Open Journal of Energy Efficiency, 2016, 5, 19-29

http://dx.doi.org/10.4236/ojee.2016.51003

Designing an Automatic Control System for the Improved Functioning of a Solar Wall with Phase Change Material (PCM)

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Received 10 January 2016; accepted 27 March 2016; published 30 March 2016

Abstract

Solar walls constitute an important green architectural feature that positively contributes to energy saving in buildings. Different configurations may be proposed, such as, solar wall with Phase Change Material (PCM), composite solar wall, photovoltaic solar wall, zigzag solar wall, and solar hybrid wall. Being environmentally friendly, these passive solar components can provide thermal comfort and help save energy. Their disadvantages include principally unpredictable heat transfer, heat losses by night for some systems or inverse thermo-siphon phenomenon. Appropriate energy management techniques can be used to control and optimize the performances of solar walls. An experimental study for energy management of a PCM based solar wall is described in this paper. The experimental results show the effectiveness of the proposed automatic control system in regulating the capture of solar energy.

Keywords

Solar Walls, Solar Energy, Energy Storage, Phase Change Material, Energy Management

1. Introduction

Solar Energy, along with the other renewable energy resources, such as wind, hydroelectricity, tidal waves, and geothermal, provides a viable solution for reducing the continuously increasing global energy needs. Solar energy offers a clean, environmental-friendly, and abundant energy resource. The use of solar energy for the

How to cite this paper: Favier, P., Zalewski, L., Lassue, S. and Anwar, S. (2016) Designing an Automatic Control System for the Improved Functioning of a Solar Wall with Phase Change Material (PCM). *Open Journal of Energy Efficiency*, **5**, 19-29. http://dx.doi.org/10.4236/ojee.2016.51003

heating of buildings through passive solar systems and more rarely for the cooling, known as solar walls has been the subject of numerous research studies [1]-[6]. The solar walls offer an effective technique to collect, store and use in a right way, the "free energy" to make buildings comfortable with very low environmental impact. Bojic *et al*. [7] estimated the annual final energy saving during heating at 20% when the building Trombe wall was used. The estimation was done for a French building complying with the French thermal regulation (2012) with Trombe walls located in Lyon, (France) [8]. As described in [9], a salient characteristic of solar walls is their storage capacity. However, a thick and massive wall increases a building's heat load. Generally, every passive solar is built as an experimental set up and it is necessary to find how to do prefabrication of such component to extensively disseminate this technology. S. Lassue [10] proposes to replace the storage device of a solar wall, usually a heavy capacitive material such as concrete, by a phase change material (PCM). For example, phase eutectic salts or salt hydrates may be used as storage device [11]-[13]. Phase change materials (PCM) are latent heat storage materials, so the component is lighter than a classical one with the same storage capacity. Thus, the dynamics of the thermal evolution of solar wall changes as the PCM stores and releases heat at a nearly uniform temperature. For a PCM to be used in the design of a solar storage wall, it must exhibit certain important chemical, thermal and kinetic properties. Included among these properties are suitable phase-change temperatures, high latent heat, no or low supercooling, and long term chemical stability. Onishi [8] had established that use of PCM in solar walls was helpful in reducing energy consumption in buildings.

The experimental studies conducted on solar walls with PCM have shown that different phase-change materials affect the performance of solar walls differently [9]. Some of these studies are discussed in [12] [14], and [15]. An experimental study conducted by Zalewski *et al*. [16] involves the replacement of a concrete storage wall by another one that contains hydrated salt. This project called Prebat Project is supported by the National Research Agency (ANR). It is demonstrated for an equivalent heat capacity (calculated for the same range of temperature: 15˚C - 60˚C) that the use of 2.5 cm thick of hydrated salt contained in a polyolefin brick results in the release of solar gains with a time lag of 2 hours and 40 minutes.

In this paper, an automatic control system design construction and testing is described. The system provides 1) overheating protection to the PCM and 2) improves the efficiency of the energy management of solar wall through an optimal control of solar irradiation. The experimental results obtained through data logging following the integration of this control system in two *in-situ* solar walls are also presented in this paper.

2. Experimental Set-Up

The vertical section of the solar wall used in this experimental study is shown in **Figure 1**. This solar wall is mounted on two Houses A and B located in the village of Croisilles, situated in the Pas-de-Calais (62) region of northern France. **Figure 2** and **Figure 3** show the solar wall mountings for House B and House A, respectively.

In case of long duration of direct solar irradiation, the temperature inside the solar wall can increase and reach a level of more than seventy degrees. Such overheating can induce damage to the PCM. The PCM will become heterogeneous due to a segregation of salts that induce a decrease of the heat capacities. The energy storage

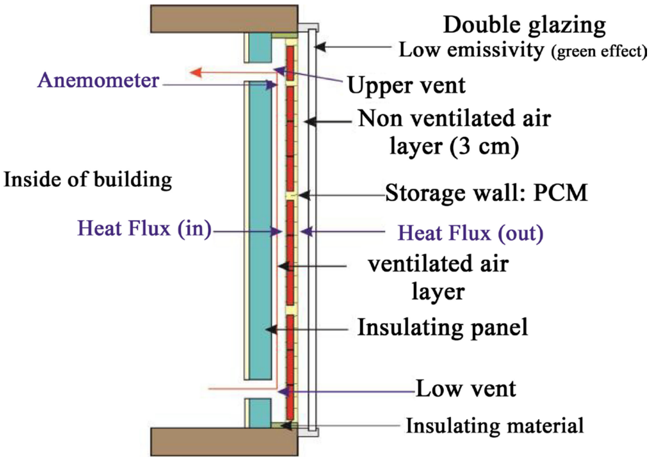

Figure 1. Vertical section of the solar wall with the sensors positions.

Figure 2. Solar wall on the House B.

Figure 3. Solar wall on the House A.

bricks which constitute the wall and contain salts, are made with polyolefin which do not with stand high temperature. To prevent this problem, a protection system is needed to limit or stop the incoming flow of solar energy. This system must operate throughout the year. In winter during sunny days, the incoming sunlight level can be high because of the low elevation of the sun. In summer, the average temperature is higher and the solar irradiation duration is long. Moreover, in summer the house doesn't need to be heated by the wall.

In the set up described in this paper, a rolling shutter was placed in front of the outer glass of the solar wall. **Figure 4** gives the block diagram of the protection system. **Figure 5** depicts hardware of the protection system.

To set up the overheating protection, a safety thermal contact system is installed to close the shutter if the temperature becomes too high.

To increase the efficiency, a programmable time switch has been added to close the shutter during different times. In summer, residential heating is not required, so the shutter is always rolled down from May 15th to October 1st. During the winter season, the shutter is rolled down at night from 5 pm to 9 am to reduce the thermal night losses.

The electrical shutter is automatically controlled from an electronic board on which a PIC 16F877 digital microcontroller is the main processing unit. It receives and processes the data consisting of temperature, time and, switch state. The microcontroller outputs a control signal which is sent to the shutter through a relay. The relay controls the electrical shutter to go up or down as needed.

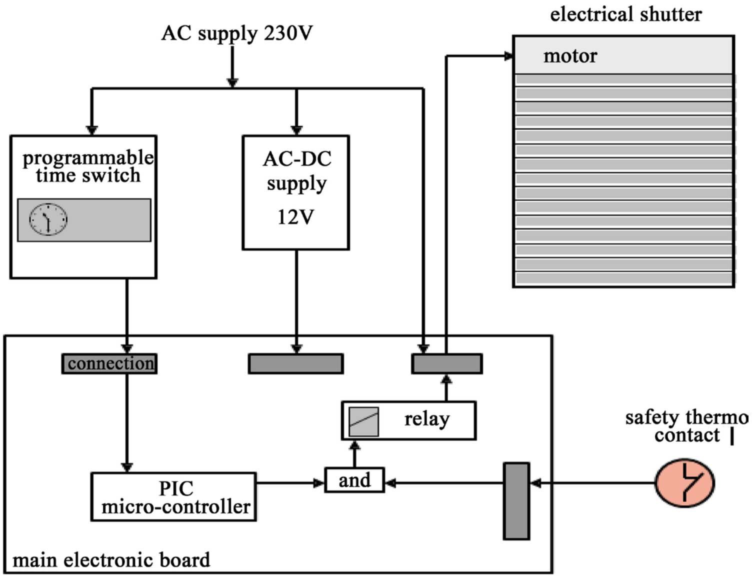

Figure 4. Block diagram of the automatic protection system.

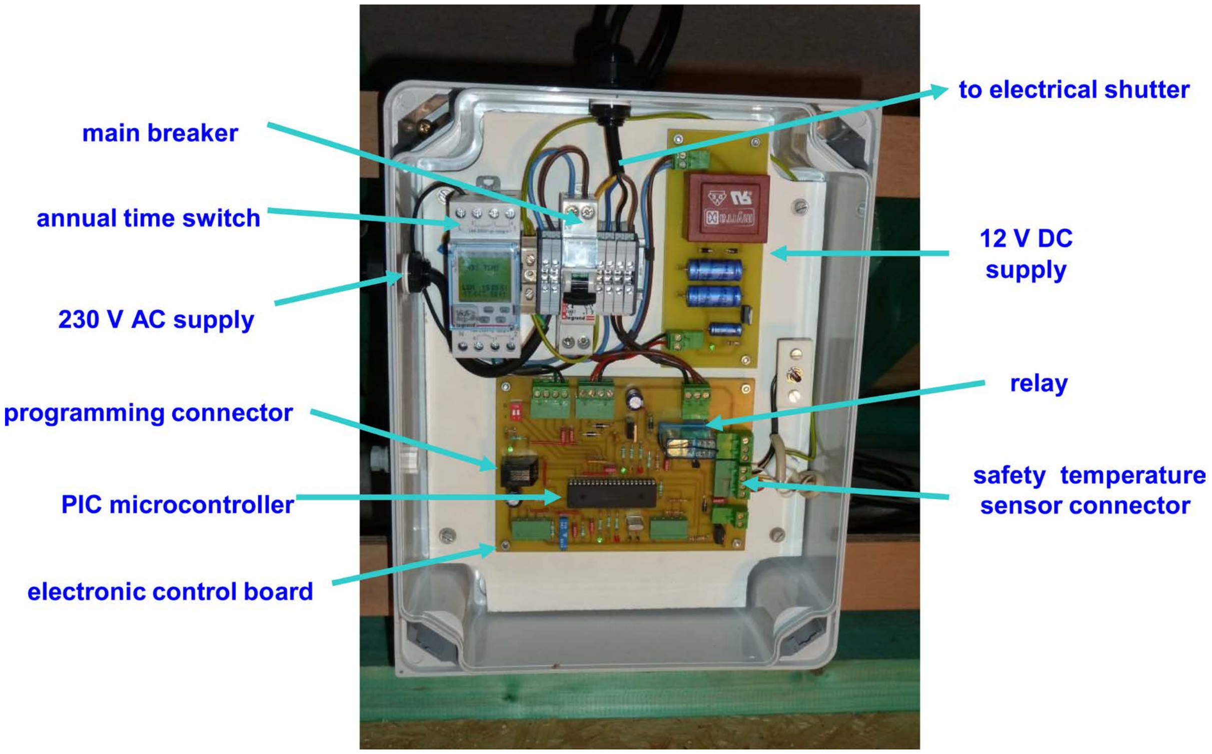

Figure 5. Picture of the electronic control box.

3. The Experimental Results and Discussion

Figure 6 shows the recordings during four very sunny days of January 2012. The mark ① indicates the successive closings down of the shutter when the temperature of the storing bricks reaches 60˚C. When the shutter is closed, the bricks temperature is limited as well as the flux on the outside surface of the bricks.

The mark ② during the night corresponds to the solidification of the PCM. With the fall temperature at 23˚C, the latent heat inside the brick is quickly released to the inside ventilated layer. The natural convection heat transfer is not sufficient to evacuate the latent heat which is released suddenly. It is observed that when the sun is coming again the next day, the bricks are not totally discharged. Thus, the stored thermal energy has not been fully used.

Figure 7 shows recordings during four cold days of February. The average outside temperature is below zero Celcius degree, reaching minus ten degrees during the night between second and third day. The solar irradiation

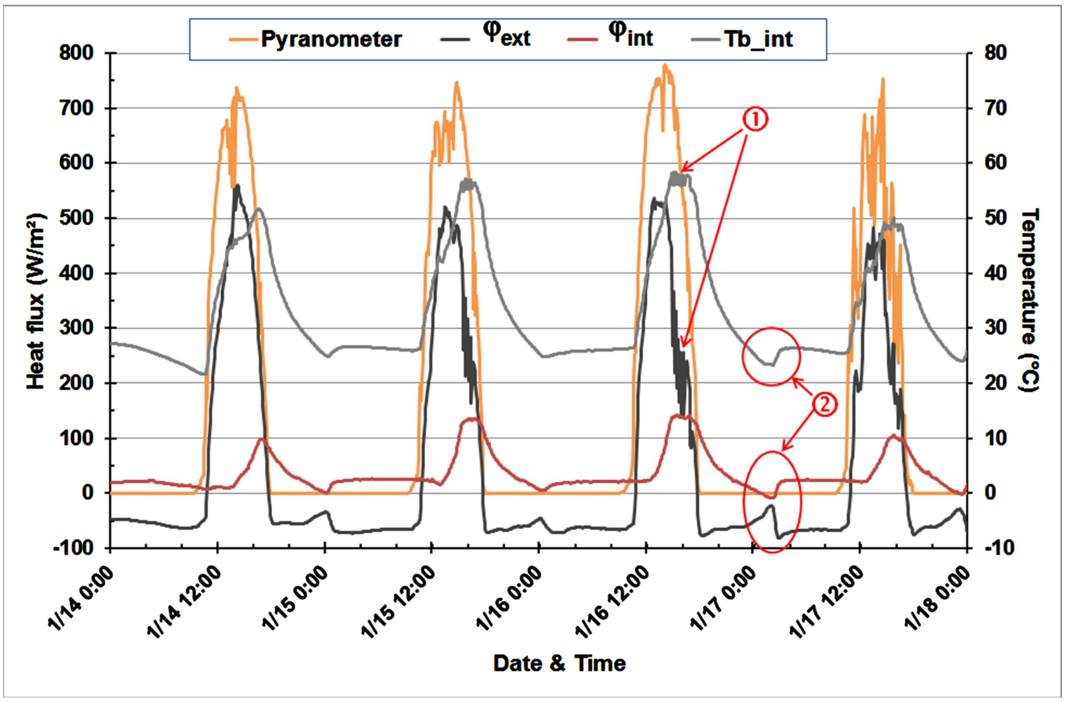

Figure 6. Solar irradiation, temperature and heat fluxes measured on the outside and on the inside surface of the storage wall.

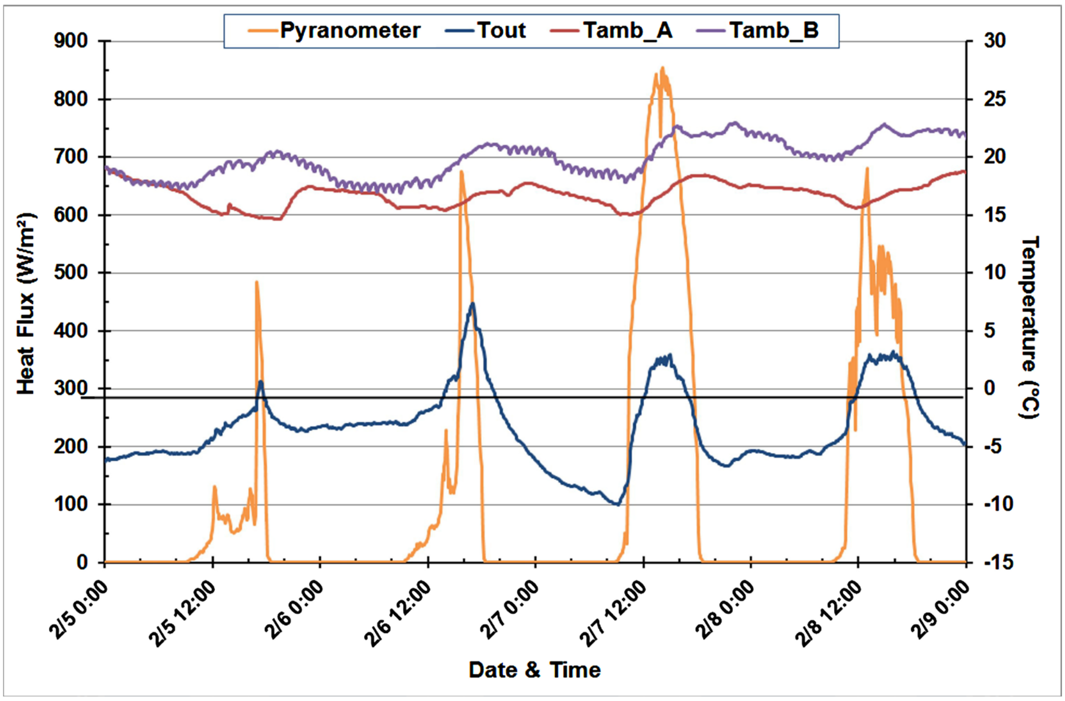

Figure 7. Solar flux, outside temperature and ambient temperature of the housings.

is low during the two first days and increases afterwards. It is noted that the temperature in the House A (red line) is lower than the temperature in the House B (purple line). The increasing curves of the housing temperature during the afternoons show the benefit from the solar irradiation.

Analysis of the solar wall functioning for House A is provided in **Figure 8**. As shown in this figure, the weather is very cold. The outside temperature is always below 7˚C and reaches −10˚C at 8 am on February 7, 2012. The fresh air incoming through the inlet vent is at the housing temperature. The normal flow of the air flux is from the lower vent to the upper vent to heat the housing. So, when the air is heated in the ventilated layer, the temperature of the lower vent air is practically equal to the temperature of the housing to within about the room temperature gradient. On the other hand, when the storage bricks are colder than the housing, the air flux tends to flow layer from the upper vent to the lower vent. But a mechanical system avoids this reverse thermal circulation. The cold air is blocked at the lower vent. At the upper vent, the orifice is always open and the air temperature is also under the influence of the main heating system of the house. In fact, the thermocouple sensor is just behind the fencing, so it measures the air temperature variations.

Figure 9 shows the same recording in House B. The temperature of the upper vent (Tuv B) reaches 38˚C on February 7, 2012 (6:00 PM), although the outside temperature is below 0˚C.

Figure 10 provides a comparison of the thermal behavior of the two solar walls in the context of flux density on the outside and inside surfaces of the storing part. The energy exchange occurred on the inside surface of the storing part. The energy passing through the inside surface is the energy exchanged with the ventilated layer and released to the housing to be heated when the flux is positive. A negative flux should correspond to a reverse exchange from the housing to the storage part with a top to bottom circulation in the ventilated layer. This should have resulted in the cooling effect for the housing. As it has been explained above, this functioning is not possible due to the anti-reverse circulation system.

The shapes of the flux curves are similar. The curves (blue and purple) of the wall of House B are slightly delayed. In fact, the direct solar irradiation is arriving later because of the neighbor's house which hides the sunlight early in the morning and because of the opening time of the shutter.

In **Figure 10**, the numerical integration of the flux values provides the estimation of the stored and released energies. When the flux on the outside surface (green and blue lines) is positive, the wall is storing energy. When this flux is negative, the energy is lost to the outside. For the inside flux (red and purple lines), a positive value indicates energy released to the housing, whereas a negative value corresponds to a loss of energy. The

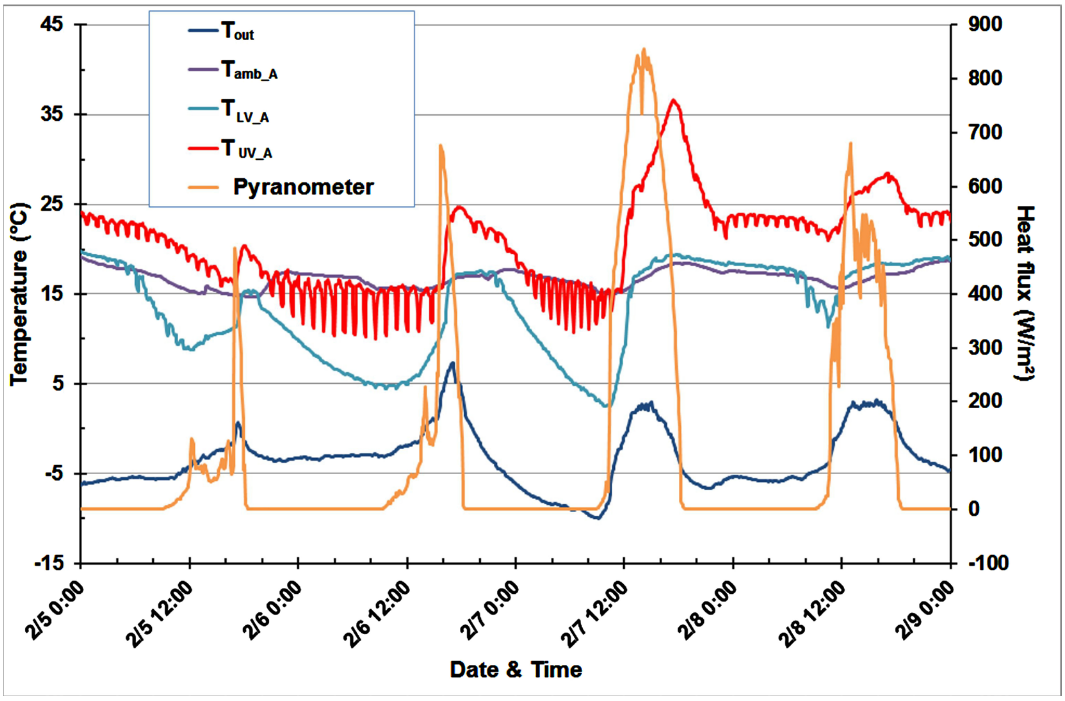

Figure 8. Analysis of the functioning of the wall—House A.

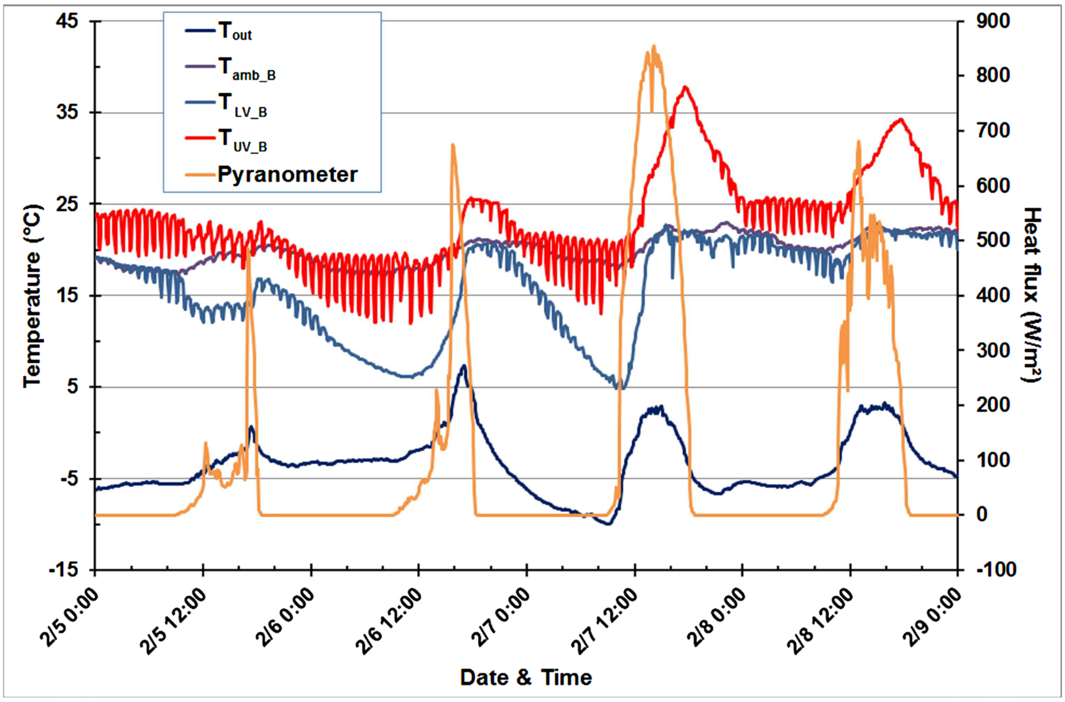

Figure 9. Analysis of the functioning of the wall—House B.

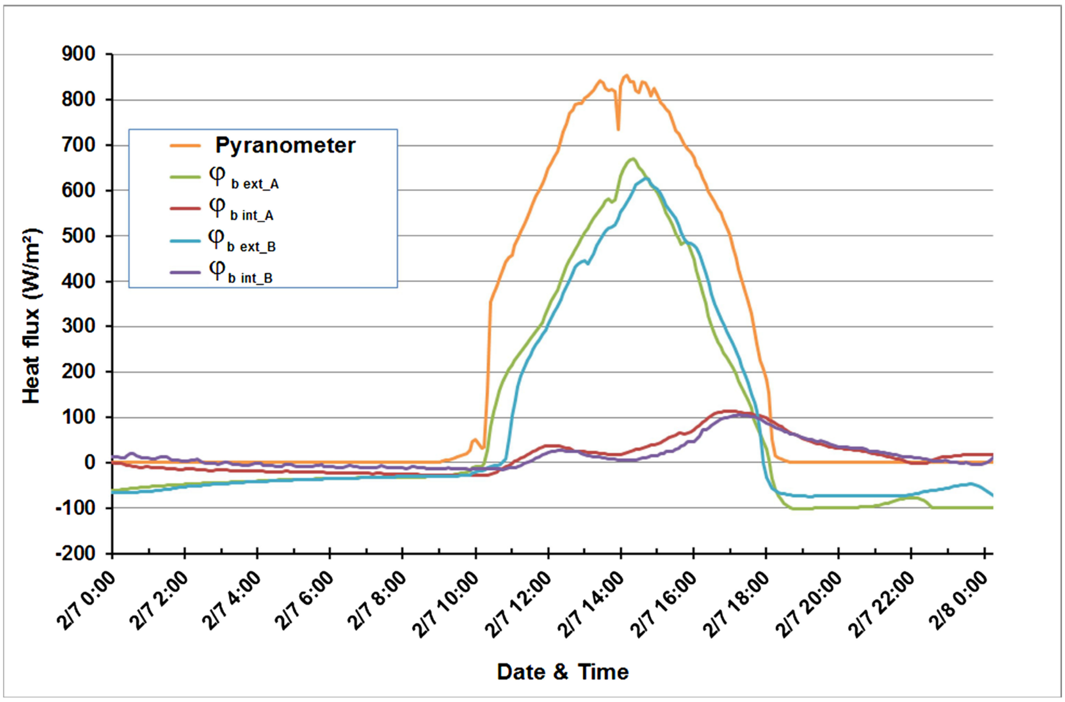

Figure 10. Analysis of the functioning of the two walls on February 7, 2012.

integration of the positive outside flux provides a good value of the energy capture and demonstrates that the wall stores a large quantity of energy. On the other hand, the calculation for the inside flux provides a much lower value. This shows that the efficiency of the solar wall can definitely be improved.

On February 7, 2012, after 6 pm, it is noticed that the outside flux is more significant on the wall of the House A (green line) than on the wall of the House B (blue line). The flux value on the wall of House A equals −100

W/m² compared to −75 W/m² on the wall of the House B which is protected by the closed shutter during the night. So it is concluded that the shutter reduce the losses when it is closed during the night.

In March 2012, the shutter position was recorded. A contact of the relay controlling the shutter was connected to the data logger. On the following two figures, the grey line on the bottom shows the shutter positions. Lower level (0) indicates that the shutter is closed. Upper level (1) indicates that the shutter is rolled up. Observations were recorded on March 22, 2012. During the night, the shutter was closed. At 9 am, the programmable time switch controlled the opening of the shutter. It was a very sunny day. The solar irradiation in **Figure 11** is greater than 500 W/m² during six hours from 10 am to 4 pm. The bricks are quickly storing energy due to the incoming thermal flux, indicated by blue line.

Figure 12 shows the solar wall operation onwards from 10 am. The upper vent temperature increases up to 35˚C, indicated by yellow line. The housing temperature red line and the lower vent temperature blue line increase too.

On the purple line, it is noted that the bricks temperature increases to reach the threshold temperature of 52˚C at 1 pm. This excessive temperature changes the safety thermal switch which shuts off the relay and the shutter rolls down and closes the wall to the sunlight. The incoming flux is turned off and the rise of the bricks temperature is stopped. This effect validates the protection against overheating of the inside components, in particularly, the bricks' material.

During afternoon, a special functioning of the complete solar system is in effect. The inside temperature decreases, the safety switch returns to its normal state, and the shutter rolls up and opens the solar wall to the sunlight. So a new cycle starts again. The shutter motion is noted on the curves in **Figure 11** and **Figure 12**. From 1 pm until half past 5 pm, there are almost 14 cycles with way up and way down of the shutter.

In **Figure 12**, the purple line corresponding to the temperature of the storage bricks depicts the active control of the incoming energy. The temperature is regulated around 52˚C. This reference can be changed by the thermal contact adjustment.

During this afternoon, the bricks are fully charged and the solar system continues heating the housing. The upper vent temperature reaches 40˚C and at 3 pm the housing temperature increases to 26˚C.

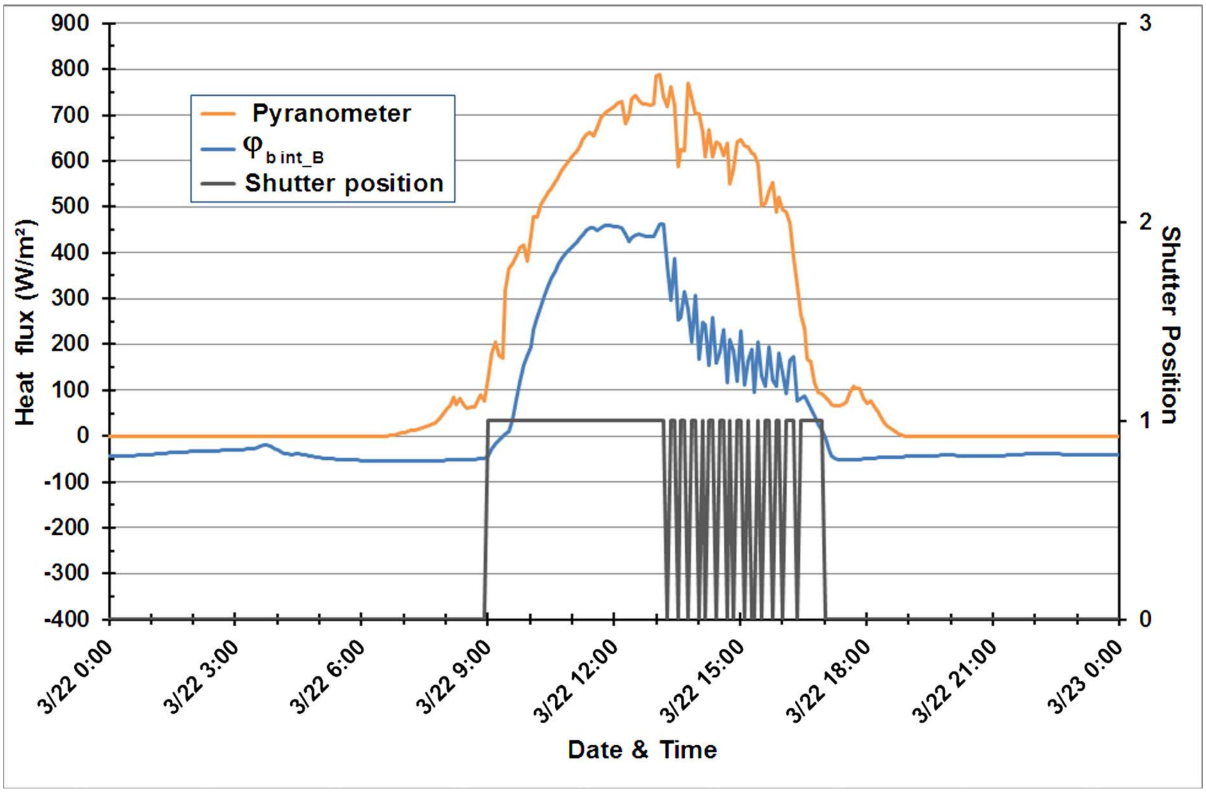

Figure 11. Protection with the shutter, energy flux.

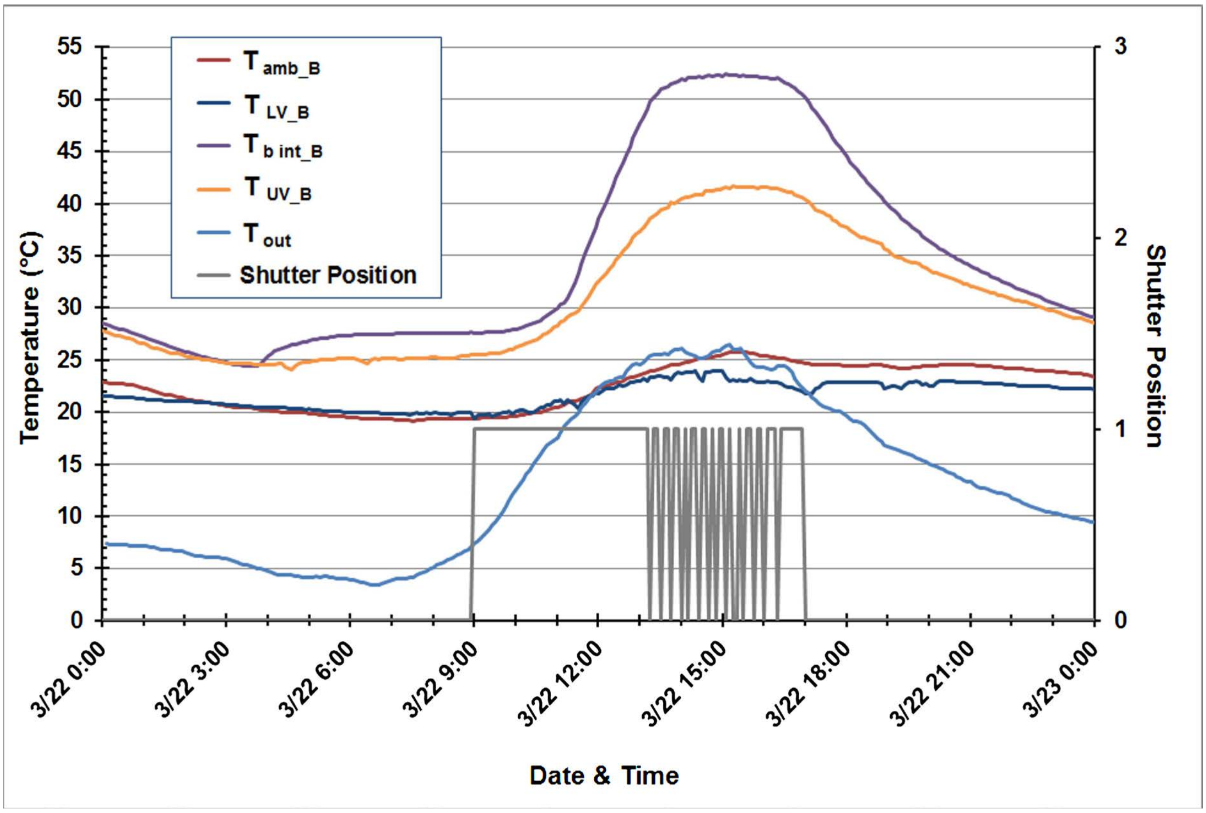

Figure 12. Protection with the shutter, limitation of the bricks' temperature.

4. Conclusion

In this paper, an experimental study for the energy management of a solar wall with PCM is presented. Its key feature is that it is a real size setup mounted *in situ* in two houses with habitants. The experimental results demonstrate the effectiveness of the proposed micro controller based automatic control system in providing overheating protection to the PCM and in improving the efficiency of the energy management process for solar wall. A time switch is used in this experimental study to allow a day/night control for the reduction of thermal losses during the night. This annual switch permits the programming of a summer/winter seasonal control. This control involves the shut off of the solar intake that is useless and can be harmful to the saving of this solar system during summer sunny periods. Future investigation can be focused on the use of an electric fan to accelerate the ventilation in the internal layer to extract more thermal energy during the afternoon, for example, to discharge the PCM material. This compound convection can increase the efficiency of the solar wall. Another solution can be tested with an electric gate at the orifices with the housing to control accurately the reverse thermos circulation and to avoid periods of possible overheating in the housing room.

Acknowledgements

To the National Research Agency (ANR) for the support of the PREBAT project "INPASOL-B—Integration of solar walls in buildings".

To "Pas de Calais Habitat"—Social landlord—for its collaboration and financial support.

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Nomenclature

S	Area	m^2
t	Time	s
T	Temperature	˚C
V	Velocity	$m \cdot s^{-1}$

Greek Letters

ρ	Density	$kg \cdot m^{-3}$
φ	Heat Flux density	$W \cdot m^{-2}$

Subscripts/Superscripts

A	House A
Air	Air
ambient	Ambient B
B	House B
b	Brick of PCM
out	Outside/climatic condition
exc	Exchange area
ext	Exterior (exterior side)
int	Interior (Interior side)
lv	Lower vent
solar	Solar radiation
uv	Upper vent
PCM	Phase Change Material