Modeling of a thermal storage system incorporated into a solar cooling installation in an office building.

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MODELING OF A THERMAL STORAGE SYSTEM INCORPORATED INTO A SOLAR COOLING INSTALLATION IN AN OFFICE BUILDING

Olivier Marc[a], Paul Guillou [a], Frantz Sinama [a], Franck Lucas [a], Jean-Philippe Praene [a], Jean Castaing-Lasvignottes [a]*

[a] *Physical and Mathematical Engineering for Energy, Environment and Building (PIMENT), University of Reunion Island, 40 Av.de SOWETO, 97410, Saint Pierre, France,*
** Corresponding author: omarc@univ-reunion.fr*

Abstract:

During the last twenty years, the comfort and cooling requirements of office buildings and occupants have evolved significantly in Reunion Island, particularly during the summer period. This intensive use of air conditioning has resulted in a significant increase in electricity consumption such as traditional cooling technologies (mechanical vapor compression systems). In this context, solar cooling systems are one of the more interesting alternatives to conventional air conditioning systems. Thus in 2008, the PIMENT laboratory in Reunion Island proposed to set up an experimental platform called "RAFSOL", on the University Institute of Technology of Saint-Pierre, to study the absorption solar cooling technology for a University building. Experimental and numerical investigations of RAFSOL allowed to identify several research topics to improve global performances of the installation. One of them concerns the incorporation of a new thermal storage into the solar cooling system. Indeed, the addition of thermal storage (hot and/or cold) give the following advantages: (i) sufficient cooling power to cover the entire building's needs, (ii) intelligent use the weekend energy potential, (iii) prevents overheating of the solar loop because of lower cooling needs. This thermal storage would also improve the system performance since it brings the temperatures of the hot and cold sources closer to their nominal values and thus optimizes the running time of the absorption chiller. In this work we decided to study only the incorporation of a hot thermal storage composed of a phase change material, and to investigate the influence of this storage on the solar cooling system performances. Three different phase change temperatures are investigated according to the state of art of this technology: 79, 84 and 90°C. Simulation results are then analyzed and discussed to identify the optimal configuration of the thermal storage.

Keywords:

Solar cooling, modeling, thermal storage, phase change material.

1. Introduction

Absorption solar cooling systems are one of the more interesting alternatives to conventional air conditioning systems to reduce the electricity consumption [1]. Thus in 2008, the PIMENT laboratory in Reunion Island proposed to set up an experimental platform called "RAFSOL" (Fig. 1), on the University Institute of Technology of Saint-Pierre, to study the absorption solar cooling technology for a University building. The main components of the RAFSOL installation are: (i) a 90 m² double glazed solar collector field, (ii) two hot and cold buffer tanks, 1500 and 1000 L respectively, (iii) a 30 kW single-effect absorption chiller, (iv) a 80 kW opened cooling tower, (v) 13 fan coil units installed to cool a total area of 180 m². The initial aim of the RAFSOL installation was to cool four classrooms using only solar radiation i.e. without any real hot and/or cold storage (except little buffer tanks) or backup systems [2].

Fig. 1. RAFSOL installation with, on the roof, the solar collector field and the cooling tower (left) and, in the technical room, the absorption chiller and the 2 buffer tanks (right).

Experimental feedback on five years of functioning highlighted three main problems:

- The first one can appear when building loads are low and when the solar irradiance is high. In this case the cold source temperature decreases to its lower limit (7°C), leading to the shut-down of the machine for safety reasons. In the same time, the solar irradiance contributes to increase the temperature of the solar collector field and can lead to the overheating of the solar hydraulic loop and make irreversible damage to the equipment.
- The second problem is the incapacity of the solar cooling system (SCS) to cover the cooling loads of the building all over the day. Indeed the cooling demand can vary from 8am to 5pm due to the occupancy of the four classrooms. However the SCS cannot start before 10h30am due to the heating time of the solar hydraulic loop and the absorption chiller (between 7am and 10h30am). Moreover, during the day, a significant decrease of the solar irradiance can affect the refrigerating capacity produced by the chiller and cannot meet the cooling demand of the building.
- The third point concerns the unexploited solar resource during the weekend. Indeed solar cooling systems coupled to office or teaching buildings induce a non-occupancy during the weekend while the solar irradiance continues to heat the solar loop. In this case, the regulation of the installation forces the cooling production (and the distribution) to avoid the overheating of the solar loop. This forcing mode involves electric consumptions while there are not any cooling demands inside the building.

Thus, this paper proposes a numerical study of the incorporation of a thermal storage into the existing SCS. Indeed, the solar resource can be stored during the weekend, and powers the absorption chiller when the solar irradiance is not sufficient during the week. Phase change materials (PCM) have been chosen as thermal storage technology for their interesting energetic density, their good technological application and the great stability of the temperature of the system. This work is focused only on the use of a hot storage in order to limit overheating problems of the solar loop and stabilize the hot source temperature of the chiller.

The first part of this study concerns the analysis of the experimental data of the SCS to identify the amount of thermal energy to be stored during the weekend. Then, two numerical models are developed in addition of previous works [3, 4, 5]. The inputs of the global model are weather data and the building loads file. Performance indicators are presented for measuring the influence of the integration of a hot storage to the existing system (Fig. 2). Three different phase change materials have been chosen in the literature depending on their melting temperature [6]: 79, 84 and 90°C. Numerical simulations will be carried out according to each melting temperature and for three different start-up scenarios of the installation.

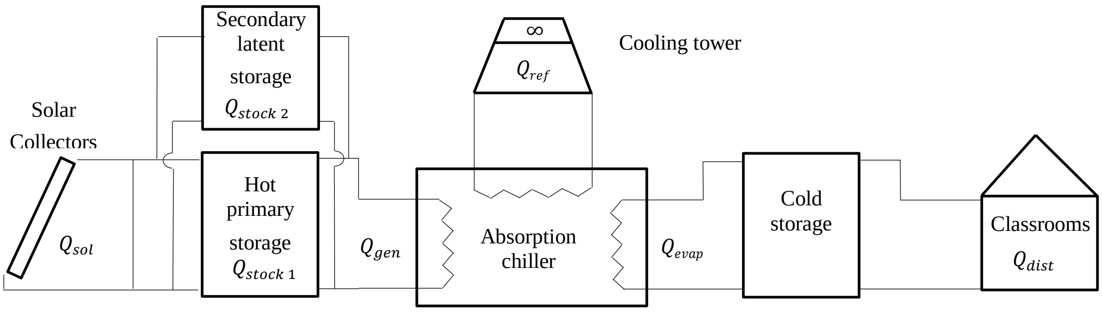


Fig. 2. Installation diagram with additional latent heat storage.

2. Energy analysis of experimental data

The aim of the installation is to produce and distribute refrigerating energy to meet the cooling demand of the building. To illustrate a typical operating day, Fig. 3 is presented. The required capacity of refrigeration of the building ($\dot{\boldsymbol{Q}}_{required}$) is given by a dynamic thermal simulation carried out on the building according to internal and external thermal gains. The distributed capacity ($\dot{\boldsymbol{Q}}_{distributed}$) is the real refrigerating capacity distributed by the SCS into the building. Two time slots (Fig. 3: p1 and p2) are defined, when the distributed capacity is lower than the required capacity. In the first case (p1), the SCS can never provide refrigerating capacity before 10h30am while there is a cooling demand of the building from 8am, then the first missing energy is observed and noted Q_{p1}. In the second case, when the solar irradiance decreases (at about 12h30pm), the distributed capacity decreases too, while cooling loads are required until 5pm; the SCS provides to the building a refrigerating energy lower than the required one and the difference between both energies in noted Q_{p2}. Then, Q_{p1}, Q_{p2} and the global missing energy (Q_{global}) are defined as:

- $Q_{p1} = \int_{p_1} \dot{Q}_{required}.dt$: First missing energy.
- $Q_{p2} = \int_{p_2} (\dot{Q}_{required} - \dot{Q}_{distributed}).dt$: Second missing energy.
- $Q_{global} = Q_{p1} + Q_{p2}$: Global missing energy.

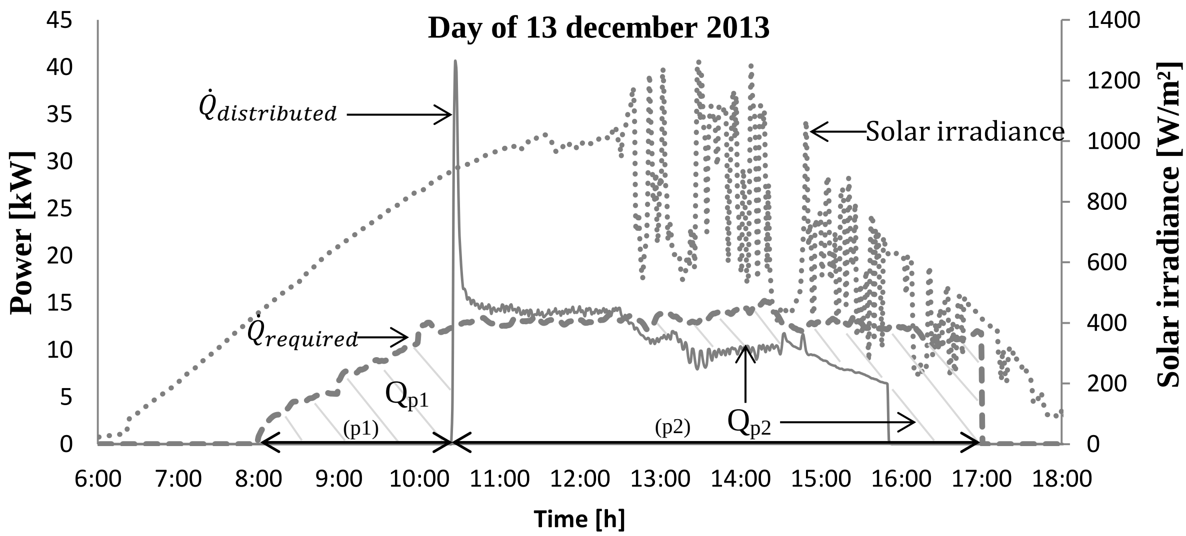


Fig. 3. Typical operating day of the SCS.

The analysis carried out on a typical operating day is extended over a full week to quantify main energies of the installation for the weekend and for the week (tab. 1). Solar energy during the weekend ($Q_{sol\ weekend}$, table 1 (a)) is the solar thermal energy collected by the solar loop during the weekend; distributed energy (Q_{dist}, table 1 (b)) is the refrigerating energy distributed in the building during the week i.e. from Monday to Friday; ΔQ (table 1 (c, d, e)) represents the difference between the required and distributed energies from Monday to Friday for three different start-up scenarios of the SCS (8am, 9am, 10am). Table 1 presents the results of an average week calculated from 8 experimental studied weeks. These results will be used in the last part of this paper when the numerical simulation will be carried out.

Table 1. (a) Solar thermal energy during the weekend; (b) distributed energy during the week; (c) refrigerating energy for a start-up at 8am; (d) refrigerating energy for a start-up at 9am; (e) refrigerating energy for a start-up at 10am.

Energies	$Q_{sol\ weekend}$ (a)	$Q_{dist\ week}$ (b)	ΔQ_{8am} (c)	ΔQ_{9am} (d)	ΔQ_{10am} (e)
Average Energies [kWh]	297.5	324.6	-246.4	-221.1	-184.0

The objective of the integration of the latent storage is to use the solar thermal potential during the weekend (tab. 1 (a)) to fill the lack of refrigerating energy distributed and to meet the cooling demand of the building during the week i.e. from Monday to Friday (tab. 1 (c), (d), (e)). Thus the hot latent storage is charged during the weekend when the outlet temperature of the solar loop is higher than the PCM melting temperature. The discharge phase occurs during the week when the primary hot water tank temperature is lower than 75°C and when there is a cooling demand into the building.

3. Presentation of models and performance indicators

In this part two new models are presented. The first is the absorption chiller model and the second represent the latent storage model, in addition to previous works [3, 4, 5]. Furthermore different performance indicators are introduced to compare and quantify the influence of each parameter (as the melting temperature or the chosen start-up scenario) on the performance of the installation.

3.1. Numerical models

3.1.1. Absorption chiller model

To model the absorption chiller, we have used the work of Maria Puig-Arnavast *et al.* [7]. This model allows a reduction in calculation time when compared to models used in previous work [3]. The equations governing heat transfer are presented as follows:

$$\dot{Q}_{evap} = s_{evap} * \Delta\Delta\mathrm{T} - s_{evap} * \Delta\Delta\mathrm{T}_{\min\_eva} \quad (1)$$

$$\dot{Q}_{gen} = s_{gen} * \Delta\Delta\mathrm{T} - s_{gen} * \Delta\Delta\mathrm{T}_{\min\_gen} \quad (2)$$

$$\dot{Q}_{abs/cond} = s_{abs/cond} * \Delta\Delta\mathrm{T} - s_{abs/cond} * \Delta\Delta\mathrm{T}_{\min\_abs/cond} \quad (3)$$

Where:

$$\Delta\Delta T = T_{gen} - T_{\frac{abs}{cond}} - B * \left(T_{\frac{abs}{cond}} - T_{evap}\right) \tag{4}$$

The calculated outputs, by matrix resolution are: $\Delta\Delta T$, T_{gen}, T_{evap}, $T_{abs\,/\,cond}$. The identification of characteristic parameters ($\Delta\Delta T$, B, S) was performed in different steady-state conditions of the machine.

3.1.2. Latent heat storage

Different mathematical models are used to describe the behaviour of latent storage [8, 9, 10]. In this work, a consistent approach was used. The internal energy variation of the PCM is given by:

$$\frac{dU_{mcp}}{dt} = \dot{m}.Cp_{water}.\left(T_{e\,mcp} - T_{s\,mcp}\right) + K_{mcp}.S_{mcp}.(T_{ext} - T_{mcp}) \tag{5}$$

Where K_{mcp} is the global heat loss coefficient of the hot primary storage and S_{mcp} is exchange area with the ambient air.

3.1. Performance indicators

Four performance indicators (Table 2) are used to quantify the influence of different parameters on the installation. The COP_{th} (Thermal Coefficient Of Performance), the PER (Primary Energy Ratio) and R_{sol} (Solar loop efficiency) were defined by Julia Nowag *et al.* [11]. The coverage rate (τ_{cov}) is added to take into account the influence of the latent storage on the SCS.

Table 2. Performance indicators.

Indicators	$\boldsymbol{COP_{th}}$	**PER**	$\boldsymbol{R_{sol}}$	$\boldsymbol{\tau_{cov}}$
Formula	$\frac{Q_{evap}}{Q_{gen}}$	$\frac{Q_{dist}}{Welec}$	$\frac{Q_{gen}}{Q_{sol}}$	$\frac{Q_{dist}}{Q_{required}}$

Where Q_{evap} is the refrigerating energy produced on the evaporator; Q_{gen} is the energy consumed by the generator; Q_{dist} is the refrigerating energy distributed in the building; W_{elec} is the electric energy consumed by the SCS; Q_{sol} is the solar energy collected by the heat transfer fluid on solar collectors; $Q_{required}$ is the refrigeration energy which is required in the building.

4. Results and Discussion

This paper focuses on the study of three different melting temperatures (79, 84 and 90°C) and according to three different start-up scenarios of the SCS: 8am, 9am, 10am (the refrigerating distribution stops always at 5pm). The building is occupied from 8am to 5pm every day from Monday to Friday. The numerical simulations are carried out over a typical operating week with a storage phase during the weekend and a releasing phase during the week when the temperature of the primary hot water tank is too low to power the generator of the absorption chiller i.e. below

75°C. The amount of heat stored during the weekend, is set to 297.5 kWh and is given by the analysis of the experimental data presented above (table 1). The mass of PCM is then calculated from the amount of heat stored and the latent heat of fusion of each PCM [6]. Firstly, simulation results are presented to validate numerical models by comparing experimental data with simulated values for the absorption chiller and by observing the charge and the discharge phases of the latent storage for a week. Secondly, the simulation results will be extended to a full week according to the three start-up scenarios (8am, 9am and 10am) and three melting PCM temperatures (79, 84 and 90°C).

4.1. Simulations and experimental comparisons

Regarding the absorption chiller model, the inputs are: the flow rates and the temperatures at the inlet of the generator, absorber and evaporator. In view of the results presented in Fig. 4, it can be pointed out that the model matches the general aspect of the experimental data. The average and the maximum absolute errors committed for the evaluation of the outlet temperatures are respectively: 1.05°C and 2.55°C for the generator; 1.09°C and 3.5°C for the evaporator; 0.28°C and 1.75°C for the absorber/condenser (Fig. 4).

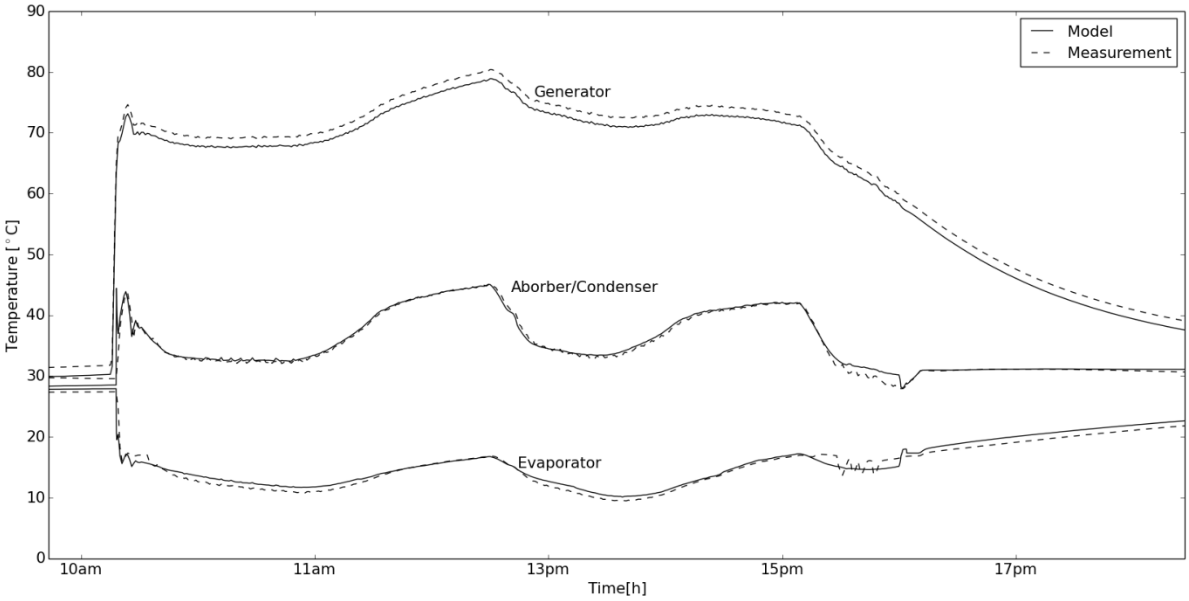


Fig. 4. Simulated and measured outlet temperatures of the generator, the condenser and the evaporator.

Then, to validate the latent storage model, a typical week is shown in Figure 5. The amount of heat stored during the weekend is 297 kWh, corresponding to the average of the solar energy potential calculated before (Table 1). For this simulation, the PCM melting temperature is fixed at 79°C. In this condition, the latent heat of fusion is 209 kJ/kg and the mass associated with the energy stored is 5124 kg [6]. The start-up scenario was chosen at 9am i.e. the SCS starts to provide refrigerating capacity in the building at 9am and stops at 5pm. During the weekend, the solar energy is stored inside the latent storage when the output temperature of the solar loop is higher than the melting temperature of the PCM. The discharge is carried out during the week, from Monday to Friday, when the primary hot water tank feeding the generator does not reach a sufficient temperature set at 75°C. It can be noted two discharge situations during the week. The first is between 9 and 10.30; the second occurs when the solar irradiance is insufficient to power the absorption chiller.

Moreover, it can be observed that largest discharges of the latent storage occur on Monday morning (about 25%) and Friday afternoon (about 15%) when the solar irradiance is very weak.

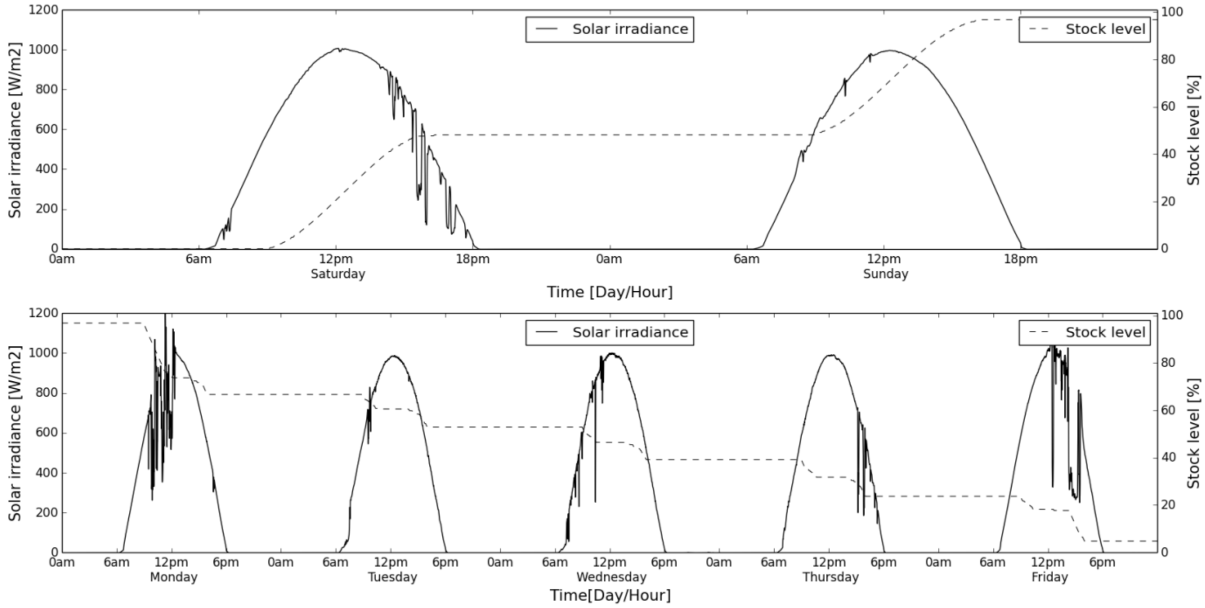


Fig. 5. Load (on top) and discharge (at the bottom) of the latent heat storage.

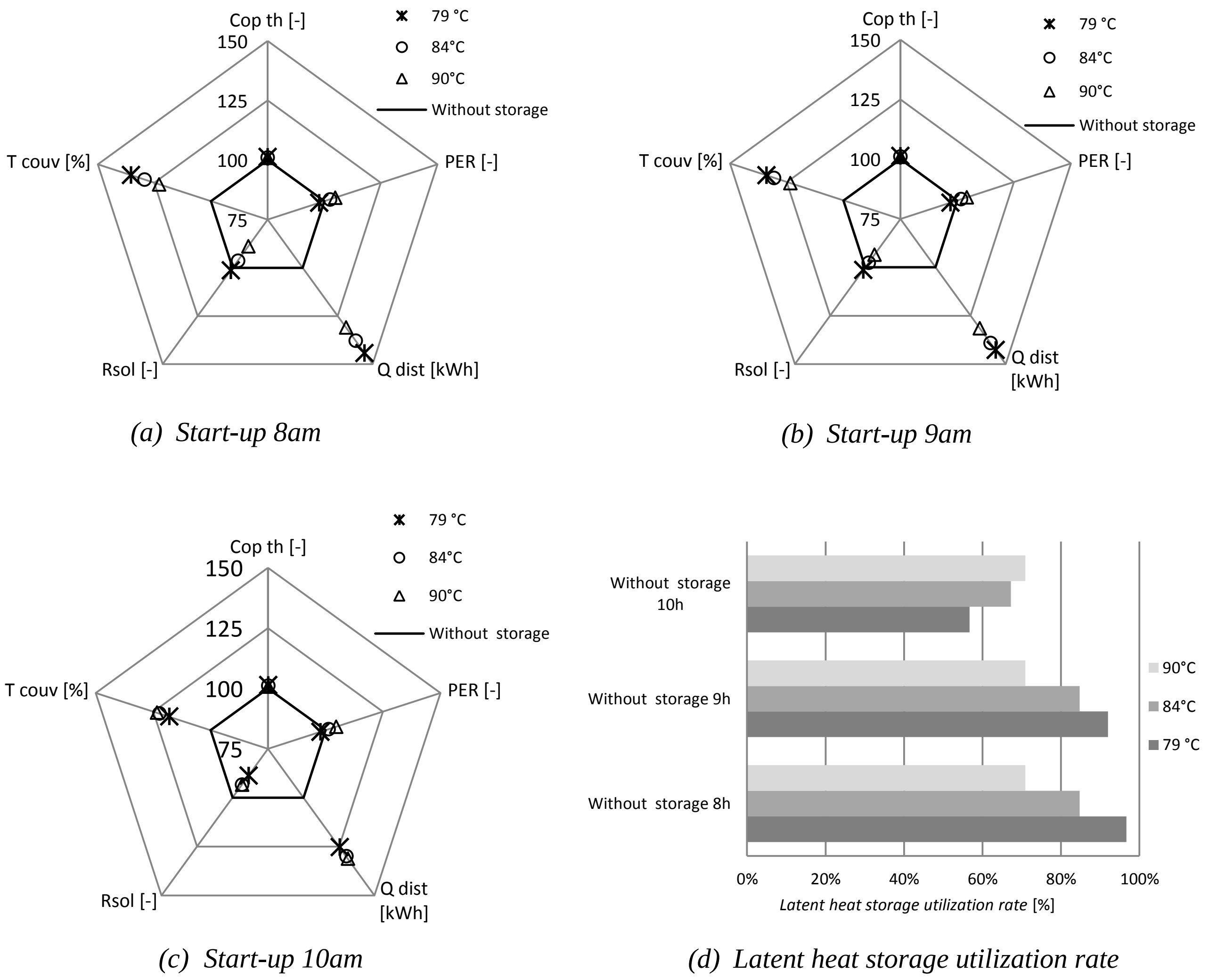
4.2. Energy analysis of a typical week

Figure 6 shows the different performance indicators, defined before, for the three melting temperatures and for three start-up scenarios considered on this study. The results are compared to the performance of the SCS operating without storage, and represented by the "base 100". The first results highlight a strong increase of the coverage rate of the cooling demand and the refrigerating energy distributed for 8am and 9am scenarios, with values between 120% and 135%. It can be noted that it is more interesting to choose a low melting temperature (79°C) to increase these two performance indicators.

Regarding the Primary Energy Ratio (PER), the same behavior is observed for the scenarios 8am, 9am or 10am with increasing values according to the melting temperatures. The maximum value is given for a melting temperature of 90°C.

However, the efficiency of the solar loop (R_{sol}) is inversely proportional to the increase of the melting temperature for 8am and 9 am scenarios. This is due to the fact that when the melting temperature of the PCM increases, the heat losses of the solar loop (pipes, collector field and primary storage) also increase. Regarding the thermal COP of the absorption chiller, it does not vary so much with values ranging from 101 to 102% for all simulations.

Finally the utilization rate of the latent storage (Fig. 6 (d)) highlights the interest to choose the melting temperature of 79°C for start-up scenarios of 8am and 9am. The reverse trend for 10am scenario shows the good coverage rate of the existing SCS during the time slot 10am-5pm since the solar loop can feed the generator of the chiller above 75°C.



(a) Start-up 8am

(b) Start-up 9am

(c) Start-up 10am

(d) Latent heat storage utilization rate

Fig. 6. Performance indicators (a,b,c) and latent heat storage utilization rate (d).

5. Conclusion and prospects

This work studied the integration of a latent storage system into an absorption solar cooling system coupled with a teaching building. Simulation results have been compared with the existing solar cooling system thanks to different performance indicators (COP_{th}, PER, R_{sol}, Q_{dist}, τ_{cov}). Through the study carried out on three melting temperatures (79°C, 84°C and 90°C), it can be noted that the most interesting melting temperature, to improve the coverage rate, the thermal COP, the efficiency of the solar loop and the utilization rate of the latent storage is 79°C. However the most important improvement of the Primary Energy Ratio (PER) is given by a melting temperature of 90°C.

The first results presented in this paper can improve knowledge about the influence of adding a latent storage on an absorption solar cooling system coupled with a teaching building. The results show that an agreement must be find to take into account both the global performances of the system and the service provided to users i.e. the thermal comfort condition inside the building.

Nomenclature

Symbols	
C_p	Specific heat capacity , $J.kg^{-1}.K^{-1}$
dt	Time step, s
K	Heat loss coefficient, $W.K^{-1}.m^{-2}$
L_f	Latent heat of the PCM, $J. kg^{-1}$
$\dot{m}$	Mass flow rate, $kg.s^{-1}$
$\dot{Q}$	Heat flux, W
Q	Thermal energy, J
S	Area of hot primary storage, m^2
T	Temperature, K
U	Internal energy, J
W	Electric energy, J
$\Delta\Delta T$	Characteristic temperature difference, K
$\Delta\Delta T_{min}$	Minimum temperature difference, K

Performance Indicators

COP_{th}	Thermal Coefficient Of Performance
PER	Primary Energy Ratio
R_{sol}	Solar loop efficiency
τ_{cov}	Coverage rate

Subscripts and Superscripts	
abs	Absorber
capt	Solar collector
cond	Condenser
dist	Distribution
elec-prod	Electric-production
ext	Exterior
evap	Evaporator
fusion	Fusion
gen	Generator
mcp	Phase change material
P1, P2	Range 1 and 2
sol	Solar loop
required	Required
stock 1	Hot heat storage
stock 2	Latent storage

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