State-of-the-Art for the use of Phase-Change Materials in Tanks Coupled with Heat Pumps

Ángel Á. Pardiñas[a],*, María Justo Alonso[b],*, Rubén Diz[c], Karoline Husevåg Kvalsvik[d],

José Fernández-Seara[c]

[a] Department of Energy and Process Engineering, NTNU, Trondheim, Norway

[b] SINTEF Building and Infrastructure, Trondheim, Norway

[c] Área de Máquinas e Motores Térmicos, Escola de Enxeñaría Industrial, University of Vigo, Vigo, Spain

[d] SINTEF Energy Research, Trondheim, Norway.

*Corresponding author. Department of Energy and Process Engineering, NTNU, Trondheim, Norway.

E-mail address: angel.a.pardinas@ntnu.no

ABSTRACT

With the goal of increasing heat storage in the same accumulation volumes, phase-change materials are considered. There are different substances with different phase-change temperatures that can be used for storing heating or cooling implemented in heat pump systems for applications of space heating and cooling, ventilation or domestic hot water production. Reducing the size of the buffer tanks used with heat pumps, avoiding the oversizing of heat pumps or detaching thermal energy production and consumption are among the benefits that could result from the combination of heat pumps and latent heat thermal energy storage. In addition, this form of thermal energy storage allows enhancing the use of renewable energy sources as heat sources for heat pump systems.

Most previous review works focus mainly on the different materials available that can be used as phase-change materials. Conversely, this review encloses, classifies and describes the results of different works found in the literature that studied individual solutions to enhance the performance of systems combining heat pumps and latent heat thermal energy storage.

COP: Coefficient of Performance
DHW: Domestic hot water
PCM: Phase-change material
TES: Thermal energy storage
TRESE: Triple-sleeve energy storage exchanger
VSD: Variable speed drive

1. INTRODUCTION

Thermal energy storage (TES) systems are often implemented to decouple thermal energy generation and demands. This prevents expensive oversizing of production equipment and enables reduced electric power and energy consumption, optimizing equipment size due to the peak load smoothing. It also has a considerable potential to decrease energy consumption by operating heat pumps under more favourable conditions. In addition, thermal energy storages prove to be very useful when working with discontinuous heat generation systems, such as solar thermal energy systems, applications with waste heat recovery or other renewable sources. This kind of energy storage for solar thermal systems was deeply studied by the partners participating in IEA SHC Task 32 [1] and for systems in general in IEA SHC Task 42 [2].

Heating demands for space heating and heating of ventilation air in new built building stock have been radically reduced, particularly in Northern Europe countries, due to large insulation levels, increased air-tightness and utilization of high-efficiency heat recovery units in the ventilation system. In high-efficient buildings the ratio of the annual energy demand for domestic hot water (DHW) heating to the annual space heating demand typically ranges from 0.5 to 1.4, as detailed in Table 1 for Norway. The ratio depends on the region and its climate, and the construction standard requirements [3]. Finocchiaro et al. [4] studied the effect of maximizing solar heat gains and minimizing heat losses during the whole year as a result of using the new standards in constructions. He concluded that the demands of active and passive cooling in highly insulated buildings have to be accounted for and the design has to be adapted for their minimization. In this line, a survey by Berge and Mathisen [5] showed that between 60 and 70% of occupants of low energy passive house apartments are sometimes bothered by overheating. In Germany, 40-50% of all passive houses use an integrated heat pump system for space heating and DHW heating [6]. In Norway, there is an ongoing discussion on the need of using TES when using heat pumps with variable speed drive (VSD) compressors. The use of a water tank when using VSD helps to reduce the size of the heat pump when used for heating and to diminish the volume of the accumulation tank or even eliminate it [7]. In other countries with larger heating or cooling loads, this question is not important anymore.

Table 1. Energy demands in new buildings in Norway [3]

General requirements	Low-energy house type 2, Oslo Climate	Passive house, Oslo Climate
Building envelope insulation	Low-Energy house 2 NS 3700	NS3700
Balanced ventilation – heat recovery efficiency	70 %	80 %
Annual heating demand	**Normal house**	**Passive house**
Space heating (SH)	58 kWh/m^2	22 kWh/m^2
DHW heating[1]	30 kWh/m^2	30 kWh/m^2
Ratio DHW and SH	0.52	1.40

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[1] DHW heating strongly varies depending on the building type and user type.

Total annual energy demand	88 kWh/m²	52 kWh/m²

The need of compact TES systems adequate for short-term storage strategies at the different temperature levels required for heating, cooling and DHW heating requires exploration of different TES technologies and their effect on the production solution. The scope of this paper is set on heat pumps as a production solution and on compiling, classifying and analysing the existing individual solutions to couple heat pumps and compact TES systems, particularly with phase-change materials (PCMs).

2. Phase-Change Materials and heat pumps

Thermal energy can be stored as sensible heat, latent heat or chemical reactions. Phase-change materials (PCMs) are included in the second storage mechanism, since they take advantage of the latent heat of the freezing and melting processes. Many different eutectics and mixtures can be potentially used as PCMs, but to be considered PCMs there are some requirements to be fulfilled. Among these requirements are a high storage capacity, a melting point suitable with the application and chemical stability [8]. Barreneche et al. [9] reviewed the available PCMs as a function of the application (melting temperature) and the results can be a useful tool for the PCM selection process.

From a theoretical point of view, using PCMs in storage systems leads to a higher density of thermal energy storage than systems based on sensible thermal storage only. This would yield a reduction in the size of the storage tank. This would be useful in buildings, especially in cities, where there is a space limitation. According to Sharma et al. [10], the thermal storage density of PCM systems is between 5 and 14 times higher than in sensible heat storage systems such as water, masonry or rock. The final report of IEA SHC Task 32, Subtask C [1] suggests that the range of this theoretical factor is between 1.2 and 5, compared to water. PCM systems lead to more stable temperatures during the process of thermal energy charging and discharging [11]. This means in many cases lower thermal losses [12] and higher efficiency of the heat pump provided that the system is designed for operation at an optimized, nearly constant temperature. However, these positive characteristics of PCMs can be limited by the temperatures losses due to transient heat transfer and their low thermal conductivity [1].

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

Combining heat pumps and PCMs has two main advantages. On the one hand, the energy stored in the PCMs can be used as heat source for the evaporator. This leads to an almost constant evaporation temperature. Given that the solar radiation is not constant, and the air temperature varies so much within a normal day in a cold climate, using PCM as intermediate storage would be beneficial for the heat pump to work in more stable conditions. In addition this prevents defrost cycles in air-source heat pumps. On the other hand, using a storage based on PCMs would reduce the required installed cooling capacity of the heat pump, reduce the compressor's start stop cycles and simultaneously cutting down the investment.

Heat pumps cover demands ranging from space heating or cooling to ventilation or DHW production. This applies even when the energy requirements have different temperatures depending on the demand. In high-efficiency buildings, space heating is provided at temperatures ranging between 25 ºC and 50 °C. For space cooling, the temperature requirement varies between 12 ºC and 20 °C depending on the country and risk of condensation. The conditions for ventilation depend on the country and on the main load (heating or cooling), the air temperatures varying between 18 ºC and 35 °C. Thus, the existence of PCMs with different melting points allows optimizing PCM selection.

3. Space heating

3.1. Buffer tanks connected to condenser

The most direct application of PCMs for space heating is their implementation in a tank heated by the heat pump condenser to store thermal energy and shift the production and consumption processes. Leonhardt and Müller [13] modelled a PCM storage tank in Modelica and implemented it into a model of a heat pump for space heating. The paraffin based PCM used melts at 47 ºC, has 180 kJ/kg latent heat and 2.4 kJ/kg·K heat capacity. The authors also carried out simulations with a similar model using a sensible heat buffer tank and compared both systems' performance for a day of low heating demand. The system with PCM storage needed a lower number of compressor starts and stops than the system with sensible heat storage tank due to larger energy stored in the PCMs for the same volume. In addition, the heat losses diminished due to the lower storage temperature.

An experimental study by Agyenim and Hewitt [14] focused on the use of fins for enhancing the heat transfer in a PCM energy storage system. This PCM tank was planned to be used in combination with heat pumps to shift electricity demand for space heating to off-peak electricity periods. The main device of the experimental setup, represented in Figure 1, is the PCM container/heat exchanger, which consists of a cylindrical shell (375 mm outer diameter), with a concentric tube (65 mm outer diameter) with 8 longitudinal fins braced on its surface (1.1 m long, 120 mm wide and 1 mm thick). The water of the space heating installation flows through the tubes. The authors placed the PCM, RT 58 bulk (melting temperature range between 56 ºC and 63 ºC and solidification temperature range between 51 ºC and 60 ºC), in between the two tubes.
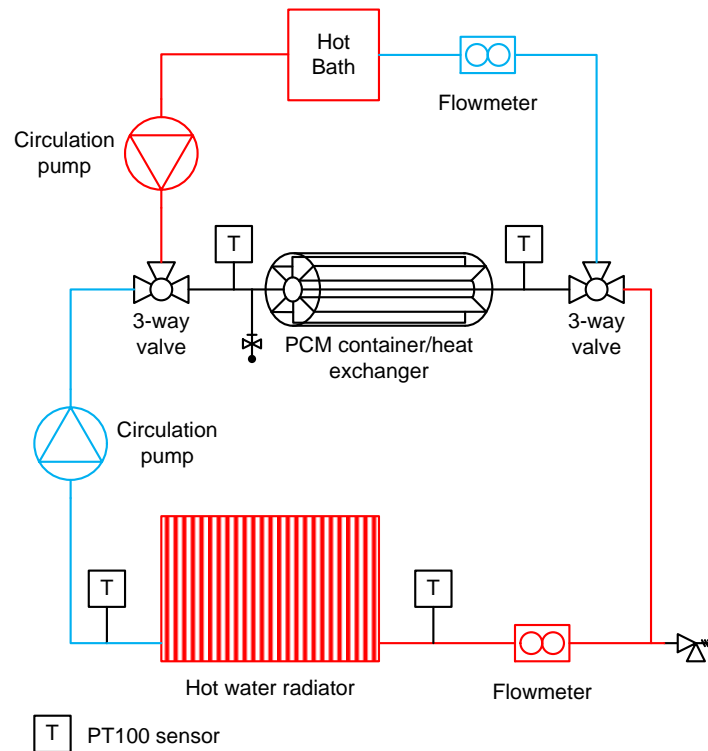
Figure 1. Simplified sketch of the experimental facility by Agyenim and Hewitt [14] *to test the PCM energy storage*

The main result of this work is that a PCM tank of 1116 L is needed to meet the daily space heating demand of 25 kWh (in 4 hours) for a UK semi-detached house (105 m^2) if the heat is produced during the low-cost period for electricity (7 hours a day according to this work). This is due to the low thermal conductivity of RT58, which causes that the PCM storage is not fully charged during the low-cost period. According to the authors, the tank volume can be reduced by up to 30 % if the heat transfer is improved by means of enhanced heat exchangers in PCM energy storage.

Maaraoui et al. [15] analysed the possibility of integrating PCMs in the condenser of air-to-air heat pumps to produce the thermal energy when the external temperature is at its highest (at noon) and thus, achieve the best COP possible for space heating production. The outdoor-temperature-based production can be used to shave peaks. Peak hours are defined at the end of the afternoon according to the authors. The dwell is heated with the heat stored in the PCM instead. The authors used a model in Modelica (Dymola commercial environment) to properly design and dimension the condenser with integrated PCMs. The design proposed allows heat exchange between PCM, refrigerant and air, and comprises fins to enhance heat transfer both in the PCM and air. Maaraoui and co-workers indicated that the main issue that limits these systems with PCMs is their low thermal conductivity and suggest that controlling the air velocity through the indoor units is interesting to maintain the heat capacity.

A simulation work by Kelly et al. [16] analyses the effect of introducing a buffer tank, with and without PCMs, in an air-to-water heat pump system for space heating and DHW production. They studied the possibility of shifting the thermal energy production to off-peak periods (Figure 2b). The selected PCM had a melting temperature of 48 °C and latent heat of 210 kJ/kg. The authors stated that for a winter week in the UK, a typical detached house needs a 500 L accumulation tank with 50% its volume of PCMs or a 1000 L accumulation tank without PCMs to shift the daily load completely. However, the

consequence of shifting the thermal energy production to off-peak periods is an increase of the electricity demand for the heat pump between 60% and 65%, and correspondingly much of the CO_2 emissions, compared with a tankless system (Figure 2a). This increase is justified due to the additional heat exchanger and the heat losses of the system with tank. Operation during off-peak periods does not compensate for the rise in the electric demand of buffered systems.
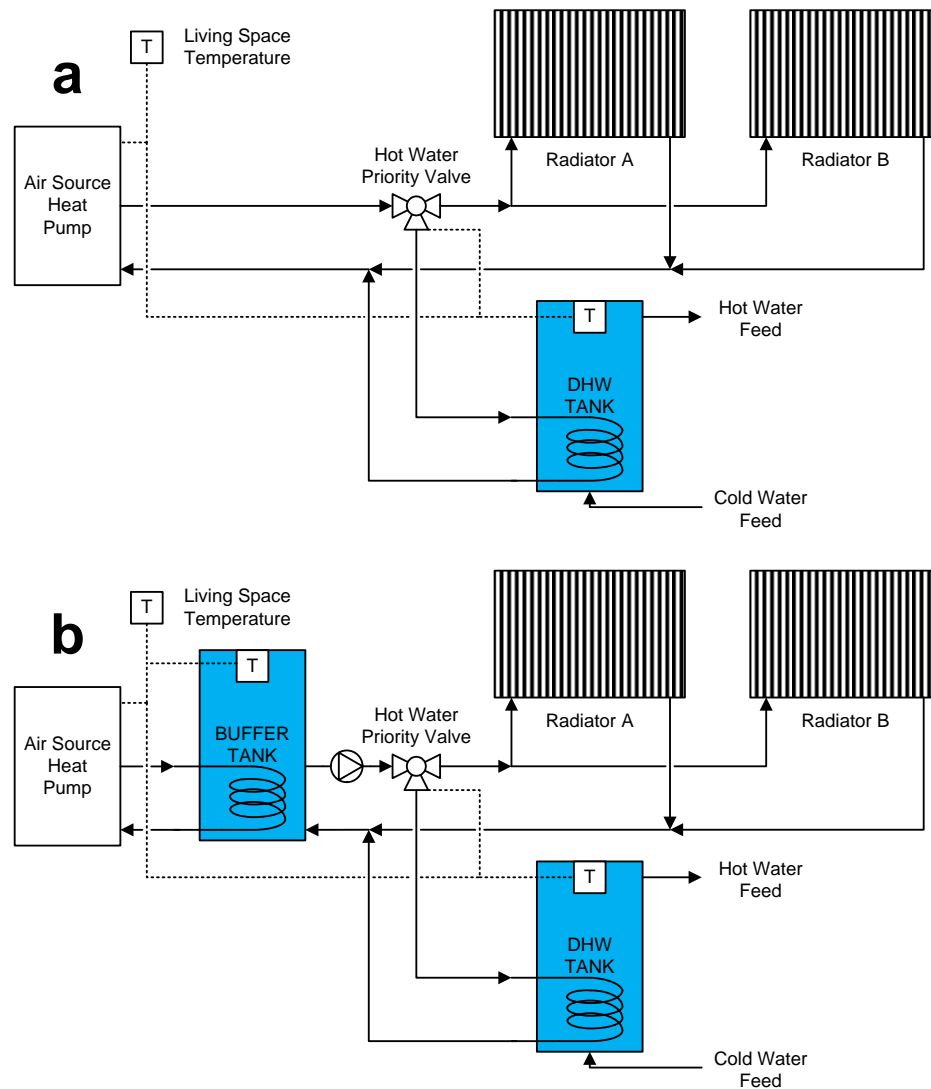

Figure 2. Simulated systems for space heating and DHW production [16]. a) No buffer tank. b) PCM enhanced buffer tank. DHW production with shuttle valve system.

Benli and Durmuş [17] and Benli [18] studied a similar application of PCMs applied to greenhouse heating (Figure 3) during the period from September to April in Turkey. The experimental work analysed the use of a ground-source heat pump attached to a PCM tank with 300 kg of calcium chloride hexahydrated (melting temperature 32 to 45 ºC and latent heat 190 kJ/kg). The air that cooled the heat pump condenser charged the PCM tank. The heat released by the PCM to the air in the greenhouse compensated for the heat losses of the greenhouse to the surroundings. They concluded that horizontal ground heat exchangers and PCM energy storage are an appropriate solution for this application, if considered the low investment of horizontal ground source heat exchangers compared to other solutions.
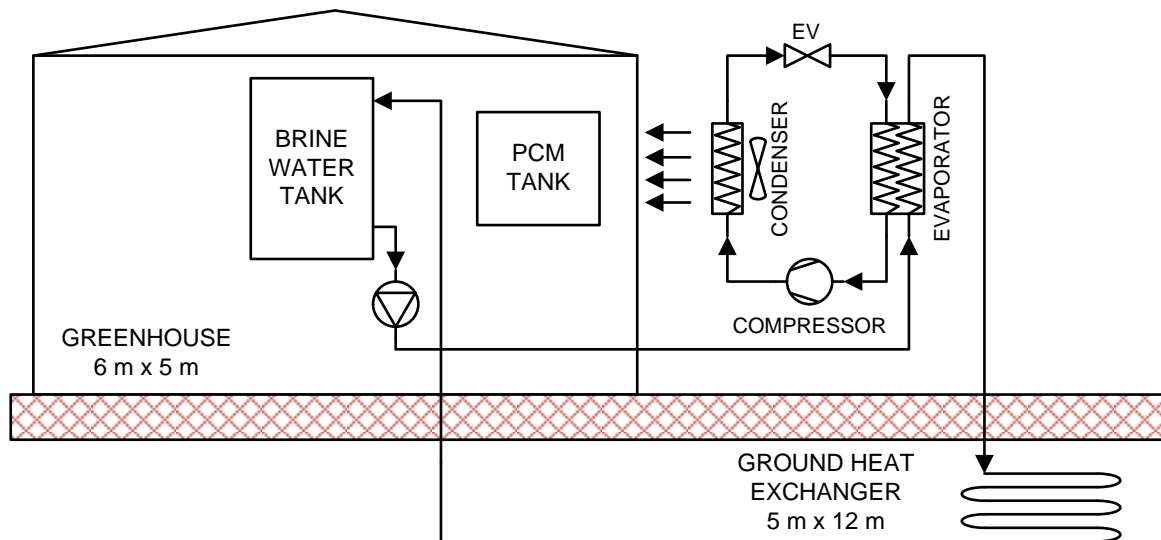
Figure 3. Ground-source heat pump coupled to PCM tank used in Benli and Durmuş [17] and Benli [18]

3.2. Solar-assisted heat pumps

Another approach for providing space heating with heat pumps and PCMs was first pointed out by Comakli et al. [19]. The idea consists in using solar-assisted heat pumps to improve the evaporation conditions of the heat pump and, if possible, provide space heating directly with the solar collectors. Comakli and co-workers experimentally tested the following configurations for the solar collectors, the PCM storage tank (1500 kg of encapsulated calcium chloride hexahydrate and melting temperature around 29 ºC) and the heat pump:

- Series system (Figure 4a). During daytime with solar radiation, the hot water from the solar collectors heats the PCM in the storage tank and this hot water is also the heat source of the heat pump (if there is a space heating demand). During night time, or under no radiation conditions, the heat pump refrigerant absorbs heat at a relatively high temperature from the PCM storage tank to improve the heat pump performance.

- Parallel system (Figure 4b). The heat pump uses ambient air as heat source and heats the room air by transferring heat from the condenser. In parallel, when radiation is available, the hot water from the solar collectors heats the PCM in the storage tank and as much of the room air as possible.

- Dual source system (Figure 4c). The heat pump has two evaporators and uses either of them depending on the ambient and tank temperatures. In addition, if the tank is warmer than a certain value, it heats the room air directly.
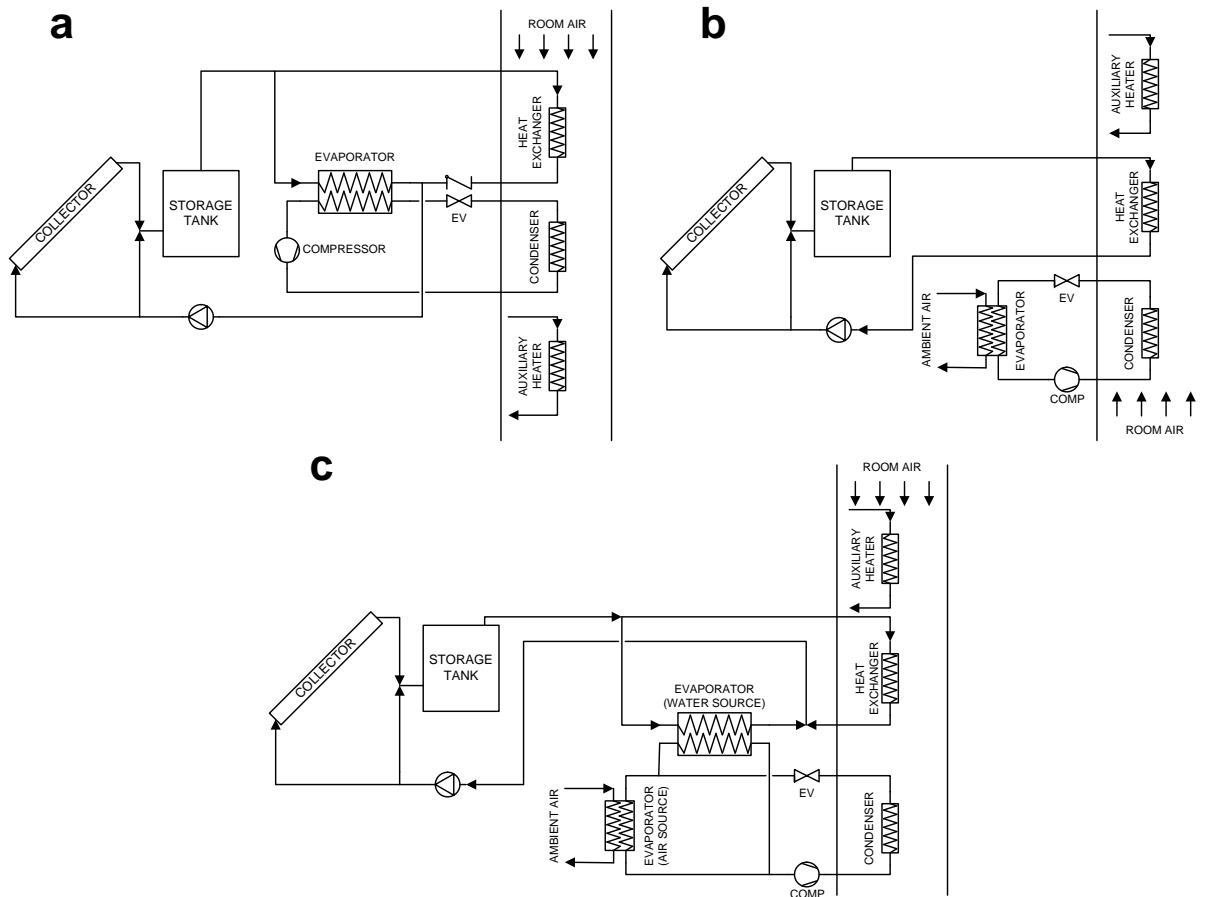
Figure 4. Solar-assisted heat pumps with PCM energy storage [19]. a) Series system. b) Parallel system. c) Dual source system

Comakli et al. [19] analysed the two first operating modes, theoretically and experimentally, under clear sky conditions and with a wide range of ambient temperatures during the heating season (minimum outdoor temperature -3.4 °C, maximum outdoor temperature 29.1 °C). The series configuration system, mainly using the solar energy as heat source for the heat pump, had an average seasonal COP of 4.6. (78% energy saving compared to electrical heating). The parallel configuration system, using ambient air as heat source for the heat pump and solar energy to heat the room air directly, had an average seasonal COP of 3.0 (approximately 67% energy saving compared to electrical heating). The share of the heating demand supplied by the series configuration system was 0.6 and by the parallel configuration system was 0.75. The rest was supplied by an auxiliary heating system. The parallel system covered a greater share since the heat pump had two energy sources (air and solar energy stored in the tank) and the series system only one (solar energy stored in the tank). The authors indicated that the parallel system is more suitable for regions with a large number of cloudy days.

Esen and Ayhan [20] developed a model to analyse the transient behaviour of a PCM tank with a function analogous to the series configuration by Comakli et al. [19] (Figure 4a). Esen and Ayhan performed a parametric analysis with different PCMs, always encapsulated in cylindrical packages, which where heated and cooled by a heat transfer fluid flowing parallel to these cylinders. They varied parameters such as the heat transfer fluid mass flow, the heat transfer fluid inlet temperature or the diameter of the PCM cylinders. The authors concluded that, even with high inlet temperatures of the

heat transfer fluid, the time for melting the PCM in the cylinder is long (minimum of 8 hours). They blamed this effect to the inappropriate material of the encapsulation cylinders and to their dimensions. They also stated that the selection of the characteristics of the encapsulation cylinders should be improved to optimize the performance and thermal storage capacity of tanks.

Kaygusuz and Ayhan [21] complemented the study of Comakli et al. [19] by performing computer simulations of the three configurations of solar-assisted heat pumps. Their simulations under quasi-steady state conditions use their experimental correlations. Their goal was to determine the COP and condenser heating capacity of the heat pump as a function of the evaporator used, type of heat source (water or air), and the temperature of the fluid. They also simulated the solar collectors and solar contribution, the tank with encapsulated PCMs and the heating demand. According to Kaygusuz and Ayhan, the average COP of the series system, equals to 4.0, the dual source system, has a COP of 3.5 and the COP of the parallel system is 3.0. However and in line with Comakli's results, the series system covers only a 60% of the heating demand and the remaining 40% has to be covered by auxiliary equipment. The auxiliary coverage decreases to 25% of the total demand with the parallel configuration and to 20% with the dual source configuration. Thus, the seasonal performance factors for the series, parallel and dual source systems were 3.3, 3.7 and 4.2, respectively. The main conclusion of their work is that the dual source system is the optimal configuration since it makes the most out of the features of both the series and parallel systems.

Kaygusuz [22] aimed at validating a model based on the previous works on solar-assisted heat pumps with latent heat storage systems. The author validated a simplified model with experimental data. Kaygusuz again concludes that the parallel system outperforms the series system, but other considerations such as the economic viability or environmental impact should be taken into account when designing such installations.

Esen [23] developed and validated a model to simulate the PCM storage tank series configuration (Figure 4a) used in the experimental facility of Comakli et al. [19]. Esen stated that a shorter tank, with shorter cylinders of PCMs, improves the heating performance at the beginning of the charging process. He also concluded that the pipe wall thickness should be minimised to allow implementing a large number of cylinders of small radius in an optimal manner.

Qi et al. [24] developed a mathematical model for the PCM system using the geometry and concept of Figure 5b, and analysed numerically the system shown in Figure 5a. The PCM chosen is calcium chloride hexahydrate (melting temperature around 29 ºC and latent heat 187.5 kJ/kg). According to the simulation, the PCM reduces the storage temperature, compared with a typical solar system with water as storage medium. Consequently, the PCM storage diminishes the losses from the tank to the environment and enhances the solar collector performance. The main disadvantages concerning these energy storage systems with PCMs lie in their greater cost and complexity compared to sensible heat storage. Therefore their viability needs to be further evaluated. The case study simulated by Qi and co-workers for a villa located in Beijing (China) showed that the average COP during the heating period of this solar-assisted heat pump was 4.2, which was higher than that of air-source heat pumps.
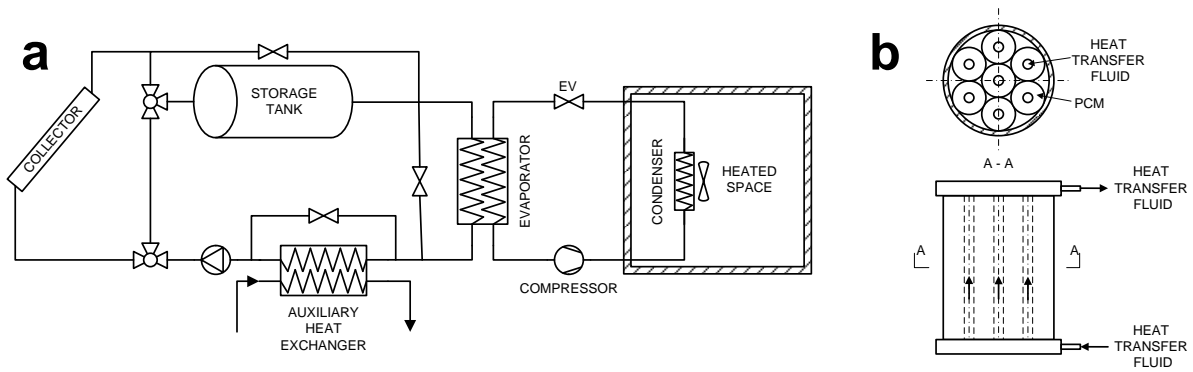
Figure 5. a) General system and b) PCM energy storage unit modelled in Qi et al. [24]

Han et al. [25] combined ground-source heat pumps with solar collectors and a PCM tank. The proposed system is shown in Figure 6 and has up to 8 modes of operation. The solar collectors and PCM storage tank can provide direct space heating if they have enough energy available, or may work as a heat source for the heat pump. Additionally, the heat pump is connected to vertical boreholes and may use the ground as heat source if needed or as heat sink for the solar collectors. The modelled energy storage tank consists of a serpentine, water and encapsulated PCMs of calcium chloride hexahydrate (29.9 ℃ melting temperature and 187.5 kJ/kg latent heat).
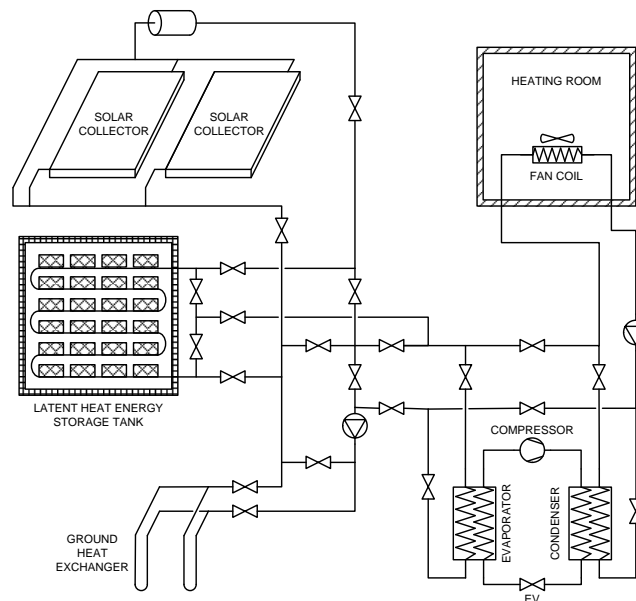

Figure 6. Solar-assisted ground-source heat pump with PCM energy storage described in [25]

The authors used MATLAB to perform a year simulation of the system under the climatic conditions of Harbin (China). The simulation includes a heating period (from mid-October to mid-April) and a ground charging period (from mid-April to mid-October). The ground-source heat pump operation mode was the one that occurred most frequently during the heating period. The average COP of the whole heating system during the heating period was 3.3, and it rose up to 6 at the beginning and the end of this period, when the system made the most of the solar collectors. Han and co-workers concluded from their simulations that the COP of the system improves due to the ground recovery with the solar energy from the collectors. In addition, the use of the ground as heat source allows the permanent operation of the heat pump, and the PCM tank stabilises the system.

Niu et al. [26] and Niu et al. [27] developed an innovative solution combining PCM heat storage, heat pumps and solar collectors, shown in Figure 7a. The authors present a heat exchanger design, called triple-sleeve energy storage exchanger (TRESE), with concentric tubes and three passes (Figure 7b). The PCM chosen was RT6, with a phase change temperature of 6 ºC and latent heat of 183 kJ/kg, and was designed to flow through the inner annulus. The refrigerant for the heat pump should flow through the inner tube and the fluid from the solar collectors through the external annulus. According to the authors, this device was not only supposed to store solar energy, but was was an alternative evaporator for those conditions at which cold ambient air was could affect the performance of the heat pump. It also worked as cooling energy storage for summer conditions.
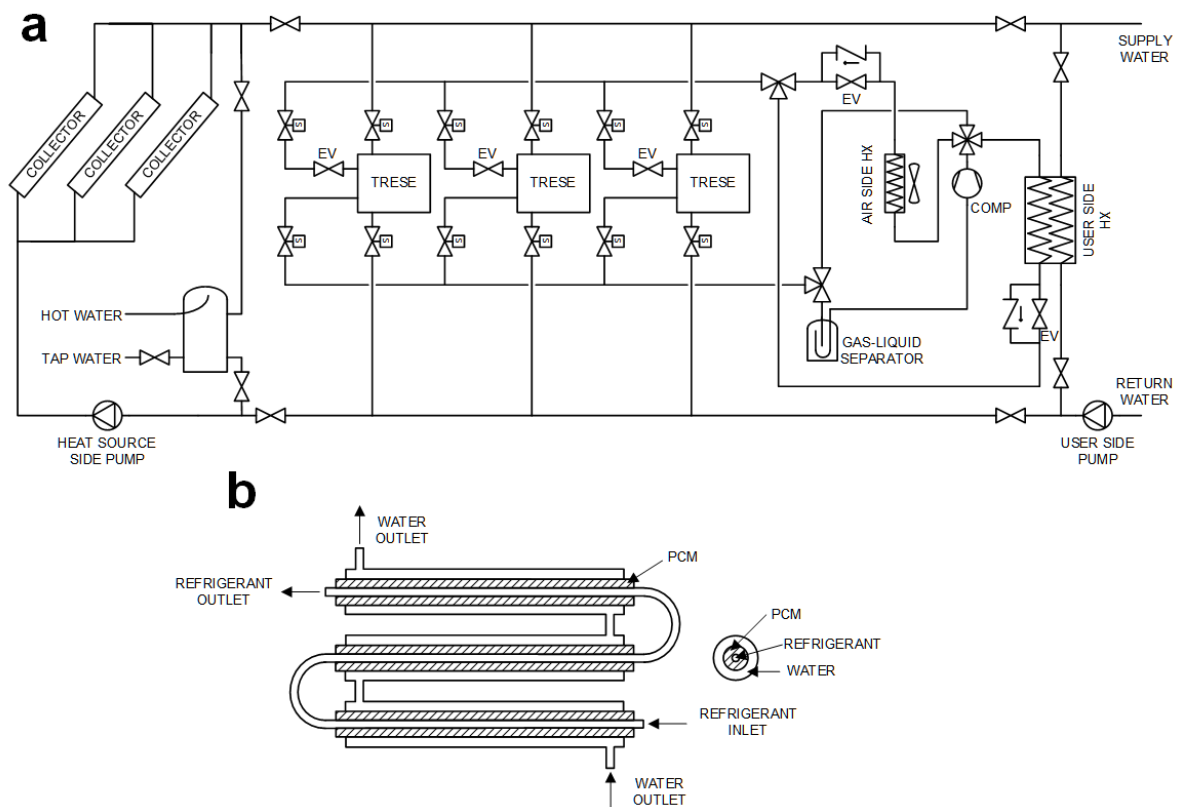

Figure 7. a) Solar-assisted heat pump with PCM energy storage and b) triple-sleeve energy storage exchanger (TRESE) with embedded PCMs as described in [27]

Niu et al. [26] performed a parametric analysis of the charging process with the TRESE device varying the temperature and water flow rates. They observed that the amount of energy stored and the mean heat storage rate in the PCM at 24 ºC, were 50% and 62% larger than at the low temperature condition, 18 ºC. The charging process to achieve the maximum energy stored was almost 400 s faster when the flow rate was high ($4.4 \cdot 10^{-2}$ kg/s) than when it was low ($3.3 \cdot 10^{-2}$ kg/s), and the mean heat storage rate 22% greater. Niu et al. [27] analysed experimentally one out of the 9 possible operation modes. They focused on the performance of the TRESE working as solar-assisted evaporator for the heat pump. The results show that with the input of solar energy, simulated with a 20 ºC water flow, the evaporation temperature was maintained around 8 ºC during the space heating process. The COP reached 3.9 when steady state occurred.

The same experimental system, but with a RT5HC PCM (melting temperature range between 5 ⁰C and 6 ⁰C and latent heat of 245 kJ/kg) in the TRESE device, was used by Qv et al. [28]. This work includes experiments with the different operation modes of the system. The results showed that the system allows shifting the production to periods with inexpensive electricity. In addition, it allows enhancing the COP of the whole system by up to 17%, compared with an air-source heat pump under the same conditions with space cooling demand. This system applied to space heating shows a greater performance than an air source heat pump during low ambient temperature days (ambient temperature lower than -10 °C), and it should improve furtherif there is energy available in the solar collectors.

3.3. Defrost

Frost deteriorates the performance of air-source heat pumps for space heating by adding a thermal resistance on the heat exchanger and increasing the required fan power due to reduce face area [29]. The most typical defrosting systems are electric resistance heaters, which increase the electricity consumption significantly, or reversing the heat pump cycle (hot gas defrost), which worsens the comfort of the heated room and has a negative effect on the seasonal performance factor. Several research works propose a defrosting solution with the implementation of PCMs to these heat pumps.

To the best of our knowledge, Minglu et al. [30] were the first to include a PCM tank in parallel to the heat pump indoor heat exchanger (Figure 8a). They propose to use a shell-and-helical coil heat exchanger, with refrigerant through the tube side and PCM on the shell side (Figure 8). Minglu and co-workers paid special attention to the selection of the PCM, which finally was a calcium chloride hexahydrate. This defrosting method uses the surplus of condensing heat to release thermal energy in the PCM tank during normal operation. When defrosting is needed, the heat pump reverses its operation and the PCM tank functions as evaporator and the external unit as condenser.
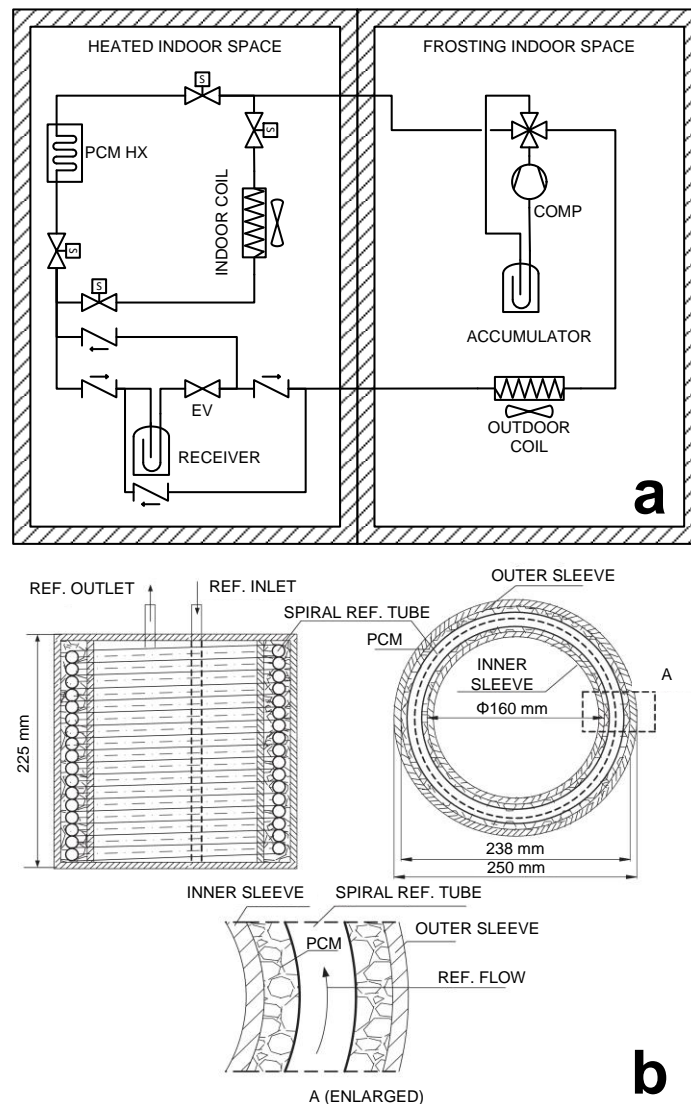
Figure 8. a) Air-source heat pump with PCM defrost method and b) PCM tank for defrosting, designed by [30]

Minglu et al. [30] compared the defrosting time needed for the typical reverse cycle method and their method. The conclusion of their experiments is that the defrosting time was reduced by 36% compared with the typical defrost process due to the higher evaporating temperature. In addition, this new method improves the thermal comfort in the heated house and reduces the risk of refrigerant leakage from the evaporator due to cyclic heating/cooling and consequent fatigue fracture.

Wenju et al. [31] experimentally tested the same system and PCM shell-and-helical coil heat exchanger and the same phase change material (calcium chloride hexahydrate) as Minglu et al. [30]. According to the authors, the defrosting time for this method compared with the standard reverse cycle system, is 38% shorter, and the risk of the compressor shutting down due to low suction pressure almost disappears. These advantages result of storing around 2.6% of the heat produced by the heat pump in the PCM tank and have negligible effect on the COP of the heat pump. The main drawbacks of this solution are associated with cost and durability of the PCM. The authors reported that, in their experimental facility, the cost increase due to the additional devices was approximately 30%, but they

estimated that it could be reduced to 10% with mass production. Concerning the PCM durability, they stated that it should be replaced yearly by a new bulk of PCM (1000 cycles of lifetime).

A similar system was tested by Dong et al. [32], with calcium chloride hexahydrate mixed with 2% mass fraction of strontium chloride hexahydrate as PCM. By doing so, the degree of supercooling should be 0 ºC according to this work. The authors stated that the PCM tank defrosting process is 60% shorter than the standard reverse hot gas defrost process and consumes 48% less energy.

3.4. Other solutions

Other strategies appearing in the literature combine the use of PCMs with heat pumps to enhance their behaviour when producing space heating. Justo Alonso et al. [33] simulated a CO_2 heat pump for production of space heating and DHW, shown in Figure 9. The heat pump is based on a system proposed by Stene [34], with triple gas cooler to optimize the CO_2 heat rejection. The suggested modification includes two evaporators: one that absorbs heat from the ambient and another that absorbs heat from an ice thermal storage. The main objective of this configuration is to increase the evaporation temperature and enhance the heat pump COP when the ambient temperature drops below -5 ºC. Justo Alonso and co-workers stated that only when the ambient temperature is lower than -10 ºC, the COP improves slightly. Taking into account the percentage of hours at which the temperature is below this value in almost any location, the seasonal performance factor is almost unaffected by this solution.
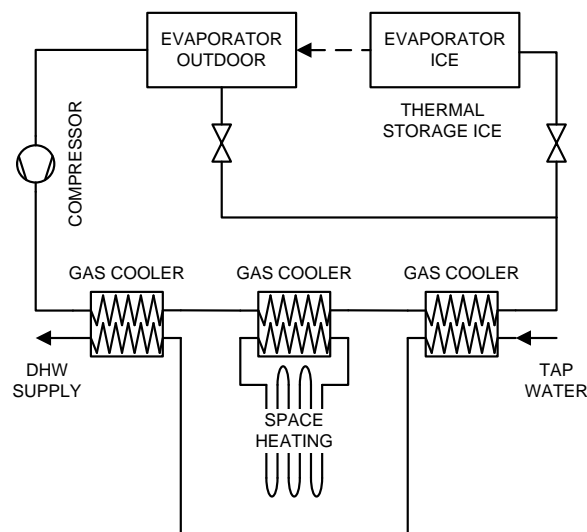

Figure 9. Heat pump with ice storage proposed by Justo Alonso et al. [33]

Another issue researched was how adding PCMs in a radiant floor may affect the space heating and indoor temperature achieved with a heat pump. Mazo et al. [35] simulated this solution with a numerical model they developed of the radiant floor with integrated PCM and validated it with the results of a commercial simulation software. The validated model was used to study a case where the radiant floor (concrete) is mixed with 20% PCM (melting temperature near 27 ºC). According to the simulations, when using PCM radiant floor, the space heating demand can be covered during off-peak electric periods. The authors quantified 18% cost savings compared with typical radiant floor systems and concluded that PCM radiant floors are economically viable. Mazo and co-workers remark that this study

should be continued to determine its impact in colder climates, since it was simulated under conditions of a mild winter, and in building types that are more relevant.

Cabrol and Rowley [36] simulated a radiant floor heating system with air-source heat pump in different locations in the UK. TRNSYS allowed an approach to model the radiant floor with a layer representing the PCM. The authors conducted simulations for PCMs of different melting temperatures and pointed out the importance of choosing an appropriate PCM to reduce the temperature fluctuations of the radiant floor and, consequently of the air in the heated space. A second result from this work is that, during summer, the radiant floor with PCMs may reduce room overheating.

4. Water heating (DHW)

PCMs appear as a solution to store energy for the production of DHW, which represents a growing share of the demands in dwellings. Gu et al. [37] proposed a PCM system to recover the rejected heat in air conditioning equipment. The system, shown in Figure 10, consists of two PCM tanks in series with the condensing outdoor unit. These are heated by the refrigerant (R22) discharged by the compressor when there is an air conditioning demand. The three-way valve bypasses the tanks when they have achieved the tank temperature set-point and the heat produced by the air conditioning system is rejected in the cooling tower. The authors suggested using PCMs of different melting temperatures for each tank. When DHW is to be produced, it passes through both PCM tanks. If the water temperature is not sufficiently high for consumption, it receives additional heat from an auxiliary heater. The authors modelled the system at different condensation temperatures and defined a parameter in order to analyse its performance (integrative energy efficiency ratio, IEER). They observed that the more recovered heat, the better the performance of the system.
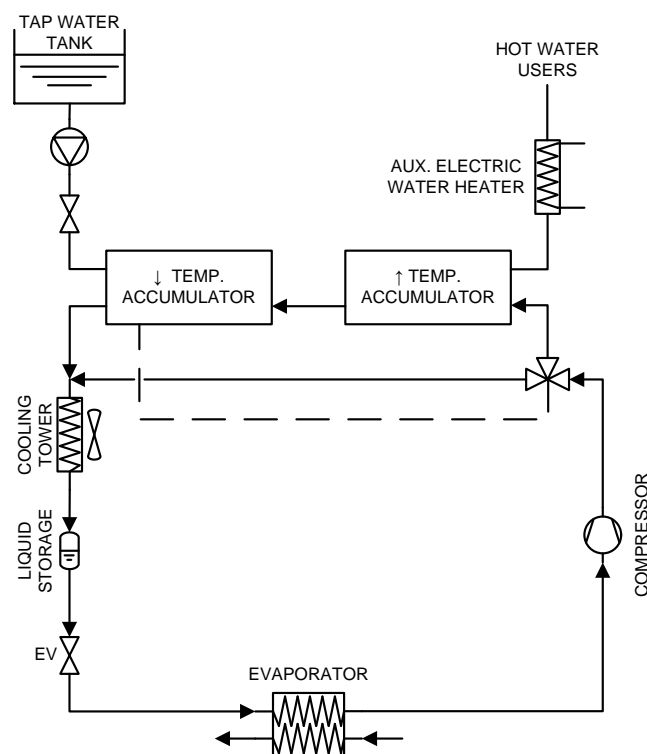

Figure 10. Air conditioning system with PCM tanks for heat recovery and water heating [37]

A second part of the work from Gu et al. [37] focused on the experimental optimisation of the selection of the PCMs for the tanks. They stated that the best options for this heat recovery application are technical grade paraffin wax with the additives, liquid paraffin or lauric acid, since they have a congruent melting process, they freeze without supercooling and are stable (they tested up to 20 melting and freezing cycles).

Zhang et al. [38] also studied the method of storing the heat recovered from air conditioning systems in PCM tanks. They used only one tank with PCMs for the energy storage and subsequent water heating. The PCM used in this case was a paraffin wax with a melting temperature range from 45 ⁰C to 48 ⁰C and latent heat of 191 kJ/kg. The authors included an aluminium mesh to enhance the conduction and nucleation in the PCM energy storage.

Zhang and co-workers observed that the addition of the energy storage to recover heat from the air conditioning system increases the cooling capacity and power consumed by the air conditioning system, compared to the basic systems without PCM tank, and decreases the air conditioning condensing temperature. The discharging experiments, used to produce hot water with the energy stored in the phase change material, showed that it is possible to lift its temperature by up to 11.5 ⁰C.

Long and Zhu [39] used the PCM connected to an air-source heat pump to shift the production to hours with off-peak electricity demand (Figure 11). The authors chose paraffin #56 (melting temperature around 56 ⁰C and latent heat of 254.9 kJ/kg) to perform the experiments, charging and releasing heat. The discharge process, which was developed by heating $7.3 \cdot 10^{-2}$ kg/s of water at 24 ⁰C, allowed 21 minutes of hot water consumption with an outlet temperature that changed from 57 ⁰C at the beginning to 35 ⁰C at the end. This temperature of 35 ⁰C is insufficient for direct consumption, but it could be applied for a preheating stage. This time is approximately 1/3 of the time needed to completely melt the PCM from 24 ⁰C. Long and Zhu also developed a model to simulate both processes.
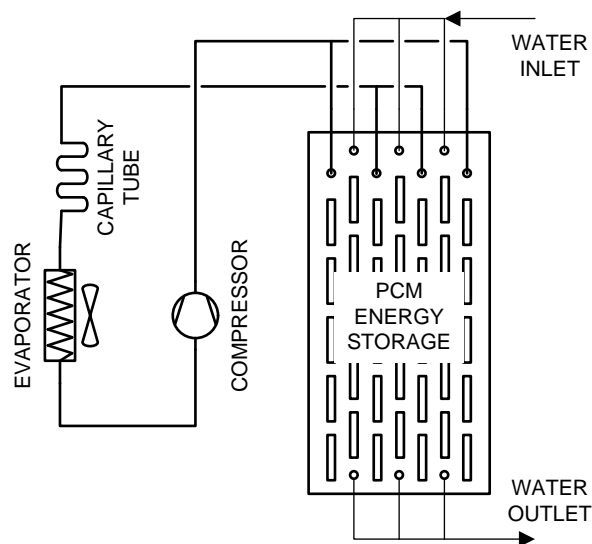

Figure 11. Air-source heat pump with condenser coupled to PCM energy storage [39]

Wu et al. [12] implemented a PCM module in the water tank of an air-source heat pump that can operate both with single and cascade vapour compression cycles (Figure 12). The main goal of this study was to determine which of these two cycles performed better as a function of the ambient temperature and

of the temperature of the water in the tank. In addition, Wu and co-workers analysed the performance of the water tank with and without the PCM module. The module had circular channels and was filled with granular compounds of paraffin and expanded graphite (75 wt.% and 25 wt.%, respectively), having a melting temperature of 55 ºC and latent heat between 140 kJ/kg and 160 kJ/kg. The comparison showed that the tank without PCMs is slightly more efficient. According to Wu and co-workers, the energy storage capacity with PCMs is not high enough to compensate for their lower heat transfer performance and heat capacity. They concluded that the best use of PCMs is to decouple energy production from demand and reduce losses to the ambient, for which it is essential to select PCMs of greater energy storage capacity and heat transfer performance.
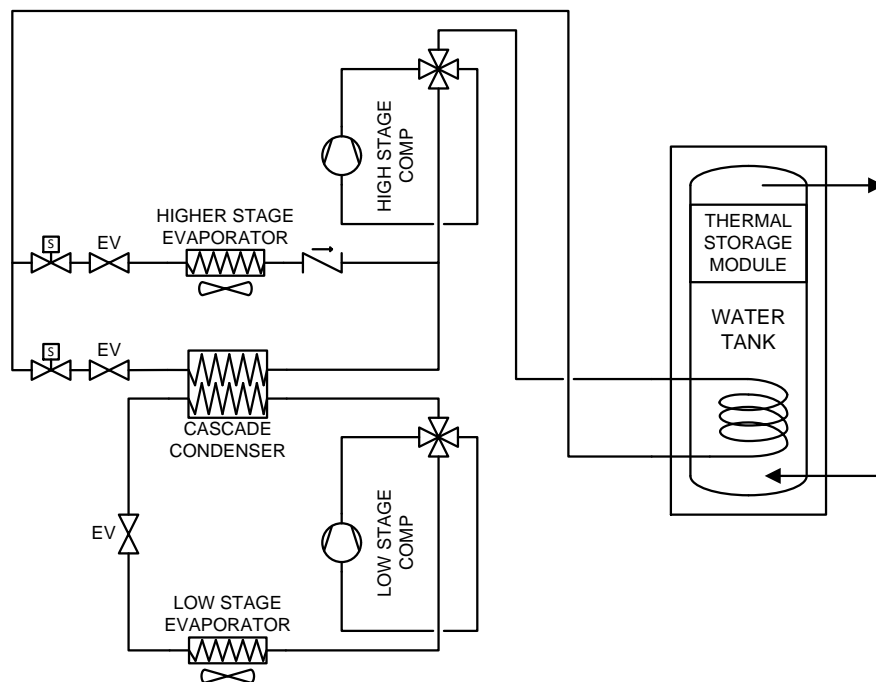

Figure 12. Cascade heat pump system coupled to a water tank with PCM modules [12]

5. Space cooling

There has also been an effort on coupling PCM energy storage systems with heat pumps to enhance the space cooling process and/or to shift the electric consumption of these units to off-peak electricity periods. Fang et al. [40] studied an innovative air conditioning system with an ice storage (Figure 13). The particularity of this system is that it has a heat pipe in parallel to the evaporator. The goal of this heat pipe is to absorb heat from the ice storage system with its evaporative part (HEAT PIPE EVAP in Figure 13) and to transfer it to the refrigerant in the condensing part (HEAT PIPE COND in Figure 13). According to the experimental results of Fang and co-workers, the system was stable during the complete charging period and in 5 hours, half of the water in the tank froze. Up to 70% of the energy absorbed from the ice tank during the charging process was transferred from the ambient air at the indoor unit to the ice tank during the discharging process. In addition, during the discharging process the temperatures of the water at the outlet of the ice tank and of the air at the outlet of the indoor unit were stable.
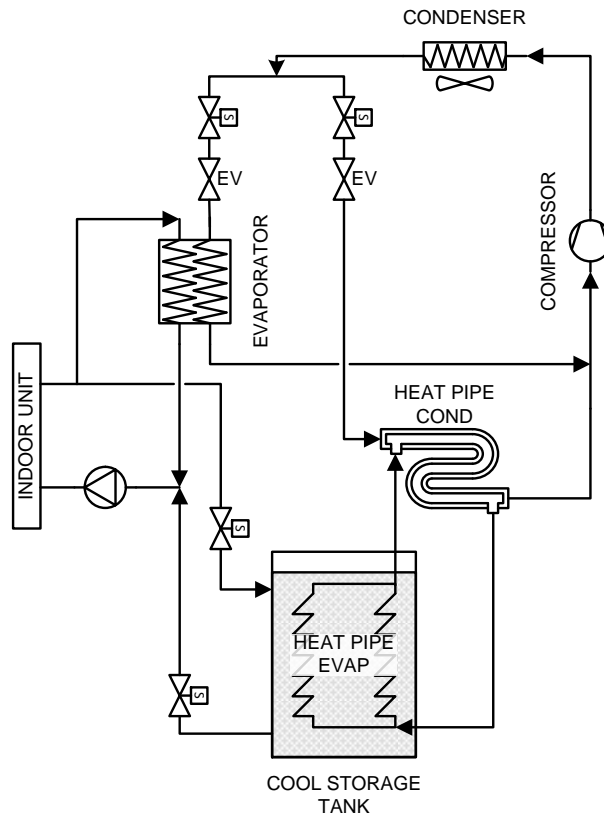
Figure 13. Air conditioning system with ice storage [40]

Ekren et al. [41] investigated the effect of using different compressor speed control (VSD) strategies on the charging process of an ice storage tank using an air conditioning unit. Control of the glycol temperature at the outlet of the evaporator led to the best system stability compared with on/off control or using other variables. In addition, the authors calculated the energy and exergy efficiencies and the COP when charging the tank with each strategy, and the strategy of controlling the glycol temperature outperformed the rest.

A rather different system to take advantage of PCM tanks for space cooling was conceived by Real et al. [42]. It smartly used the charging and discharging of tanks to enhance the performance of an HVAC unit. In contrast to a traditional system, this proposal uses a PCM tank, with flat containers filled with a commercial product of 27 ºC melting temperature, as the air conditioning heat sink during the day. The heat stored in this PCM tank is released to the ambient at night. The authors also propose the use of a PCM tank, with flat containers filled with a commercial product of 10 ºC melting temperature, for cooling purposes.

In this paper, Real and co-workers first presented the results of the simulation of the conventional system vs. that with their innovative strategy. The results of the simulations showed that the electrical consumption of the heat pump was reduced by up to 19% with the latter. The authors stated that an experimental validation of the proposed system is needed.

Moreno et al. [43] presented an experimental installation with a heat pump connected to two tanks, one used for cooling and one for heating. This work, which is in the framework of the IEA SHC Task 42 [2], focused on the cooling tank for the summer period and space cooling. They compared the suitability of

the system for shifting the cooling load, with the tank full of water and with PCM flat slabs filled with a hydrate salt with melting temperature of 10 ºC and water. The experimental results showed that the supercooling needed to charge the PCM slabs was different for each test and that the freezing temperature was also lower than 10 ºC. Moreno and co-workers also observed that, on average, the tank with PCMs allowed storing 36% more low-temperature thermal energy. However, the time needed to charge it was approx. 5.5 times the time for the water tank.

Concerning the discharging process of the PCM tank, the authors observed that it was highly affected by the low thermal conductivity of the material used to encapsulate the PCM. They suggested to improve their thermal conductivity by using metal encapsulations or techniques to improve heat transfer in the PCM bulk. In addition, the discharge process with the water tank was more efficient than with the PCM tank, what caused that only 14.5% more energy could be absorbed from the load with the PCM tank than with the water tank. The PCM tank system also kept the temperature of the space cooled at the set-point value for approx. 21% longer time than the water tank.

A numerical study on the use of PCMs and a ground-source heat pump with dominant space cooling load was developed and presented in Zhu et al. [44]. The aim of the PCM tank was to supplement the cooling that the heat pump was not able to provide, since its capacity was lower than the cooling load, by connecting both in series. The heat pump reloaded the storage at night. The PCM simulated is based on a hydrate sodium sulphate with an additive (melting temperature of 8.3 ºC and latent heat of 95 kJ/kg).

Zhu and co-workers performed the simulations using TRNSYS with a 20-year calculation time. They also evaluated their solution from an economical and cost perspective. The authors observed for their individual case that 40% is the optimum of the cooling storage ratio (ratio of the PCM stored cooling capacity to the heat pump total cooling capacity). With this ratio, the investment and operation costs were minimum and the annual cost was 34.2% lower than without the PCM storage.

A very recent study on the use of latent heat energy storage with air conditioning units is that from Hoseini Rahdar et al. [45]. The authors compared, numerically, the performance of the same equipment attached to an ice storage tank (Figure 14a) and to a commercial PCM, RT3HC, of 3 ºC melting temperature and 200 kJ/kg latent heat (Figure 14b). The systems are designed to lift the cooling production to off-peak hours (night-time). They successfully validated the model with the results from Prasad et al. [46] (maximum deviation of approx. 8%).
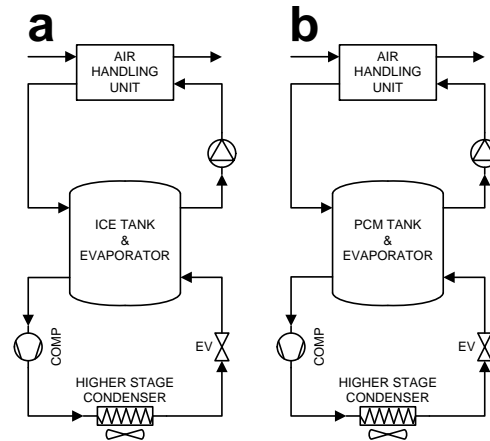
Figure 14. Air conditioning systems with latent heat energy storage tanks [45]. A) Ice storage. B) PCM storage

The analysis includes exergetic, economic and environmental aspects. The optimal exergy efficiency of the PCM tank system outperformed the ice tank system in 6.5 %-points, but the investment is greater for the former than for the latter (payback periods of 5.5 years and 3.2 years, respectively). Any of the latent heat storage solutions, but particularly the PCM storage, led to reduced power consumption and CO_2 emissions compared with a conventional configuration. The authors concluded that the environmental issues justified the use of the PCM tank system, even with the greater payback periods.

6. General conclusions

The combined use of PCMs and heat pumps may be beneficial mainly from several points of view. On one hand, it is possible to reduce the total tank size used for storing thermal energy. However, this reduction might be negligible within applications where the temperature lift at the storage is large, as stated in the IEA SHC Task 32 final report [1]. On the other hand, it has been a common objective:

1. to detach production from consumption periods. In order to be successful, very large tanks are needed, even with PCMs.
2. to further stabilise the operation temperatures of heat pumps decoupling from variable heat sources and due to the isothermal state change of many PCMs. Associated with objective is to reduce the number of start/stops of compressors.

The most important issue lies in the selection of the PCM melting temperature, which should be appropriate for the application, but the latent heat, thermal conductivity of the PCM, stability, etc. should be also considered. Another feature to be evaluated is the economic viability of using PCMs, since they are expensive materials, if compared to water, and do not normally provide important enhancements that justify the investment [1].

Table 2 summarises different research works on the use of heat pumps and energy storage solutions with PCMs and classifies them as a function of the main heat pump application.

Table 2. Research works combining heat pumps and energy storage solutions with PCMs.

Work	Type	Heat pump application	Material (Phase change temperature/range)	Observations
Leonhardt and Müller [13]	Numerical	Space heating	Paraffin (47 ºC)	Condenser to tank with PCMs
Agyenim and Hewitt [14]	Experimental	Space heating	RT58 (51 – 63 ºC)	Finned tube with PCMs for air source heat pump
Maaraoui et al. [15]	Numerical	Space heating	Paraffin (35 – 36 ºC)	Condenser to energy storage with PCMs
Kelly et al. [16]	Numerical	Space heating + DHW	Inorganic hydrated salt (48 ºC)	Condenser to tank with PCMs
Benli and Durmuş [17]	Experimental	Greenhouse heating	$CaCl_2 \cdot 6H_2O$ (32 – 45 ºC)	Condenser to tank with PCMs
Benli [18]	Experimental	Greenhouse heating	$CaCl_2 \cdot 6H_2O$ (32 – 45 ºC)	Condenser to tank with PCMs
Comakli et al. [19]	Experimental	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Solar collectors + tank with PCMs
Esen and Ayhan [20]	Numerical	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Solar collectors + tank with PCMs
Kaygusuz and Ayhan [21]	Numerical	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Solar collectors + energy storage with PCMs
Kaygusuz [22]	Numerical	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Solar collectors + energy storage with PCMs
Esen [23]	Numerical	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Solar collectors + LHTES tank with PCMs
Han et al. [25]	Numerical	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Solar collectors + LHTES tank with PCMs
Qi et al. [24]	Numerical	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Solar collectors + LHTES tank with PCMs
Niu et al. [26]	Experimental	Space heating	RT6 (6 ºC)	Solar collectors + triple sleeve energy storage heat exchanger with PCMs and air source heat pump
Niu et al. [27]	Experimental	Space heating	RT6 (6 ºC)	Solar collectors + triple sleeve energy storage heat exchanger with PCMs and air source heat pump
Qv et al. [28]	Experimental	Space heating and cooling	RT5HC (5 – 6 ºC)	Solar collectors + triple sleeve energy storage heat exchanger with PCMs and air source heat pump
Minglu et al. [30]	Experimental	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Defrost with LHTES tank with PCMs
Wenju et al. [31]	Experimental	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Defrost with LHTES tank with PCMs
Dong et al. [32]	Experimental	Space heating	$CaCl_2 \cdot 6H_2O$ (29 ºC)	Defrost with LHTES tank with PCMs
Justo Alonso et al. [33]	Numerical	Space heating + DHW	Ice (0 ºC)	Ice storage to enhance COP
Mazo et al. [35]	Numerical	Space heating	(27 ºC)	Radiant floor with PCMs connected to heat pump
Cabrol and Rowley [36]	Numerical	Space heating	$CaCl_2 \cdot 6H_2O$ (28 ºC)	Radiant floor with PCMs connected to heat pump
Gu et al. [37]	Experimental Numerical	DHW	Liquid paraffin, lauric acid	Condenser of air conditioning unit to LHTES tank with PCMs
Long and Zhu [39]	Experimental Numerical	DHW	Paraffin (56 ºC)	Condenser to LHTES tank with PCMs
Zhang et al. [38]	Experimental	DHW	Paraffin wax (45 – 48 ºC)	Condenser of air conditioning unit to LHTES tank with PCMs
Wu et al. [12]	Experimental	DHW	Paraffin and graphite (55 ºC)	Condenser of cascade heat pump to water tank with PCM units
Fang et al. [40]	Experimental	Space cooling	Ice (0 ºC)	Evaporator to LHTES ice tank and heat pipe
Ekren et al. [41]	Experimental	Space cooling	Ice (0 ºC)	Evaporator to LHTES tank with PCMs and variable speed compressor
Real et al. [42]	Experimental Numerical	Space cooling	Hydrated salt based (10 ºC and 27 ºC)	Two LHTES tanks with PCMs
Moreno et al. [43]	Experimental	Space cooling	Hydrate salt (10 ºC)	Cooling LHTES tank with PCMs
Zhu et al. [44]	Numerical	Space cooling	$Na_2SO_4 \cdot 10H_2O$ (8.3 ºC)	Cooling LHTES tank with PCMs
Hoseini Rahdar et al. [45]	Numerical	Space cooling	Ice (0 ºC) and RT3HC (3 ºC)	Evaporator to LHTES tank with PCMs

There have been several approaches for the application of PCMs with heat pumps for space heating production. The first of them was with the integration of PCMs connected to or in the condenser, mainly with the aim of shifting the energy production to off-peak periods. Leonhardt and Müller [13] observed that this solution allows reducing the number of starts/stops of a system. Agyenim and Hewitt [14] and Maaraoui et al. [15] agree that the critical point for the implementation of PCMs is their low thermal conductivity, which should be addressed by means of enhanced heat exchangers. In addition, Kelly et al. [16] state that the energy shift may cause an important increase of the electric power demand and may not compensate the production in off-peak periods.

Another approach concerning space heating production was the use of the energy stored in PCM tanks mainly as heat source for heat pumps. Comakli et al. [19] and subsequent works combined PCM energy storage with solar collectors and even air as source of the heat pump. They observed that having more than one heat source for the heat pump is convenient from a performance point of view, but the economic viability has to be studied.

PCM energy storage systems were also proposed in order to improve the defrosting process of air source heat pumps for space heating production. Minglu et al. [30] or Wenju et al. [31] observed that the process could be importantly shortened and the thermal comfort in the heated house could be improved, without important surplus in the cost of the whole system. However, the cost-effectiveness of such a solution can be importantly influenced by the stability of the PCM, which might need to be replaced regularly Wenju et al. [31].

Concerning the production of DHW with heat pump and using PCMs, there are mainly two proposals. The first consists on taking advantage of the heat of condensation of air conditioning units to charge PCM tanks, as described in Gu et al. [37] or [38]. The second includes heat pumps intended for DHW production, with works such as Long and Zhu [39] and Wu et al. [12]. Even though Wu and co-workers failed to attain any improvement in the efficiency of a DHW tank with a PCM module, they stated that such a solution may allow decoupling energy production from demand and reducing heat losses to the ambient if selected PCMs of greater energy storage capacity and heat transfer performance.

Finally, there has been an effort to implement PCM energy storage in heat pumps for space cooling production with three main objectives. The first is enhancing the performance of heat pumps, such as in Real et al. [42], where a PCM tank is used to reduce the refrigerant condensation temperature when the ambient temperature is high. The second is shifting energy consumption to off-peak electricity periods, for instance by the use of ice storage connected to the indoor unit [40]. The third is preventing the oversizing of heat pumps in periods of high cooling loads, using the PCM tanks as support for cooling production [44].

7. Acknowledgements

8. References

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