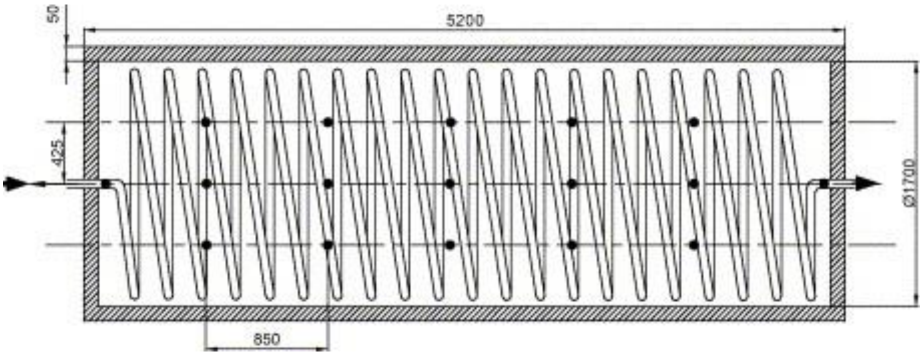


Figure 13. Horizontal tank with helical coil [23]

Five small heat exchangers with different geometries were studied by Medrano [24], working as latent heat storage systems with Rubitherm RT 35, and water as the heat exchange fluid. This PCM was chosen since the desired storage temperature 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 (Figure 14). It was concluded that the double tubes and plate heat exchangers are not suitable for thermal energy storage; the first due to the reduced heat exchange surface and the second due the reduced storage capacity. The fin-and-tube heat exchanger has a large heat exchange surface as well as a larger storage capacity and seems more suitable for real installations.

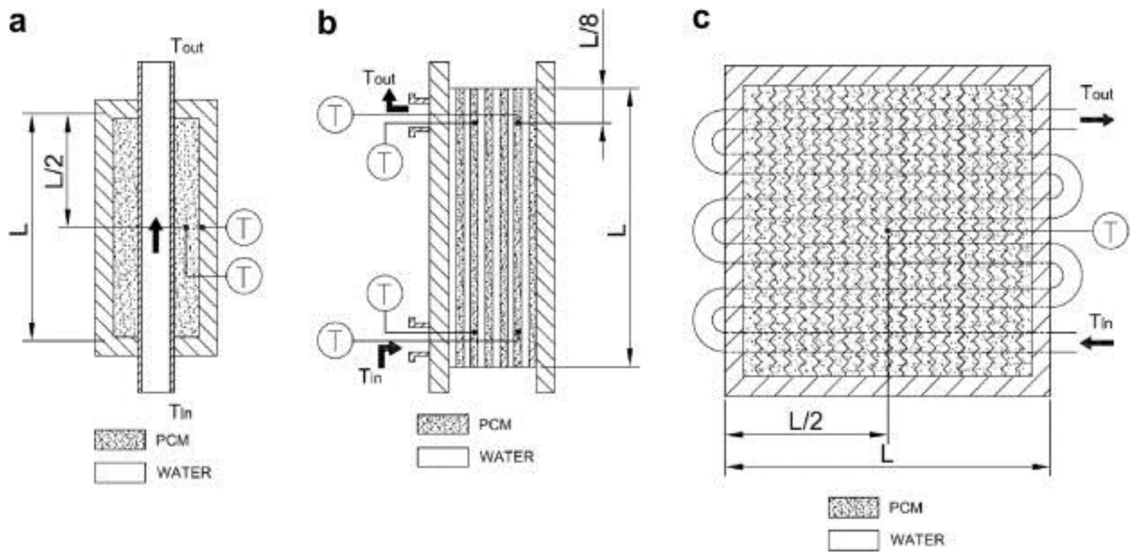


Figure 14. Sketch of the three types of heat exchangers used in [24]: (a) double tube heat exchangers, (b) plate heat exchangers and (c) a fin-and-tube heat exchanger.

4.5 Parallel plates

Another compact system for thermal energy storage, consisting of parallel plates of PCM separated by a rectangular channel, was presented and analysed in [25, 26] (Figure 15). Both works employed the same computational 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 load periods. The effect of several design and operating conditions on the thermal behaviour of the unit was studied through a parametric analysis. It was observed 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.

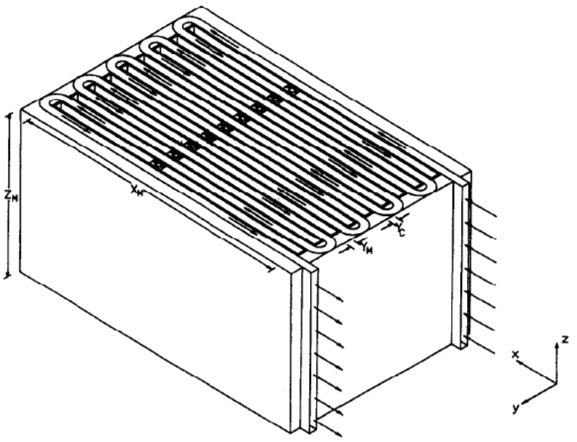


Figure 15. Thermal energy storage system with rectangular cavities [25, 26]

4.6 Encapsulation

Another possibility for the use of PCMs in thermal storage tanks 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 [27, 28]. Recommended materials for encapsulation, compatible with the most common PCMs at temperatures (between -114 and 164 °C) are stainless steel, propylene, and polyolefin [29]. Off-the-shelf examples are shown in the brochure [29]. Figure 16 presents a sketch of a PCM capsule, and Figure 17 illustrates a thermal storage partially filled with PCM capsules.

Typical diameters for the spherical macrocapsules are between 75 and 100 mm, depending on the manufacturer [27, 29] and the durability of the capsules is, in some cases, over 10000 cycles (over 20 years). The encapsulation breakage can cause health problems; hence avoiding direct contact between DHW and the PCM capsules is important when designing an installation.

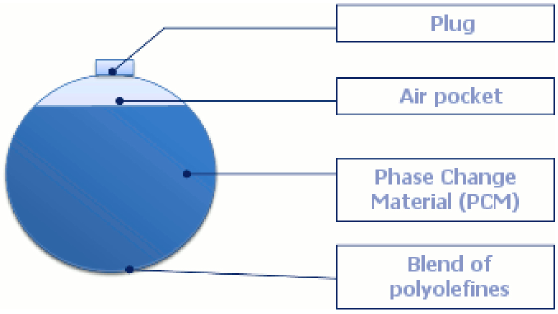


Figure 16. Sketch of a PCM capsule commercialized by Cristopia [27]].

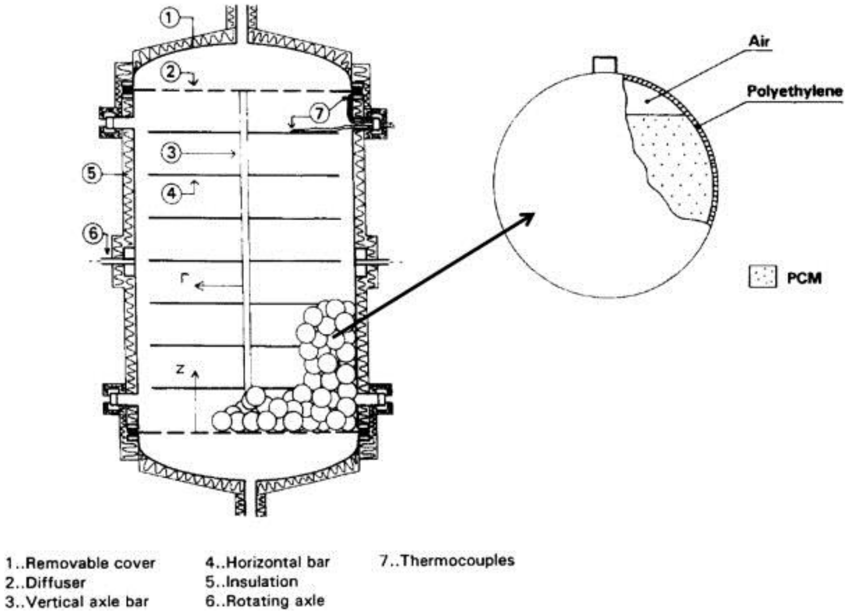


Figure 17. Thermal storage system with spherical capsules [8]

The use of encapsulated PCM modules in the upper part of storage tanks allows increasing the thermal energy storage density (as it stores in the higher temperatures). In addition, heat transfer occurs directly from the PCM capsules to the stored water, increasing the water temperature without an external heat source, both after partial discharges of hot water or to compensate heat losses to the environment. Mehling et al [30] 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. With this solution, the water temperature at the upper part of the tank could be maintained at a constant level between 50% and 200% longer compared to a storage tank without PCM.

Cabeza et al. [31] has proposed a similar use of PCM modules(see Figure 18). Taking into account that a typical storage temperature in a water tank is 55 - 60 ºC, the phase change temperature of the PCM was chosen in that range, and the PCM chosen was sodium acetate tri-hydrated. The authors obtained an increase in the thermal energy density between 40 and 67% and between 6 and 16% when the temperature difference between the PCM and the top layer of stored water was 1 ºC and 8 ºC, respectively. Latent heat storage with PCM provides high heat storage density at small temperature difference, as it is proven in this case in the top layer of the hot-water tank with stratification. This favours the combination of low price and high storage power of water as accumulation medium, while small amounts of PCM significantly increase the storage capacity of the top layer and improve performance of the storage for special load profiles (and lowers losses in this top layer). Ibáñez [32] describes the application of this solution to a single-family dwelling in Lledia (Spain). The author stated that the annual solar contribution in the production of DHW increased between 4 and 8% compared to a system where no PCM is used.

In contrast, Talmsky [33] has analyzed through simulations the use of PCMs in DHW systems with solar collectors, and obtained less promising results. The main conclusion was that adding PCMs (sodium acetate tri-hydrated with graphite particles, SAT-G, and paraffin RT 42 in a graphite matrix, RT42-G) had a negligible effect. The difference in the solar contribution was less than 1% comparing systems with and without PCM. This shows that the result depends on the solar gain, and on the time of the day when the water is consumed (favorable periods or counter-productive periods). However, this work proposes that PCMs may be interesting if the tanks are designed taking into account these parameters. Similar conclusions were drawn by Kouskou et al. [13], 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 the PCM material.

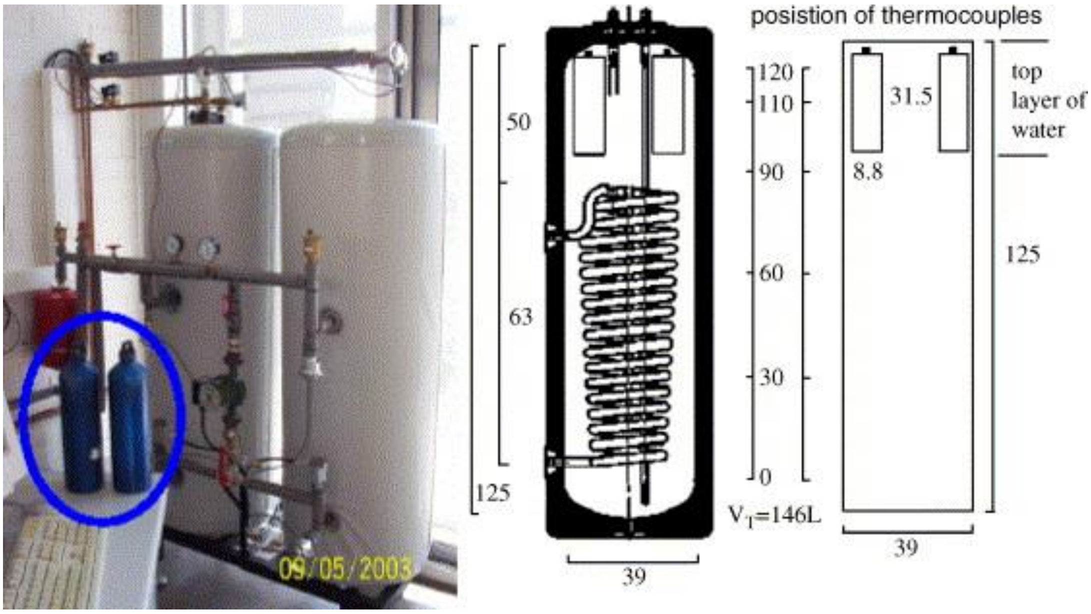


Figure 18. Water storage system with PCM modules in the upper part [31]

4.7 Enhancement of thermal conductivity

One of the major drawbacks of PCM is the low thermal conductivity and several solutions have been developed in order to increase it. Some examples of these solutions are the insertion of PCM in a metal, the use of solid high conductivity metal particles within the PCM, the encapsulation of the PCM in macro and micro packages or the use finned tubes in order to increase the heat exchange areal, and the use PCM-graphite (or other material) compounds instead of pure PCM .

The use of metallic packing materials with PCMs has also been proposed in the literature, in order to enhance the thermal conductivity of PCMs and hence increase the heat transfer rate. In [34], three different heat transfer enhancement methods were analyzed: longitudinal fins on a vertical cylinder filled with paraffin; lessing rings (Figure 19) inside a cylinder with paraffin inside it; and vapor bubble generation inside a cylinder with paraffin. The lessing rings do not have influence in the quality of the water of accumulation since they can also be encapsulated. The conclusion from the work was that the first two methods lead to a considerable increase in the heat transfer rate, both regarding the thermal energy charge time and the density of the stored heat (results in Figure 20).

Figure 19. Lessing rings for enhancing the thermal conductivity of PCM [34]

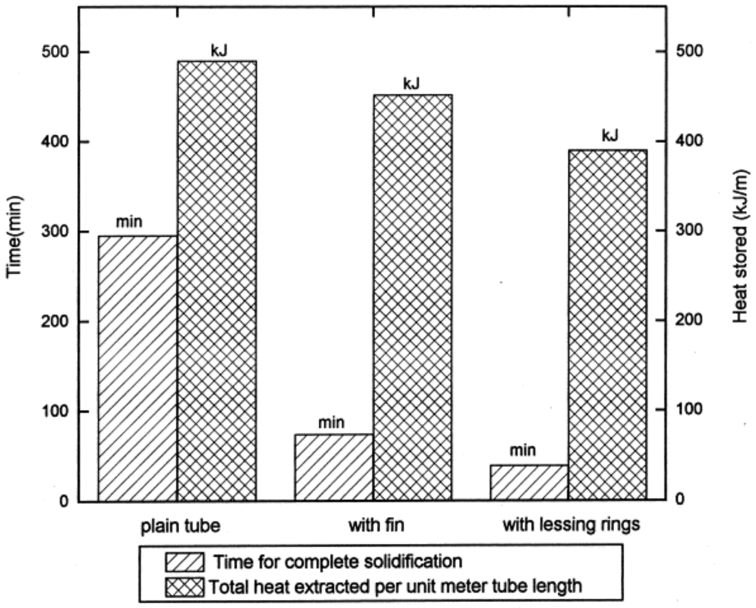


Figure 20. Results obtained in [34]

Nakaso et al. [35] have analysed experimentally and numerically the use of high conductivity carbon fibre materials to increase the heat transfer rate in a tank filled with PCM. The authors concluded that even in low volumes, fiber cloths caused a small increase in the thermal conductivity of the material. Figure 21 shows the carbon fiber cloths used in this work.

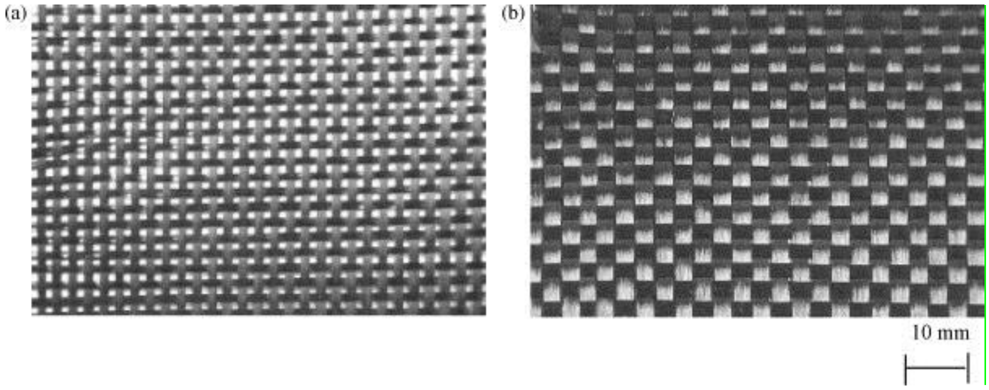


Figure 21. Microscopy images of the carbon fiber cloths used in [35]. (a) 142 g/m^2, (b) 304 g/m^2

A similar solution is the use of carbon fiber “brushes”, shown in Figure 22, studied by Hamada and Fukai [36]. With this solution, an increase of up to 40% in the energy stored in the material was obtained.

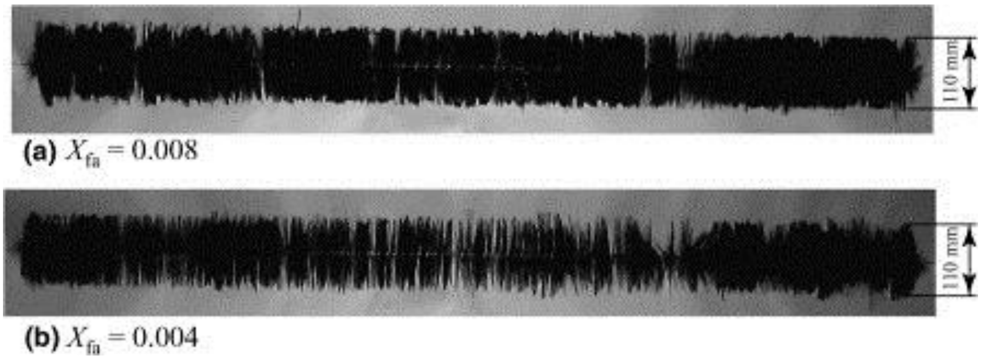


Figure 22. Carbon fiber “brushes” [36]. (a) 0.008 vol.% fibers, (b) 0.004 vol.% fibers

Hamada et. al[37] have compared the behaviour of carbon brushes with a solution that consists of carbon fiber shavings. Both solutions led to an enhancement of the heat transfer, but the brushes produced higher overall heat transfer coefficients than the shavings.

4.8 Conclusions for use of PCM in accumulation tanks

At present, different kinds of PCMs are being commercialized for a wide range of applications and temperatures, covering from -120 ºC to over 200 ºC. PCMs are usually classified into organic compounds, inorganic compounds and eutectic mixtures. There is no ideal PCM that meets all applicable requirements (thermodynamic, kinetic, chemical and economical properties) for a certain application. Thus, the correct selection of the PCM is still a crucial issue.

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

In conclusion, PCMs are a promising technology but still under development. The continuous development of PCMs towards more favorable properties and improvements in the design of heat exchange systems will however enable reductions in the size of storage tanks and increased energy efficiency for different heat supply systems.

5 Examples of combinations of PCM and heat pumps

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

Ekren [38] has conducted a study to determine the performance of a system using a variable speed refrigeration system together with latent heat thermal energy storage. A schematic diagram of the experimental setup is given in Figure 23.

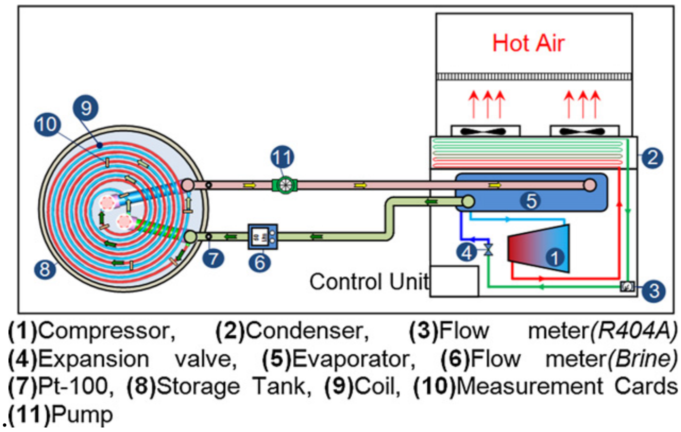


Figure 23. Schematic diagram of the installation studied in [40]

To test the installation, Ekren [38] proposed a series of experiments in order to determine the best control parameter of the system. He proposes four different possibilities: (i) control with evaporation temperature, (ii) control with ethylene glycol temperature at the outlet section of the evaporator, (iii) control with suction pressure of the compressor and (iv) on/off control. The study showed that the best COP was achieved with the control strategy (ii).

5.1 Variable speed compressors in heat pumps

Controlling the capacity of compressors, pumps and ventilators in heat pumps adds degrees of freedom for the system control. The ability to control the heat pump more accurately than simple on-off control leads to increased energy efficiency and possibly to a reduction on the size of the storage tank.

Buffer tanks are normally needed with on-off heat pumps, in order to prevent the compressor from turning on and 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 then be used, and the compressor will only be turned on again when needed.

In contrast to this, variable speed compressors in heat pumps allow matching the heating or cooling demand and production. This reduces the required buffer tank volume and might even make them unnecessary, which has an effect on 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 [39]

5.1.1 Analysis of the use of variable speed compressor in heat pumps

The complete thermodynamic potential of heat pumps is only reached when a suitable control strategy is developed and fitted for each and every installation. These considerations have been studied by Madani [40]. 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. Using the model, 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, the heat source (air or ground), the heat distribution system (radiant floor heating, 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 control strategies are compared.

Jakobsen [41] 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 [42] proposes a method to minimize the energy loss in a refrigeration system by regulation the speed of the compressor.

In a study by Diz et al. [43] three commercial air source heat pumps with inverter technology were analysed. This work concludes that inverter driven (variable speed compressor) heat pumps with support electric heaters are able to reach the DHW set temperature (55 ºC in this work) with lower energy consumption than on/off heat pumps. 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 entire heating process, while others simply minimize the heating time (which decreases the efficiency of the heating process). In Diz et al. [44] an experimental analysis focused on the storage tanks provided by the aforementioned heat pumps was carried out. This work points out that inverter technology allows increasing the amount of heat available in tanks with support electric heaters at the end of the heating process without water consumption. This improvement was also observed during a similar study with water discharge processes [45].

5.1.2 Comparison of variable speed vs on/off-control

Madani et al. [40] analyzed 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 [46] has compared the performance of geothermal heat pumps, both with variable speed and on/off compressors, using simulations for three different climates (sub-tropical, tempered and continental) and three control modes (no part-load control, part-load control for the cooling 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 control. Decrease in both the energy consumption and in the borehole length has an important effect on the costs of the installation and may compensate for the cost of the inverters. Payback periods were significantly reduced by using part-load control modes.

5.1.3 Conclusion

The use of variable speed compressors in heat pumps is interesting from many perspectives. Firstly, because it is possible to match energy demand and production almost instantaneously, there is no need for buffer tanks, which reduces the costs as well as the space demand. In addition, heat pumps with variable speed compressors are more efficient during part-load operation than on/off controlled heat pumps, and reductions in the energy consumption can be achieved. Nevertheless, suitable control strategies and variable speed circulating pumps should be used in order to optimize the heat pump performance.

6 Thermochemical storage materials

Thermochemical materials (TCMs) 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. TCMs store energy chemically, so no charge is lost over time, unlike in the case of PCMs. TCMs have a very high thermal energy storage density. Figure 24 shows the difference of space needed to store the same energy with sensible accumulation (water), latent accumulation (PCM) and thermochemical accumulation (TCM) [47]. TCM technology is still at an experimental stage despite many patents have been filled. The potential of Thermochemical Storage (including both, sorption processes and chemical reactions) for thermal energy storage solutions compared to sensible and latent storage technologies is high due to a series of advantages (i.e. high energy density and reduced storage volume, negligible thermal losses when storing). Although there are some reports gathering promising information on technical and economic aspects of TCM systems, there are still some barriers to be tackled [48].

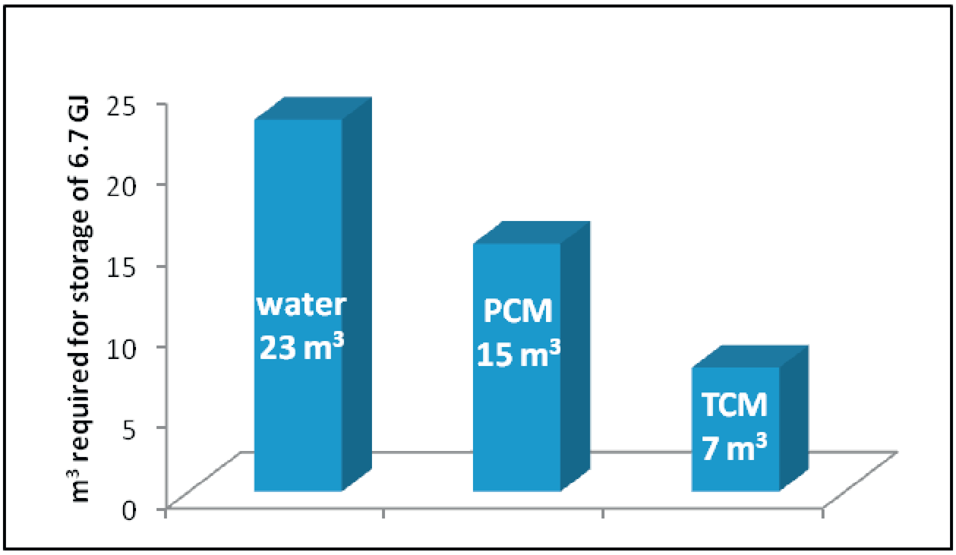


Figure 24. Decrease in storage volume with PCMs and TCMs as compared to sensible storage (water) [38]

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 [49] performed a study of the applicability of TCMs in heat production by solar collectors. The studied reactor, shown in Figure 25, was able to accumulate 1 kWh in 5 minutes working with a power of 12 kW. The contribution of TCMs to the reactor power was in this case limited by the size of the tubes. However, it should be possible to scale the system up to the capacity needed.

No further references to TCM will be done as their development will probably happen after the time of this project.

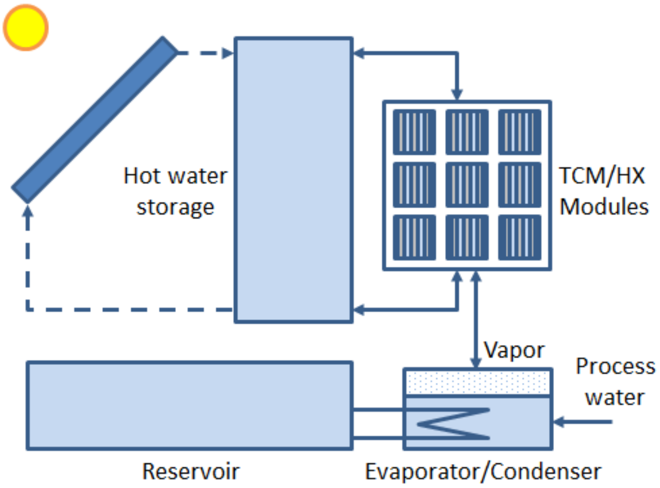


Figure 25. Use of TCM in combination with heat production by solar collector [49]

7 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 are used inside the tanks, either for heating or cooling applications, by means of different kinds of systems. A common solution is to have PCM in a pipe inside the tank; however encapsulated PCMs are also widely used and have been studied extensively. Both solutions have their advantages and disadvantages, and using one or another depends on the application.

For optimal heat exchange between the PCM and the fluid, many heat exchanger geometries of have been suggested. Shell-and-tube geometry is the most widely used geometry; however helical coils in tanks as well as plate heat exchangers are also available in the market. Different techniques have also been proposed for optimal heating or cooling the PCM, such as the alternative flow of fluids for charging and discharging the thermal energy in the PCMs.

A common issue of PCM systems is the reduction in the heat transfer rate that occurs due to the formation of a solid film around the heat exchanger surfaces. Many solutions have been proposed in the literature to minimize this problem, such as employing fins of different geometries or introducing high conductivity elements. Such elements can be for instance metallic inserts, carbon fibers or carbon brushes. Heat transfer may also be enhanced increasing the heat exchange surface available in the tanks such as for instance using parallel plates.

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 their advantages and disadvantages concerning criteria such as latent heat, thermal conductivity, safety, physical-chemical stability or price.

The main factor for the selection of the correct 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. Consequently, the types of PCMs that can be used with heat pumps are limited.

Nevertheless, using PCMs in tanks with heat pumps has a potential advantage over other thermal storage fluids. Due to the high thermal energy storage density of PCMs, the temperature at which energy is accumulated can be decreased (heating applications) or increased (cooling applications). The storage temperature decrease/increase also leads a reduction in the heat losses to the environment. In general, the COP of the heat pump and the efficiency of the installation will increase as a result of utilizing PCM in the system.

In addition, the higher thermal energy storage density of PCMs may lead to a reduction in the number of start and stop cycles of the compressor, which will reduce the electricity consumption and increase the compressor lifetime. This effect is even more important if combined with inverter technology and variable speed compressors. Furthermore, 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.

Another advantage of using PCMs is that it is possible to reduce the size of the tank due to the higher thermal energy storage density. This is highly important from a commercial point of view, irrespective of the heat source.

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.

8 Further work

This state of the art will be used as a basis for a future 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 space heating applications, temperatures around 35 - 45 ºC will be considered, and for cooling applications, around 7 - 15 ºC.

A second part of the project will be testing the selected PCMs in storage tanks, focusing on DHW tanks. The main objective is to minimize the storage tank size by combining PCMs in particularly designed storage tanks.

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