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Choice of the suitable melting temperature of Phase Change Material: Application on Solar Assisted Heat Pump

Ryad Bouzouidja
Université de Bordeaux, UMR CNRS 5295,
I2M Bordeaux
Bordeaux, France
ryad.bouzouidja@u-bordeaux.fr
<https://orcid.org/0000-0001-8192-0308>

Zakaria Aketouane, Romain Lhomer, Benjamin
Varela
Nobatek/INEF4
Bordeaux, France
zaketouane@nobatek.inef4.com,
rlohomer@nobatek.inef4.com,
bvarela@nobatek.inef4.com

Jose Lara Cruz, Sylvain Serra, Jean-
Michel Reneaume
Université de Pau et des Pays de
l'Adour, LaTEP-IPRA, EA1932,
Pau, France
jose.laracruz@univ-pau.fr,
sylvain.serra@univ-pau.fr, jean-michel.reneaume@univ-pau.fr

Alain Sempey
Université de Bordeaux, UMR CNRS 5295,
I2M Bordeaux
Bordeaux, France
alain.sempey@u-bordeaux.fr
<https://orcid.org/0000-0002-1274-3253>

Abstract—Thermal energy storage (TES) is a key issue in efficient energy systems applications. In this regard, phase-changing material (PCM) has been of interest as an active solution for efficient energy management, especially in the context of the building. This paper presents a thermal analysis on sensible and latent TES systems to investigate their thermal performance in the case of Solar Assisted Heat Pump (SAHP). The storage tank allows to store the heat produced via unglazed solar panels (Batisol®) and represents the heat source of the heat pump (HP). The objective of the study is firstly to define the suitable melting temperature of the PCM to be integrated in SAHP system, and then to compare its performance to the case of sensible storage. In order to improve the coefficient of performance (COP), the results indicate a melting temperature 15°C regardless to the volume storage. On the other hand, a melting temperature of 9°C is suitable to increase the solar coverage rate of SAHP system. Furthermore, the comparison with sensible storage shows an improvement in the COP when latent storage is used. In order to optimize the choice of melting temperature and the volume of the storage, future work will consist of conducting a multi-objective optimization study considering energy, economic and environmental criteria.

Keywords— Phase Change Material (PCM), coefficient of performance (COP), heat pump, Batisol®

I. INTRODUCTION

Energy production and consumption have a heavy environmental toll. The environmental challenges related to energy are increasingly numerous [1]. Currently, buildings are identified as one of the major energy end-use sectors worldwide; the growing demand for energy increases pressure on the environment [2]. Thus, reducing energy consumption presents a

major challenge for fundamental and technological research, as well as an economic and environmental issue. Thermal energy storage (TES) is considered as one of the most important energy technologies to correct the mismatch between energy supply and demand, especially when dealing with intermittent renewable energies like solar energy. TES can be divided into sensible heat storage (SHS), latent heat storage (LHS), and thermochemical energy storage [3]. The SHS stores the thermal energy by raising the temperature of a medium in solid or liquid states of matter. In contrast to the SHS, the LHS uses phase change materials (PCM) to change phases including solid-solid, solid-liquid, or liquid-gas [4].

Solar systems assisted by heat pumps (SAHP) are solutions combining thermal solar panels and a heat pump. The role of a heat pump in the heating system is to increase the thermal energy from a lower temperature level to a higher temperature level [5]. The combination of these two systems, in series [6] or in parallel [7], offers important energy and environmental performances. In addition, the use of a PCM storage unit between the solar panels and the heat pump has several advantages: On the one hand, the solar energy stored in the PCM can be used as a heat source for the evaporator. This leads to an almost constant evaporation temperature. Since the solar radiation is not constant and the air temperature varies so much during the day, using the PCM as an intermediate storage would be beneficial for the heat pump to operate under more stable conditions. This ultimately improves the Coefficient of Performance (COP) of the heat pump and therefore consumes less energy.

Analytical and computational models for SAHP systems with energy storage were developed using different solution techniques for annually periodic operation [8]. Kaygusuz [9] conducted an experimental study on the performance of a SAHP system coupled with a PCM-based storage system (encapsulated) for residential heating. Two different systems were tested and compared to heat a 75 m² room. Each system consisted of a heat pump coupled with solar collectors in series or in parallel with storage. The first system consists of glazed solar collectors (30 m²), a storage tank (4,500 L) filled with PCM (1,500 kg of CaCl₂-6H₂O), a heat pump with a water-cooler heat exchanger (1.45 kW compressor), an air-cooled condenser, a liquid-air heat exchanger for solar heating, and other conventional equipment. The experimental results showed that 30 m² of solar collectors were required for both systems to cover the heating needs of the room. In addition, the COP of the series system was significantly higher than that of the parallel system; the former had an average seasonal heating performance of 4 while the parallel system achieved a COP of 3.

In another study, Esen et al [10] conducted a parametric study of two SAHP systems using two different types of storage: in the first, the water occupies the tank while the PCM is encapsulated in cylindrical form, in the second storage, the PCM occupies the tank and the water circulates through coils. The storage system, modeled in this study, is assumed to be coupled with a heat pump and solar thermal panels. The optimization results showed that the choice of PCM properties, cylinder radius, mass flow rate, and inlet temperature of a heat transfer fluid is critical to optimize the performance of the storage tank.

The aim of this paper is firstly to define the suitable melting temperature of the PCM to be integrated in SAHP system. Also, the design and simulation analysis of a solar-assisted heat pump system equipped with the PCM. The system includes a Batisol[®] [11] panels supplying heat to the LHS tank.

During the winter, the heat pump receives heat at its evaporator, via storage, and supplies space heating to a building. The system is described in more detail in Section II.A. A case study was developed, using weather data of Cholet, western of France.

II. MATERIAL AND METHODS

A. Case Study

In this study, we consider the case study of a building located in western France in the Maine-et-Loire department. The site is located in Cholet, France (lat. 47° 3' 33.865" N, long. 0° 02' 50.9784" W) and located approximately 100 km east of the Atlantic Ocean. Cholet experiences a temperate oceanic climate (Cfb climate in the Köppen Geiger classification system) [12]. February is the coldest month of the year, with an average minimal (resp. maximal) air temperature of 2.1°C (resp. 20.3°C) [13]. January is the wettest month of the winter season with 84.6 mm of precipitation on average. The mean month insolation values for December, January, and February rate are, respectively 76, 73, and 97 h [13].

The heating needs of the studied building are determined by dynamic thermal simulation (DTS) using Pleiades-Comfie simulation tool [14] taking into account the climatic conditions of the city of Cholet. The heating needs of this building, in

terms of energy, are 23.3 MWh distributed over the six months of study as shown in Fig. 1.

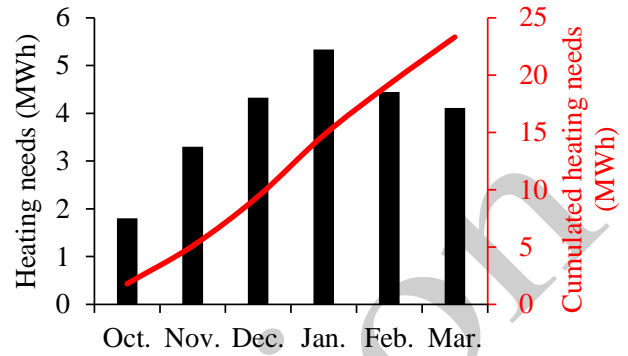


Fig. 1. Profile of heating needs for the building.

B. Description of the system

Fig. 2 shows a scheme of the main components of the heating system with latent heat storage (LHS) tank under investigation. The system consists of a cylinder TES tank, Batisol[®] panels, a heat pump unit (HP) and a house to be heated during winter season. In Fig. 3 several circuits can be identified, for the following fluids: solar panel fluid (SPF), hot fluid (HF), tank water (TW), fan-coil fluid (FCF), and air heater fluid (ATF). The main components are: Batisol[®] panels, PCM and water storage tank, heat exchanger in the circuit#1 between the panels and the tank, air heater unit (AT) for the HP behavior, Buffer tank (BT), fan-coil unit (FC) (circuit#2). In both cases of LHS and SHS, a stocker is used. The only difference is the size of the latter.

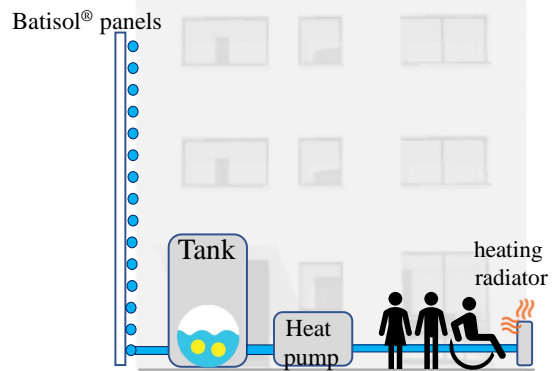


Fig. 2. House heating system with heat pump and Batisol[®] panels.

C. Model of the tank

Energy balance applied to the sensible heat storage (SHS) related to the energy received by the panels and the energy absorbed by the HP

$$m_{\text{tank}} \cdot C_{p_{\text{tank}}} \frac{dT_{\text{tank}}}{dt} = P_{\text{façade}} - P_{\text{building}} + P_{\text{electric}} \quad (1)$$

$$P_{\text{façade}} = q_{\text{af}} \cdot C_{p_{\text{af}}} (T_{\text{out-panels}} - T_{\text{in-panels}}) \quad (2)$$

$$P_{\text{façade}} = \epsilon \cdot A \cdot I_{\text{sun}} \quad (3)$$

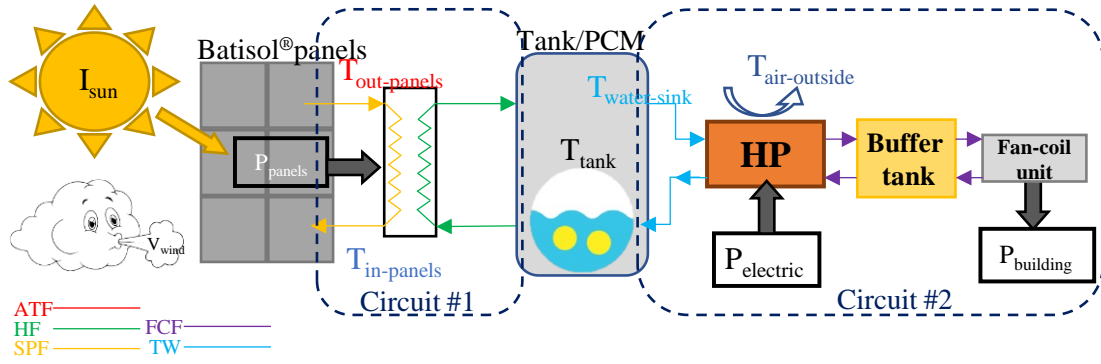


Fig. 3. House heating system with heat pump and Batisol panels. I_{sun} (W m^{-2}) is the incoming solar irradiance. V_{wind} (m s^{-1}) is the wind velocity at close to the panels. P_{panels} is the power received by the panels (W). $T_{in-panels}$ and $T_{out-panels}$ ($^{\circ}\text{C}$) are respectively the temperature of the antifreeze fluid at the entrance and exit of the panel. T_{tank} is the phase change material (PCM) temperature ($^{\circ}\text{C}$). $T_{water-sink}$ ($^{\circ}\text{C}$) is temperature of the water incoming from the tank. $T_{air-sink}$ is the temperature incoming from the air heater unit ($^{\circ}\text{C}$). $T_{air-outside}$ ($^{\circ}\text{C}$) is the temperature of the air exhausted by the air heater unit. ATF is athermo fluid; HF is hot fluid; SPF is solar panel fluid; FCF is fan-coil fluid; TW is tank water.

where $P_{fa\grave{c}ade}$ and $P_{building}$ (W) are the power produced by the Batisol[®] panels and the heating loads of the building respectively. ϵ (-) is the efficiency coefficient of the panels. A (m^2) is the area of the panels. I_{sun} (W m^{-2}) is the solar irradiance. m_{tank} and $C_{p_{tank}}$ are the mass (kg) and specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$) of the antifreeze fluid in the HF circuit respectively. $C_{p_{af}}$ ($\text{J kg}^{-1} \text{K}^{-1}$) is the specific heat capacity of antifreeze fluid in the SNP circuit. q_{af} (kg s^{-1}) is the flowrate of the antifreeze fluid in the SNP circuit. The efficiency of the panels can be written as follow:

$$\epsilon = \alpha \frac{\Delta T}{I_{sun}} - \beta \quad (4)$$

where ΔT is the difference between the panel and the air ambient temperature ($^{\circ}\text{C}$):

$$\Delta T = \frac{(T_{in-panels} + T_{out-panels})}{2} - T_{air-outside} \quad (5)$$

Using Equation (1) to (5), $T_{out-panels}$ can be written as:

$$T_{out-panels} = \frac{q_{af} \cdot C_{p_{af}} \cdot T_{in-panels} + \alpha \cdot A (T_{in-panels} - T_{ext}) + I \cdot A \beta}{q_{af} \cdot C_{p_{af}} - 0.5 \cdot \alpha \cdot A} \quad (6)$$

$$\alpha = -(7.84 + 3 \cdot V_{wind}) \quad (7)$$

where V_{wind} is the wind speed close to the panels (m s^{-1}). β is the optical efficiency (-). α is the heat loss coefficient of the panel correlated to wind speed ($\text{W m}^{-2} \text{K}^{-1}$).

D. Phase change material model

In order to establish this predictive and comparative model, it is necessary to simplify the physical phenomena by assumptions that must be taken into consideration in the analysis of the results. The main assumptions considered are the following:

- Temperature of the PCM is considered as constant during the melting process [15].

- In order to consider, the heat losses in the piping, an adjustment of 2°C is made between the outlet of the panels and the inlet of the tank.
- It is assumed that the PCM has the behavior of an exchanger and PCM is modelled using heat thermal coefficient (HTC) ($\text{W m}^{-2} \text{K}^{-1}$) [16], [17]. HTC is calculated according to the power delivered by the heat transfer fluid to the MCP, which can be determined using the temperature difference between the inlet and outlet of the exchanger (2°C) [18].

According to that, the energy balance of LHS can be defined as:

$$\frac{dE_{tank}}{dt} = P_{fa\grave{c}ade} - P_{HP} \quad (8)$$

where P_{HP} is the thermal power of the heat pump (W).

Using Equations (1) to (7), $T_{out-panels}$ can be written as:

$$T_{out-panels} = \frac{q_{af} \cdot C_{p_{af}} \cdot T_{in-panels} - \text{HTC} \cdot A \cdot T_{in-panels} + \text{HTC} \cdot A \cdot T_{ext}}{q_{af} \cdot C_{p_{af}} - 0.5 \cdot \alpha \cdot A} \quad (9)$$

To evaluate the influence of the state (liquid or solid) of the PCM on the energy balance, we assumed that:

$$T_{tank} = \begin{cases} T_{ref} + \frac{E_{tank}}{(M_{PCM} \cdot C_{p_{PCM}})_{solid}} & \text{if } T_{PCM} < T_{melting} \\ T_{PCM} & \text{if } T_{PCM} = T_{melting} \\ T_{PCM} + \frac{E_{tank} - E_{latent} - E_{solid}}{(M_{PCM} \cdot C_{p_{PCM}})_{liquid}} & \text{if } T_{PCM} > T_{melting} \end{cases} \quad (10)$$

where T_{PCM} is the temperature of the PCM inside the tank ($^{\circ}\text{C}$).

where T_{ref} is the temperature of the PCM in solid phase. $T_{melting}$ is the melting temperature of the PCM. In this situation $T_{ref} = 0^{\circ}\text{C}$. $M_{PCM-solid}$ and $M_{PCM-liquid}$ are the PCM mass (kg) at the solid and liquid phase respectively. $C_{p_{PCM-solid}}$ and $C_{p_{PCM-liquid}}$ are the specific heat capacity of the PCM ($\text{J kg}^{-1} \text{K}^{-1}$) at the solid and liquid phase respectively.

Therefore, the efficiency of a HP is usually measured by the ratio of thermal energy available for heating or cooling use (E_{th}^{HP}) and the heat pump driving energy consumption (E_{el}^{HP}) (kWh) was obtained from the heat pump (Equation 11) using heating power and supplied power. TABLE I. summarize the main parameters used in this study.

$$COP = \frac{E_{th}^{HP}}{E_{el}^{HP}} = \frac{q_{af} \cdot C_{paf} \cdot (T_{water-sink} - T_{PCM})}{E_{el}^{HP}} \quad (11)$$

where q_{af} is the flowrate of antifreeze fluid ($kg \ s^{-1}$). C_{paf} ($J \ kg^{-1} \ K^{-1}$) is the specific heat capacity of antifreeze fluid in the network.

TABLE I. MAIN DESIGN PARAMETERS OF THE SYSTEM.

Parameter	Unit	Value
Batisol® panels area, A	m^2	195
Flowrate of heat transfer medium from the panel, q_{panels}	$m^3 \ h^{-1}$	60
Mass antifreeze fluid of the tank, m_{af}	kg	1,000 to 10,000
Flowrate of antifreeze fluid, q_{af}	$kg \ s^{-1}$	16.7
Specific heat capacity of antifreeze fluid in the network, C_{paf}	$J \ kg^{-1} \ K^{-1}$	3,800
Initial tank temperature, $T_{tank-init}$	$^{\circ}C$	7.5
Specific heat capacity at the liquid phase of the phase change material, $C_{PCM-liquid}$	$J \ kg^{-1} \ K^{-1}$	2,000
Specific heat capacity at the solid phase of the phase change material, $C_{PCM-solid}$	$J \ kg^{-1} \ K^{-1}$	2,000
Latent heat of fusion, E_{latent}	$kJ \ kg^{-1}$	260

III. RESULTS AND DISCUSSION

Fig. 4 shows the COP of the SAHP in function of the temperature of the PCM for different mass of the PCM inside the tank. It can be seen that the increase in the storage volume leads to an increase in the COP of the system. In addition, we also note that whatever the storage volume, the maximum COP is reached for a phase change temperature equal to $15^{\circ}C$. For this value of melting temperature, the COP increases by 6.5% when going from a storage of 450 kg to 4500 kg.

Fig. 5 shows the available solar energy (η_{solar}) produced by the panels and transferred to the PCM Tank for different range phase change temperatures T_{PCM} and different volumes. It can be noted that the maximum available temperature is reached for $T_{PCM}=9^{\circ}C$ regardless to the mass of the PCM Tank. For a mass of 450 kg and $T_{PCM}=9^{\circ}C$, the result indicates that the heat pump can ensure the heating load by operating 88% of time on the façade and PCM storage while using air heater unit only 12% of time. Indeed, when PCM melts at a temperature higher than $9^{\circ}C$, it melts less often and thus captures (and makes available for installation) less solar energy. When it melts below $9^{\circ}C$, it melts more often but the outside temperature is more easily competitive with the PCM temperature and therefore the system counts more hours of operation in Air heater unit mode.

It can notice that the results of the suitable temperature depend on the choice of the objective to be attained by the SAHP system: $T_{pcm}=15^{\circ}C$ if the objective is to improve the COP and $T_{pcm}=9^{\circ}C$ in the case where we aim to ensure a high solar coverage rate.

Therefore, the choice of the suitable PCM can be reduced to solving a problem with several objective functions in order to find a solution that optimize both the COP and the solar coverage rate.

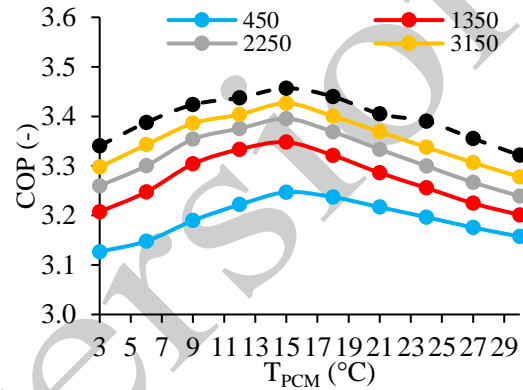


Fig. 4. Coefficient of performance of the solar heat pump (SAHP) for different phase change material (PCM) mass: 450 kg (blue continuous line), 1,350 kg (red continuous line); 2,250 kg (grey continuous line); 3,150 kg (yellow continuous line), and 4,500 kg (black dashed line).

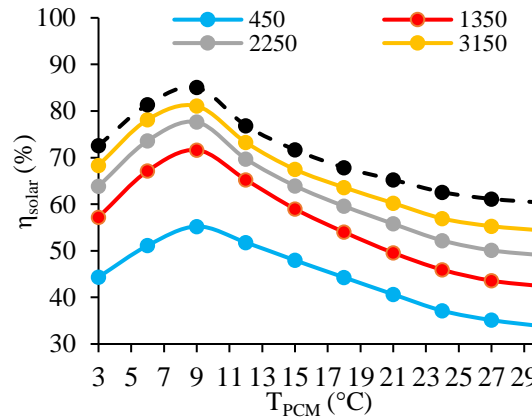


Fig. 5. Percentage of solar energy converted by the panels to the tank (η_{solar}) (%) related to melting phase change material (PCM) T_{PCM} ($^{\circ}C$) for different PCM mass: 450 kg (blue continuous line), 1,350 kg (red continuous line), 2,250 kg (grey continuous line), 3,150 kg (yellow continuous line), and 4,500 kg (black dashed line).

The results obtained by the SHS system are compared with the LHS system and are presented in Fig. 6. It is observed that for the same volume of PCM and water in the sensible storage unit, the COP of the heat pump is slightly higher 3.37 and 3.31 respectively (i.e. 2%). For the same COP of 3.25, only 400 m³ of PCM are needed for latent storage, whereas 1,200 m³ of water are needed for sensible storage. This corresponds to a ratio of MPCM to maf of 2.7. This ratio decreases to 1 when the mass of PCM is around 4,500 m³.

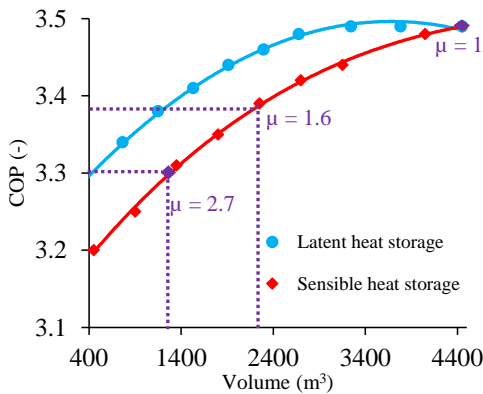


Fig. 6. Comparison between latent heat storage for a melting phase change material (PCM) at 15°C (continuous blue line and round markers) and sensible heat storage (continuous red line with diamond marker). μ is the ratio between the volume of the PCM and the masse the water (-).

IV. CONCLUSION

The simulation model of a solar-assisted heat pump (SAHP) system based on the utilization of innovative panels (Batisol®) and latent heat storage tank (PCM) was presented. The SAHP system proposed here combines solar energy, a heat pump and a latent heat storage system (LHS). Energy performance benefits of the system is calculated for a building located in Cholet, France (a temperate oceanic climate) and compared to a sensible heat storage system. In order to increase the COP of the SAHP system, the results indicate that the suitable melting temperature of 9°C is suitable for maximizing the solar coverage rate for a SAHP installation in the climatic conditions of Cholet. In addition to these energy improvements, the use of PCM as latent storage allows to reduce the volume occupied by the storage system when compared to sensible storage (400 m³ and 1,200 m³ respectively). Reducing the space occupied by the storage system is an important economic criterion, especially in the case where the price per m² of the floor represents a significant part of the investment cost of an SAHP installation. Future work will concern a multi-objective optimization study considering energy (COP and solar coverage rate), economic (operating and investment cost) and environmental (Greenhouse gas emission reduction) criteria to optimize the choice of volume and melting temperature of PCM.

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