Prototype of Integrated Collector Storage (ICS) Using Phase Changes Material and Thermosyphon Heat Pipes

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Abstract

Conventional thermal solar systems consist of roof-mounted collectors, a storage tank inside the building and various elements that ensure the operation of the system (controller, pump, etc.). This ultimately leads to relatively complex systems, leading to major disadvantages such as a relatively high cost, storage volume footprint and maintenance. The development of "passive" solar systems is therefore a strategy to be favored. It is in this context that we have studied numerically and experimentally a new concept of integral collector storage with phase change materials and heat pipes.

A prototype was tested in outside conditions at INES. Thermosiphon heat pipes work very well by transferring the absorbed solar energy to the storage located at the back of the absorber, and by acting as a thermal diode. Concerning storage, a small difference in temperature is observed between the 2 faces of the cavity containing the phase change material, which shows the efficiency of the honeycomb to transfer the heat. In terms of performance, the prototype is very well placed for its productivity. However, storage is largely discharged at night. This implies a low annual solar fraction. The metallic fixation which maintains the cavity is largely responsible for these losses. It is therefore sufficient to limit the thermal bridges to greatly improve the solar fraction.

Keywords: Type your keywords here, separated by commas,

1. Introduction

1.1. Context and Issues

Market development of solar thermal systems in France is penalized by the cost of investment compared to other solutions that use fossil fuels or electricity. Moreover, today's solar solutions are more adapted to the new than the renovation (additional space required for storage) that is the major energy issues in the building sector. The research activities should encourage the development of innovative solutions integrating these two issues. The integrated collector storage (ICS) are very interesting because they allow financial savings compared to a conventional solar thermal system: fewer components, simplicity, passive operation, possibility of industrialization "all in one" and setting work faster (Sadhishkumar and Balusamy, 2014). The first ICS exist since the end of 19th century (Smyth and Al, 2006). Currently, about ten companies propose ICS of various geometries and using water as a storage medium (http://www.sunwindenergy.com/ 1+2/2013). The ICS are suitable both for new buildings and at an energy renovation (Timilsina and Al, 2012). They avoid putting storage in a room, which is generally disadvantageous for reasons of space available in existing system and of cost of square meters in the new. The ICS are thus promising systems for the development of the solar thermal market. However, the main drawback of such systems is related to high thermal losses knowing that the storage is generally poorly isolated to the outside. Consequently, the ICS are rather used in soft climates of Mediterranean type.

The work suggested in this article presents a new prototype of integrated collector storage using phase-change materials (PCM), and thermosyphon heat pipes to transfer solar energy from a plane collector to storage. The use of PCM allows to reduce the thickness of the storage cavity as compared to water. Architectural integration is thus greatly improved knowing that it is about major problems for most currently available ICS. Through the use of PCM, storage presents no problem with the gel. A coil type heat exchanger finally allows to draw the energy contained in the ICS. The prototype is fully instrumented with flow rate, temperature and weather condition measurements. Tests are realized under real outdoor conditions.

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2. Experimental setup

2.1. Proposal for a new ICS concept

We have designed a new generation of ICS from very difficult specifications to satisfy: high energy performance in a cold climate, considering the risks of frost, simplicity of operation, quality architectural integration (low thickness), great reliability and cost comparable to conventional systems. This is the challenge of this project, which aims to demonstrate the feasibility of the new concept of ICS thanks to the experimental study carried out on a prototype. The originality of the concept is based on the use of heat pipes for the solar circuit and phase change materials (PCM) contained within an aluminum honeycomb structure for storage (figure 1).

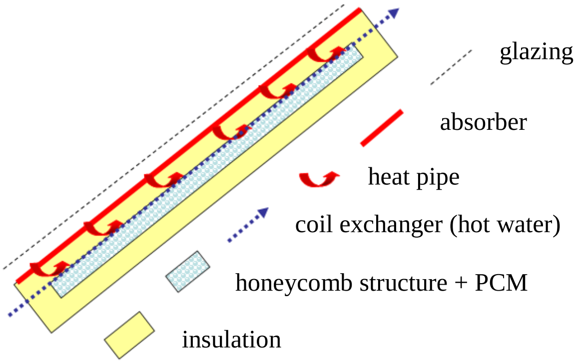

Fig. 1: Schematic of a new concept of ICS with PCM and heat pipes

We have thus developed the new concept of ICS around three points:

- Use of thermosiphon heat pipes: thermal diode operation possible, high thermal transfers and no risk of frost in the heat transfer between the sensor and the storage.

- Complete insulation of the storage volume to achieve energy performance comparable to conventional systems with hot water tank. This is very rarely the case for self-storage sensors.

- The PCM combined with an aluminum honeycomb structure seems well suited for storage in a self-storage sensor: low thickness (architectural integration), no problem with frost for the PCM (phase change), excellent characteristics of the honeycomb structure both in terms of heat transfer (compensation of the low thermal conductivity of the PCM by a large exchange surface) and mechanical strength (specific to the geometry of the honeycomb).

Concerning freezing, roof integration must be designed so that the cold-water supply to the rear is in an isolated volume. If this is not the case, an anti-freeze fluid and an exchanger must be used. This may be relevant in the case of a collective installation (limited cost). Finally, heat recovery is not provided within the self-storage sensor in the ADEME project. We considered it simply downstream of the auto-storing sensor.

We did not identify in the bibliography a ICS combining the use of heat pipes, the presence of a completely isolated storage and the use of a nida / PCM storage cavity. This is the originality of this ADEME project.

2.1. Principle of operation

The operating principle of the new ICS concept using heat pipes and PCM in a honeycomb structure (figure 2) is described in this section. Our solution is based on a conventional flat-plate collector. It has on the upper face a glazing beneath which is placed an absorber which converts the incident solar rays into heat. In our case, the solar loop is replaced by thermosiphon heat pipes which transfer the heat directly from the absorber to the storage (exchange n° 1 in figure 3). The heat pipes are in direct contact with the absorber on its rear face. This is called the "evaporator" part of the heat pipes. The heat pipes (six on the height of the prototype) are elements that conduct heat by using the phenomenon of phase change as soon as a temperature difference is observed between the evaporator and the other end designated "condenser" which is in contact with the cavity. The heat pipes are in fact hermetic copper tubes containing a fluid (methanol in our case) filled to about 30%. Methanol vaporizes due to an energy input from the absorber. The steam goes up along the heat pipes to reach the level of the storage cavity. This is the condensation zone: the vapor of the fluid contained in the heat pipes condenses because the temperature in the storage is lower than that of the steam. The fluid releases the latent heat by condensing and then transmits it to the storage (exchange n ° 2). The designation "heat pipes" in this study corresponds in fact to thermosiphons since the flow of the liquid phase is by gravity. The heat pipes used have a very particular geometrical configuration since the slope is rather small: the inclination is not directly in the direction of the height of the sensor but over its length since the cavity is at the rear of the absorber, as in Fig. 4.

About phase change material, we used polyethylene glycol (PEG). The PEG6000 is placed in the cells of the honeycomb (figure 2). Each of the cells are filled with 75% in our case. A filling level of less than 100% is necessary because of the mechanical stresses associated with the volume change accompanying the phase change (during the fusion, the volume of PCM increases). The honeycomb is closed on both sides by aluminum plates. The assembly system by bonding makes it possible to hope for the sealing of each cell containing the PCM.

Fig. 2: Honeycomb filled with PCM

A water circuit (copper coil) is also present on the upper surface of the cavity where the condenser part of the heat pipe is located. Cold water from the water supply is injected during the withdrawals linked to the needs of the users. This water circulates in the coil exchanger which is pinned around the heat pipes on the upper aluminum plate of the cavity. PCM in a liquid state releases the latent heat and solidifies when there is a transfer between the PCM and the pulsed water (exchange No. 3). The melting / crystallization temperature of the PCM is chosen close to the set point (about 55 °C.). The water circuit placed on the front of the storage with the heat pipes is an advantage which allow a direct transfer of thermal energy from the heat pipe. This is exchange 4.

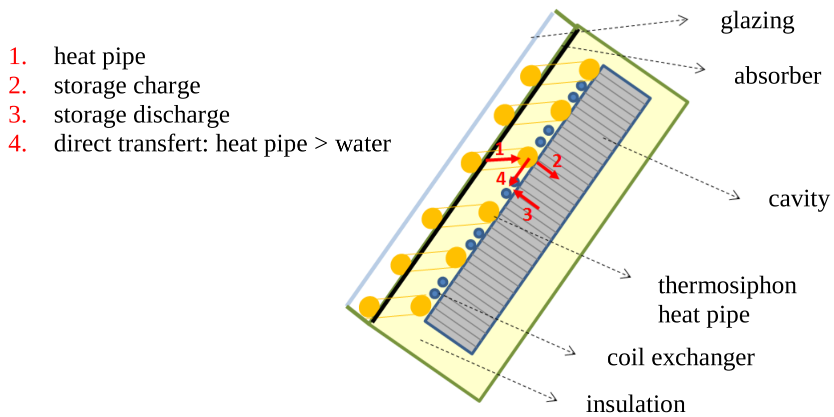

Fig. 3: Operating principle of the new concept of ICS

The table 1 shows all the characteristics of one module. For a complete installation, several modules will be required. The amount of module required will be sized according to the needs.

Tab. 1: Characteristics for each prototype module

Data for each prototype module
Surface d'ouverture : 1m x 0,5m
Storage cavity : aluminium, filled with 75% of PCM
Storage cavity size : 1m x 0,5m x 0,04m
Insulation of the cavity : 10 cm roch wool, λ: 0,04 W/(m.K)
Area of a honeycomb cell: 0,74 cm² (aluminium)
PCM : Polyethylen glycol (PEG 6000), latent heat of fusion: 192 kJ/kg ; Tfusion : 58,5°C ; 1 210 kg/m3 ; λ: 0,2 W/m.K ; volum in the cavity : 0,015 m3
Heat pipes : 6 made of copper, filled with 30% of methanol
Glazing : 4mm thick, Dim. 1006*605 mm, absorption coefficient 0,07, solar factor : 87%
Absorber : copper, λ : 380W/(m.K), 0,2mm thick
Water coil exchanger : cuivre, 12m long (diam int : 6mm, diam ext: 8mm)
ICS inclination : 30°

Photos of the prototype installed on the test platform are presented on figure 4.

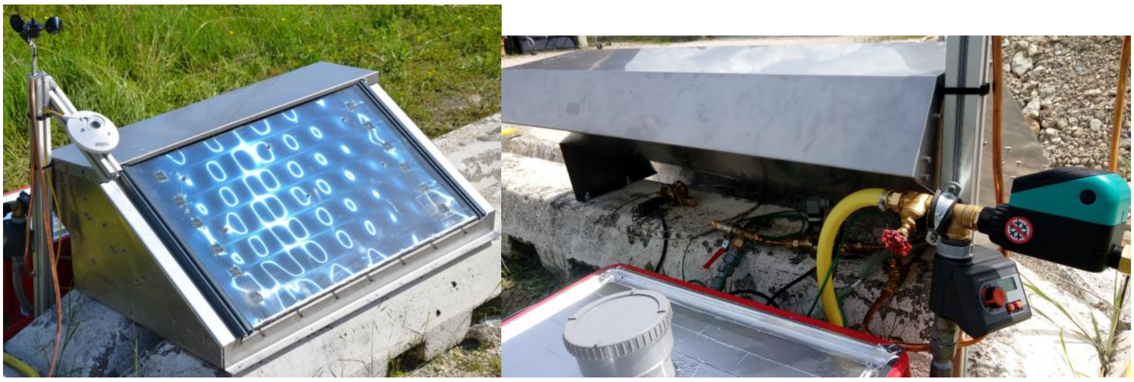

Fig. 4: Front and back view of the prototype

2.3. Instrumentation of the prototype

The prototype is fully instrumented with flow rate measurements at the inlet and outlet of the coil exchanger. Weather conditions are recorded, included global solar irradiance within the ICS plane, and the temperature at back of the system. Temperatures are measured with 35 thermocouples on the absorber, on the cavity and on either side of the insulation. These thermocouples have previously been calibrated by performing cold junction compensation. The measurement accuracy of the thermocouples thus obtained is 0.1°C. All data is recorded with an Agilent 34972A acquisition unit. These measurements allow to characterize the system.

2.2. Withdrals

Water withdrawals are made to discharge the storage of the sensor. The withdrawal flow is regulated by a valve placed upstream of the ICS and is measured by a flow meter. The programming of the withdrawal scenarios is made possible by a solenoid valve which opens at specific times and for fixed periods of time. The energy withdrawn by the water is determined by measuring the flow rate and the temperature at the inlet and the outlet of the water exchanger.

3. Experimental results

Experiments were carried out at the INES (National Institute for Solar Energy). Different withdrawals scenarios are carried out to allow the study of the charge of the discharge as well as stagnation temperature tests at the hottest of summer.

3.1. Study of the charge

The programmed withdrawal to study the charge is the following: a flow rate of 9.3L / min for 19min every morning at 6h, which represents approximately 177 liters of water per day evacuated in a single withdrawal. This choice was made to unload as much storage as possible at the beginning of each day to concentrate initially on the storage phase. This also made it possible to start each day with a maximum unloaded cavity. The first study week (May 24 to 19, 2017) revealed the following results (figure 5).

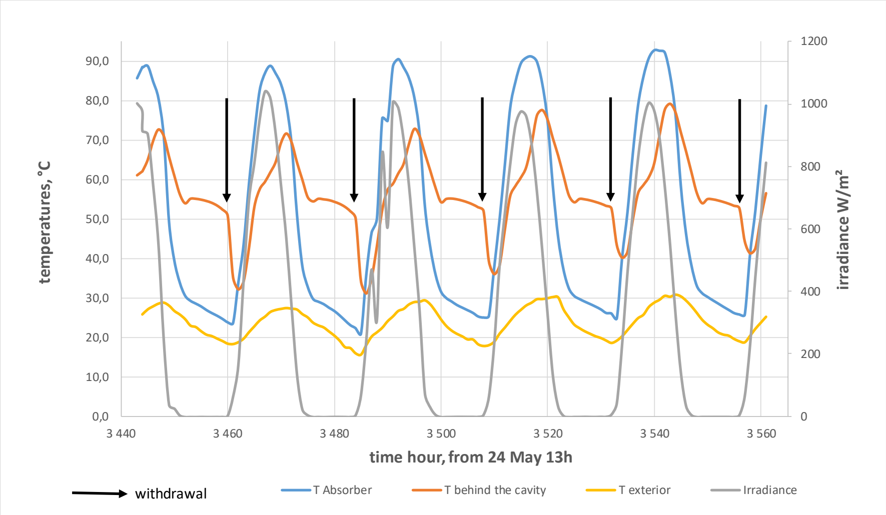

Fig. 5: Experimental results from 24 to 29 may 2017 (arrows indicate a withdrawal)

During these summer days, the irradiance reaches maximum values close to 1000 W/m² in the plane of the absorber (inclination 30°). The absorber temperatures reach 90 to 95°C in the middle of the day and follow the irradiance curve quite well. About storage (measured at the rear of the cavity), its temperature increases over the day, reaching a maximum of 70°C to 90°C in the middle of the afternoon. It is observed that the rise in temperature of the storage is rather fast in the solid phase (sensible heat). The phase change then limits this rise. The temperature change is again faster in the liquid phase (sensible heat) when the whole MCP is melted. The maximum temperature observed is approximately 90°C. Limiting the maximum temperature reduces the risk of degradation of the cavity. A plateau appears on the storage temperature every day around 9 pm for several hours because of the phase change (around 55°C) because of the crystallization of the PCM. The thermal losses of the cavity cause this phase change to be rather slow and create a long "plateau" on the temperature curve. The melting stage is much faster due to the higher solar contributions. We will again discuss the heat loss afterwards, knowing that they seem already quite important because the PCM goes down in temperature up to the level of crystallization during each night. It should be noted that this temperature profile is linked to our withdrawal profile: it would be radically different with a withdrawal in the day for example. A slight phenomenon of supercooling also appears at the end of each day. This phenomenon is related to the fact that the temperature of the PCM drops below its solidification temperature while remaining liquid. This is not inconvenient in our case given the large amplitudes of variation of the temperatures. We can also note that the daily withdrawal (indicated by the arrows) causes the temperature of the storage to drop to about 35°C before rising due to the solar contributions the following day.

This first week of study makes it possible to say that the rise in temperature of the PCM on its sensitive part is rather fast. In order to show this, the following comparison was made (from the experimental data collected):

Tab. 2: Temperature rise of PCM and water

	PCM (PEG 6000)	Water: traditional Solar water heater (TRNSYS simulation)
Initial temperature	30°C	30°C
Setpoint temperature	55°C	55°C
Temperature rise	8.3°C/h	6.2°C/h

This comparison shows the rapid rise in temperature with PCM compared to water. This phenomenon therefore implies, for an installation in operation, a reduced use of the make-up because the PCM reaches the desired setpoint more quickly. This is a particularly interesting point in terms of energy efficiency.

If the temperature of the absorber is analyzed with the outside temperatures, it is realized that for the night the absorber temperature drops very rapidly and reaches a difference of lower than 10 ° C between the absorber and the exterior (the absorber is protected from the outside by the glazing). The heat pipes thus appear to play their role as thermal diodes. Otherwise, the absorber would have a higher temperature.

A second withdrawal was scheduled for a few weeks. The flow rate was decreased from 9 to 3.3L / min for 1 hour at 3am. The total quantity of water discharged remains approximately the same, i.e. approximately 180 liters of water drawn off daily. A lower flow rate was chosen to analyze more finely the evolution of the water temperatures at the inlet and outlet of the sensor. The acquisition step has also been refined (from 1 minute to 3 seconds). The withdrawal was shifted from 6 to 3am in the morning because it coincids with the beginning of the next day's sunlight.

This second scenario allowed us to follow more precisely the evolution of the water temperatures at the inlet and the outlet of the sensor (figure 6).

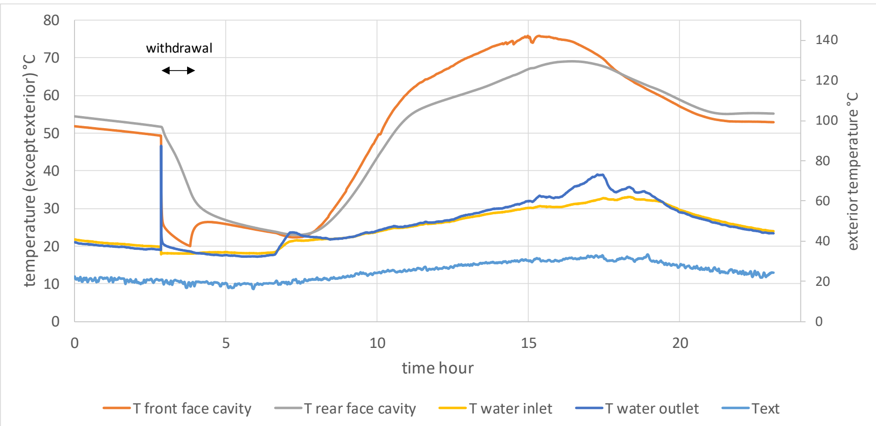

Fig. 6: Evolution of the temperature at the front and rear faces of the cavity, the exterior temperature and the water temperatures at the inlet and outlet, 5 July 2017

By considering a lower flow rate and a finer acquisition step, it is possible to observe more precisely the temperature changes during the withdrawal. Regarding the temperatures on either side of the cavity, their evolutions are similar to what was previously studied.

For water temperatures, it should first be stressed that only the withdrawal periods are meaningful because, without drawing off, the thermocouples measure stagnant water temperatures in the pipes. At the time of the withdrawal, the water in the pipes having been previously renewed, the inlet has a temperature close to 18°C. The outlet temperature rises rapidly to the temperature Tpe (front face of the cavity) which is close to 50°C (figure 6). This temperature decreases to about 25°C. very rapidly after the withdrawal. This hot water is actually stagnant water in the sensor that has been evacuated. The fact of not having water at 50°C for a sufficient time is mainly linked to the high value of the withdrawal flow rate compared to a conventional withdrawal. Moreover, the analysis of the losses during the night rises that the destocking is quite important. This is also due to the temperature of the front face of the cavity: before the withdrawal, it is at 48°C. The PCM has therefore resolidified (at least partly) because of the losses.

3.2. Case without withdrawal

The summer temperature made it possible to carry out a stagnation test on the prototype by not performing any withdrawal. The period concerned was from 13 July to 24 August. The interest is to subject the prototype to high heat and then check that it has not been damaged. During this summer period, outdoor temperatures reach up to 37°C for the hottest days and irradiance exceeds 1000W / m² in the middle of the day for almost all the study days (figure 7).

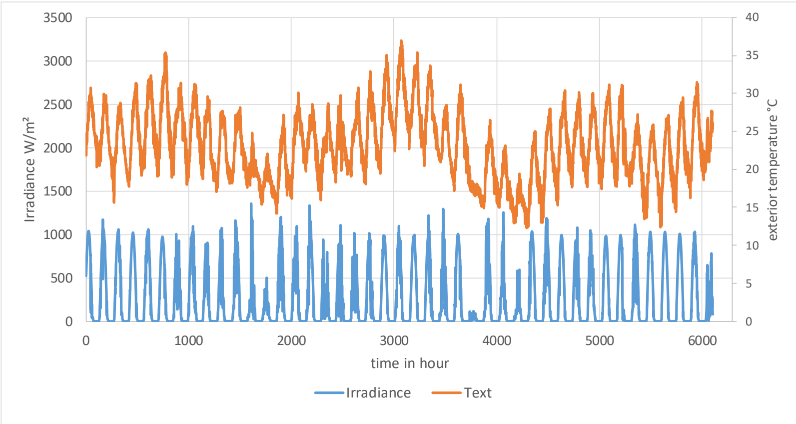

Fig. 7: Irradiance and exterior temperature from 13 July to 24 August

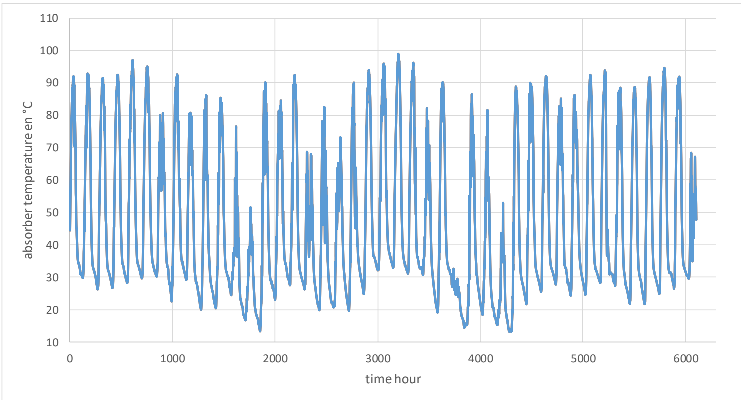

Fig. 8: Absorber temperature without withdrawal, from 13 July to 24 August

When the absorber temperatures are analyzed (figure 8), it can be seen that the absorber does not exceed 100°C. on any day and remains within the range of values observed with a withdrawal.

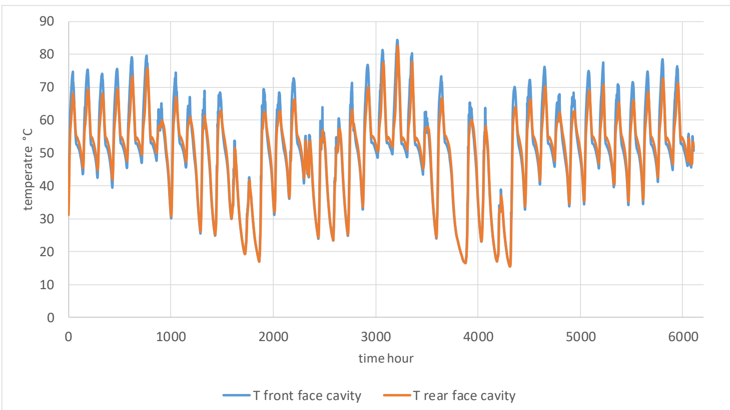

Fig. 9: Temperatures of the front and rear faces of the cavity, from 13 July to 24 August, period without withdrawal

The cavity temperature reaches a maximum of 80°C (figure 9), i.e. slightly higher levels than with a daily withdrawal. Moreover, temperatures generally do not fall as low as with a withdrawal: they are maintained between 30 and 40 ° C (or even more for warm nights) against an average of 20°C with a water withdrawal.

The results obtained in that stagnation test show that, on the one hand, the maximum temperatures reached by the absorber and the cavity remain within acceptable values: there is no rise in temperature which can damage the system. So from a reliability point of view, this is rather reassuring. On the other hand, the fact of not having higher temperature rises in this configuration shows that the sensor exhibits too high thermal losses. With an optimized prototype reducing the thermal losses of the storage, we evaluated, using a numerical model, a maximum temperature between 130°C and 140°C.

3.3. Study of the discharge

This last phase of the test was aimed at studying the phenomenon of discharge of the storage with a realistic flow. A lower withdrawal rate was selected: 0.87 L / min for 30 minutes at 17h. The withdrawal scenario was shifted at the end of the day to estimate the energy recovered by the withdrawal before the night losses partially discharge the cavity. The figure 11a represents the withdrawal at 17:00 for the day of 22 September. The same day, at 12h, flow adjustments were carried out on the experiment, resulting a short withdrawal, hence the first peak on the outlet temperature. The small temperature difference between the 2 faces of the cavity can be observed throughout the day (less than 10°C.). The thermal transfer by the honeycomb is therefore done correctly. The upper surface is logically warmer during the day (sunspot) and colder at night due to the larger losses on the front which is more exposed to the outside environment.

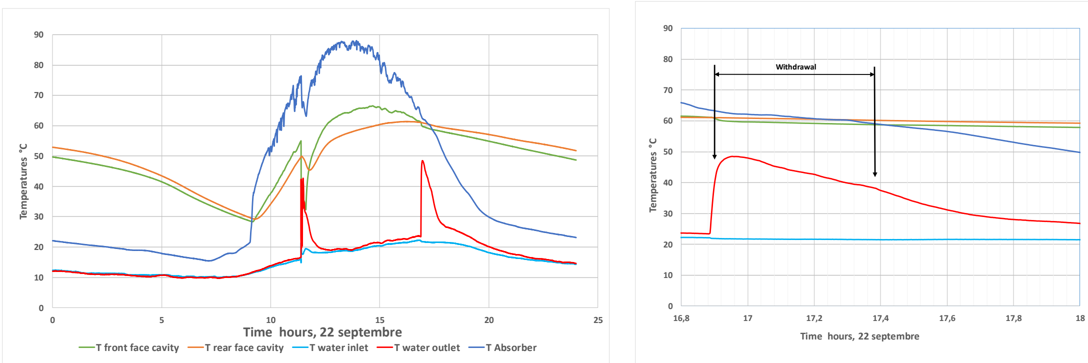

Fig. 10 : Evolution of the temperature on the front and rear faces of the cavity, on the absorber and the water temperatures at the inlet and outlet, 22 September 2017

The temperature of the absorber does not seem to be influence by the withdrawal at 17h, whereas the first at noon is accompanied by a decrease of its temperature and the cavity temperature. An explanation is that in the morning, the storage was not sufficiently charged (mainly sensitive part). Thus, when water has been drawn off, mainly the sensible heat has been removed, causing a drop in temperature. At 17h, the stored energy being mainly in latent form, the withdrawal allowed to partially discharge the cavity without causing a drop in temperature on the elements of the front face of the cavity.

If we look more specifically at the second withdrawal (figure 10b), the evolution of the temperatures allow to calculate the power extracted during the drawing (figure 11). It is about 1.6 kW for 0.5m² of sensor (ie 3.2 kW / m²), which is almost half of what was envisaged in the best case (6 kW / m²). Although the flow rate is slightly lower than expected (0.87 l / min instead of 1 l / min), it is likely that the contact between the coil and the top plate of the cavity should be improved. This explains why the outlet temperature does not reach the temperature of the cavity. Nevertheless, the outlet temperature is maintained at a level above 40°C during the withdrawal period (30 minutes), which is quite suitable.

The maximum outlet temperature is 48.7°C (61°C in the cavity at the same time), 43.5°C after 15 minutes and 40.0°C after 30 minutes. The discharge of the storage is therefore done correctly. The temperature in the cavity decrease only by 1°C.

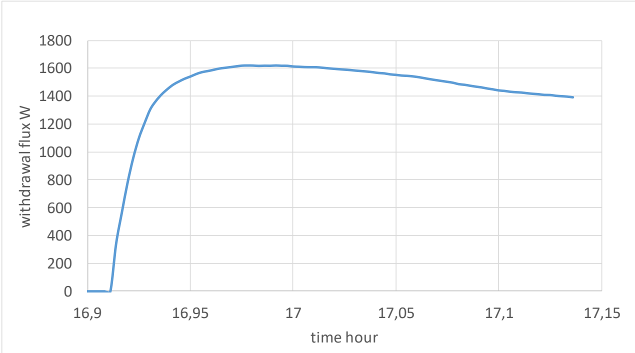

Fig. 11: Puissance récupérée grâce au soutirage d'eau le 22 septembre

4. Conclusion

This study focused on an innovative integrated collector storage concept which couples heat pipes to an MCP storage in a honeycomb. It appears that the rise in temperature of such a storage is much faster than with conventional water storage: 8.3°C/h (experimental) versus 6.2°C/h for a conventional CESI of 300L. In addition, the volume gain from this technology is important (counting at least a factor of 1.65). However, the implementation of the heat pipes proves to be quite complex. The phenomenon of thermosiphon requires to place the condenser above the evaporator.

A prototype was tested in real conditions at the INES. The concept has thus been validated experimentally. It appears that the prototype showed no signs of malfunction (leakage of MCP ...). It is charged correctly every day, the temperature levels reached by the cavity are satisfactory for the durability of the system (including without withdrawal). The solar energy is well transmitted to the storage: the heat pipes play their role well as expected. The thermal diode effect (of the thermosiphons) is also validated. A small temperature difference is observed between the 2 faces of the cavity, which shows the efficiency of the honeycomb structure to transfer the heat.

In terms of performance, it appears that the prototype is relatively well placed in terms of its productivity compared to a traditional individual solar water heater. However, storage is largely discharged at night, which explains why there is no rise in temperature during non-withdrawal periods (experimentally tested). The complete crystallization of the MCP shows that losses are almost equivalent to storage. The losses represent an average power of the order of 100W/m² permanently. This implies a fairly low solar coverage over the year. It is clear that the U-shaped profiles and the metallic fasteners which hold the cavity strongly accentuate the losses of the cavity. All this is not really worrying knowing that these problems of thermal bridges can easily be solved.

If one considers a more efficient version of the ICS, the maximum temperatures reached by the cavity could be between 130°C and 140°C. If it is desired to limit this maximum to a hundred degrees, the ICS must not have an excessive transmission coefficient of glazing and / or an absorber with low emissivity coating.

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