Design and thermo-energetic evaluation of a solar building heating system

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Abstract. This paper presents the design, construction and thermo-energetic evaluation of a solar building heating system consisting of a double-pass counter-current solar air heating collector with porous matrix and a water-bed heat storage unit connected to a prototype building located at the National University of Salta, Argentina. The experimental study determined that the solar collector has an average daily efficiency of 37% while the storage unit has an average daily efficiency of 38%. The overall daily efficiency of the complete system is 18%. During the test period, the night-time discharge of the storage unit ensured that the temperature of the room to be heated was always above 20 °C when the outside temperature was between 10 and 15 °C.

1. Introduction
The buildings and building construction sectors combined are responsible for more than one third of global energy consumption and almost 40% of total direct and indirect CO2 emissions. In 2017, the residential sector was responsible for 29% of global gas consumption [1] and 23% of global electricity consumption in 2018 [2].

At the local level, according to the National Energy Balance (BEN) 2018 [3], Argentina's primary production energy matrix is made up of 88% fossil fuels (Natural Well Gas 55% and Oil 33%). Final energy consumption depends on 68% of energy derived from oil (32% liquid fuels and 36% mains gas), 20% from electricity and 12% from other less important sources. These high percentages of hydrocarbon consumption contribute to the generation of greenhouse gases that pollute the local atmosphere. The problem is even more serious given that, according to data from the Wholesale Electricity Market Administration Company (CAMMESA) in 2019 [4], electricity production is made up of 60% fossil-fuelled thermal generation and only 28% hydroelectric generation, 6% nuclear and 6% renewable energy (wind and solar photovoltaic).

In Argentina, the residential sector consumes 26% of all energy produced and the commercial and public sectors another 9%. Therefore, the building sector is responsible for the consumption of 35% of all available energy nationally. And energy demand from buildings and building construction continues to increase, driven by improved access to energy, increased ownership and use of energy-consuming devices and tools, and population growth in cities as rural populations migrate to urban centres. The residential sector's electricity demand is 47% of the country's total demand and the commercial sector's demand is another 28% [5]. While the former registered an 8% increase during the first year of the pandemic due to mandatory confinement, the latter registered a 5% decrease for the same reason. The most important uses of electricity in households are for lighting, food preservation, spaces cooling and use of electrical appliances, some of which are seasonal.
Both globally and nationally, the largest energy consumed in the residential sector is natural gas, considering only homes connected to the natural gas network. In Argentina, 63% of the energy consumed by the residential sector corresponds to natural gas from the grid and 9% to liquefied petroleum gas. The main use of natural gas is for cooking, water heating and space heating, the latter depending on the seasonal factor.

The overall energy consumption of a household is distributed among the following uses: 45-55% for heating/cooling, 8-16% for lighting, 25-35% for water heating and cooking and 10-12% for household appliances. Gas consumption for heating and electricity consumption for room cooling in residential use corresponds to a massive consumption that is strongly affected by the seasonal climatic factor and the amount of energy to be used is notably sensitive to the energy efficiency of the dwelling.

Northwest Argentina has the highest levels of solar radiation in the country, and this renewable resource is capable of supplying about 85% of the national energy demand. Solar thermal energy has great potential in this region to reduce the high consumption of conventional energy used for heating buildings and sanitary water heating, while solar photovoltaic energy can contribute to the generation of electricity for lighting and household appliances, taking advantage of the roof area of homes and the terraces of tall multi-family or office buildings due to their privileged “access to the sun”.

Bioclimatic building design including passive (Trombe walls or greenhouses) and active (solar collector air heaters) solar collection systems can significantly reduce energy consumption for heating/cooling and lighting. However, this methodology of rational and efficient energy use is not sufficiently widespread in the country. At the regional level, very few bioclimatic buildings have been constructed, generally associated with public buildings, in which INENCO researchers have participated by designing and dimensioning the solar radiation collector systems and the thermally efficient building envelope. Examples include the neighbourhood of 15 bioclimatic dwellings built in the Cachi town, province of Salta (1984), a bioclimatic dwelling at the National Institute of Agricultural Technology (INTA) Experimental Station in Abrapampa, province of Jujuy (1986), the Maternal and Infant Hospital at Susques, Jujuy [6] and the El Alfarcito’s Mountain High School, Salta (2009). A single-family house built in the town of Vaqueros, Salta [7], is mentioned as a bioclimatic private enterprise whose main heating system is an active solar air heater collector of 23 m$^2$ of area, integrated into the building roof.

Although solar air heating collectors have reached a level of development sufficient to be transferred to industry, in Argentina there are no national companies dedicated to the construction and/or commercialisation of solar air heating collectors for heating. Therefore, in the few bioclimatic architectural projects that are emerging, it is necessary to resort to artisanal manufacturing (led by a professional solar technician), which significantly increases the initial investment required.

The best results are obtained in solar collectors of double-pass counter-flow with a porous mesh or matrix installed in its lower channel [8, 9]. Naphon [10] studied the effect of the porous mesh on the efficiency of the double-pass counter flow collector by means of a mathematical model in steady state obtaining a thermal efficiency 25.9% higher than that without porous mesh.

As part of the non-conventional heating system, the heat storage units coupled to solar collectors allow solar energy to be stored during the day and delivered at night, which is extremely important in buildings with permanent occupancy (bedrooms in dwellings and buildings with clinical hospitalisation, by example). The theory of thermal energy (heat) storage focuses primarily on sensible and latent heat storage. In recent years, much research has focused on latent heat energy storage [11], always in the search for the optimum phase change material according to the desired application, referring to sensible heat energy storage as an already developed and controlled technology.

There is considerable previous experience in the construction and evaluation of sensible heat storage systems [12, 13, 14], but the great challenge is to achieve technological solutions for installation and operation appropriate to their application in buildings, where the space available for their construction is generally limited. In addition, thermal storage systems are usually bulky and heavy (normally using stone, concrete or water), so that, in order to avoid overloading the structure, it is not appropriate to locate them on the roofs of buildings. A feasible alternative is to build them in the ground underneath
the building, taking advantage of the excavation made for the foundations, subfloors or basements and planning properly the location of the pipes connecting the storage unit to the heating system.

This paper presents the design, construction and testing of a solar system consisting of a double-pass counter-current solar air heating collector with a porous matrix and a sensible heat storage unit working in combination for building heating, with the possibility of integration into the building envelope.

2. Design and construction of the solar collector

This section describes the design and construction of the developed solar collector - heat storage system. The following requirements were set for the selection of materials:

- Availability in the local trade.
- Shelf life of more than 5 years.
- Affordable prices.

The size of the solar collector was determined on the basis of the size of the galvanised iron sheets used for the construction of the support box and the absorber plate, which are available locally. The volume of the storage unit was determined considering the size of the commercially available domestic water tanks.

2.1. Design and construction of the solar air heater collector

The solar collector is 2.51 m long, 0.95 m wide and 0.1 m thick. It is a double-pass counter-current collector with a metallic matrix in its lower channel.

Figure 1 shows its design, the different components and the internal path of the fluid.

![Figure 1](image)

**Figure 1.** Longitudinal section of the collector and detail of the absorber plate with the porous matrix.

The collector casing, made of 0.4 mm thick galvanised sheet, is thermally insulated with 5 cm thick glass wool. The transparent cover system consists of two parallel polycarbonate sheets that form a 6 mm thick tight air chamber between them. The absorber plate is a sinusoidal galvanised iron sheet painted black. Its effective corrugation angle is $\gamma = 127^\circ$ and the solar aperture area $A_c = 2.16 \text{ m}^2$. Internally, its geometry corresponds to the schematic in figure 1. The porous matrix is composed of steel chips with an experimentally determined porosity of 97%.

The air inlet and outlet ducts are of circular cross-section of 15 cm diameter, both located at the rear of one end of the collector. This design reduces pipe laying costs and thermal losses through the pipes, compared to double parallel flow designs in which the air enters at one end and exits at the other. The figures 2(a) and 2(b) shows the collector installed facing the Equator with a slope $\beta = $ latitude $+ 13^\circ = 38^\circ$ (to maximise solar collection in winter) and connected by circular pipes to a room to be heated. Corrugated aluminium pipes with a diameter of 15 cm were used for the hydraulic circuit.
2.2. Design and construction of the sensible heat storage unit with water as storage material

For the construction of the thermal storage unit, a household water tank with a capacity of 1000 litres were used, inside which ½ litre plastic soft drink bottles filled with tap water were placed in an orderly arrangement. The cylindrical tank allows maximum use of the bottles due to its shape and robustness. Figure 3 shows the selected tank and the reused soft drink bottles.

The tank was lined on the inside with 5 cm thick glass wool in order to reduce heat loss from the water in the bottles to the outside environment.

Water was chosen as the sensible heat storage material because it has a volumetric heat capacity (in J/m³K) about twice that of the solid material commonly used in stone beds. This allows the volume of the accumulator to be reduced by half in order to accumulate the same amount of thermal energy as with stone for the same temperature rise. Mineral water and soft drink bottles of different trademarks of 500 ml capacity each, discarded after its consumption, were used to fill the storage tank. The geometric shapes of the bottles vary according to the trademark and type of drink, so their stacking inside the tank had to be done looking for each level of bottles to be made up of containers of the same brand. In total 3 types of bottles were used, similar but different. 4 levels were built inside the container of which 3 were filled with the same number of bottles (175) and the fourth level was filled with 96 bottles due to the conical shape of the upper part of the tank.

All the bottles were filled to the same level with tap water and weighed with an ASPEN ek3052 electronic balance, distinguishing them according to the type of bottle. The weights were then averaged
by bottle type and the total volume of water loaded into the storage tank was obtained. A total of 622 bottles were used, reaching a volume of 326.4 L of water. Table 1 details the levels inside the tank.

| Level | Number of bottles | Weight of water per unit (gr) | Weight of water per level (kg) | Volume of water per level (L) |
|-------|-------------------|------------------------------|-------------------------------|-----------------------------|
| 1 (bottom) | 175 | 502 | 87.9 | 87.9 |
| 2 | 175 | 502 | 87.9 | 87.9 |
| 3 | 176 | 583 | 102.6 | 102.6 |
| 4 (top) | 96 | 500.5 | 48.0 | 48.0 |
| Total | 622 | 326.4 | 326.4 | |

2.3. Component installation and system start-up

An axial fan with a power of 0.25 HP, 1400 rpm and 50 Hz was installed to drive the air through the collector-accumulator system circuit. The smallest diameter fan with spin inverter available on the market (63 cm) was chosen in order to minimise the pressure drops due to the section expansions/reductions between equipment and pipes. To direct the airflow towards the solar collector during the daytime charging process of the storage unit and towards the room to be heated during its night discharge, two double-way T valves were designed and built with a galvanised iron sheet whose operation is shown in figure 5.

The interconnection of the different elements of the system was made with 15 cm diameter corrugated aluminium pipes, thermally insulated with 5 cm thick glass wool. The complete system, connected to the room to be heated, is shown in figure 4.

3. Thermal storage unit loading and unloading processes

During the thermal load period (daylight hours), the fan-driven air circulates between the solar collector and the heat storage tank as shown in figure 5 (a). The hot air coming from the solar collector transfers part of its enthalpy to the water contained inside the bottles, thermally stratifying the bed (hot top and cold bottom).

The loading period runs from 10:00 am to 5:30 pm, at which time the solar radiation is no longer enough to heat the air inside the collector. At this time, the fan is turned off and the valves are manually repositioned.

**Figure 4.** Solar collector-heat storage system connected to the room to be heated.
It’s known that the efficiency of the storage unit loading-unloading processes is higher when the air circulates downward during loading (to stratify the bed) and upward during unloading [15]. In this installation, during both loading and unloading, the air enters the storage tank at the top and leaves it at the bottom. This is because, although the fan is a reversible rotation fan, it was not able to operate by driving the air upwards during unloading due to hydrodynamic problems generated by the casing surrounding the fan and the section reducing cones at the inlet and outlet of the fan. This, obviously, affected the overall efficiency of the system.

During the unloading period (at night), the position of the two-way valves is changed and the air circulates between the room to be heated and the heat storage tank as shown in figure 5 (b). The fresh air from the room draws heat from the bottles as it passes through the storage tank and returns to the room at a higher temperature.

The unloading period runs from 21:00 to 10:00 of the next day. At this time, the two-way valves are repositioned and the loading process of the storage tank is restarted.

4. Experimental evaluation

The collector-storage system was tested in a closed circuit connected to a 7.15 m² prototype building constructed at the National University of Salta, in the city of Salta, Argentina (24° 43.7' South Latitude, 65° 24.6' West Longitude and 1 200 m above sea level), as shown in figure 4. The walls are made of 15 cm thick hollow ceramic bricks. The roof is metallic, built with galvanised trapezoidal sheets and the floor is made of 10 cm thick concrete. Expanded polystyrene plates 5 cm thick form a thermally insulating ceiling below the galvanised sheet roof. The carpentry is made of pine wood and consists of a door to the east and a single glazed window to the west.

All these materials are commonly used in the construction of single-family houses through government programmes, although ceramic bricks are also used in multi-storey buildings and in many houses of the richest social sectors in our country. This means that, in terms of the characteristics of its envelope, the monitored building prototype represents a vast sector of typical Argentinean constructions. The azimuth of its north façade is 170° (10° East of North).

The experimental tests were carried out at the end of winter, between 8 and 16 September.

4.1. Measurement instruments

By means of K-type thermocouples connected to an ADAM 4018 datalogger with 8 analogue channels, the following air temperatures were recorded at 1 min intervals:

1) At the inlet and outlet of the solar collector
2) At the inlet and outlet of the thermal storage unit
3) At the inlet and outlet of the building prototype
4) The indoor air of the building prototype
The outdoor temperature and solar irradiance over the tilted plane of the solar collector were recorded by means of an autonomous weather station, HOBO model H21, at intervals of 10 min. By means of a hot wire anemometer TSI, the air velocity at the collector inlet (necessary to estimate the circulating mass flow) was manually recorded two times by day.

4.2. Measurement results

4.2.1 Evolution of the indoor temperature of the room to be heated

Figure 6 plots the values of outdoor temperature, indoor temperature of the room and solar irradiance over the collector plane.

![Figure 6. Weather variables and indoor temperature of the room to be heated.](image)

As shown in the figure, the outdoor temperature varied between a minimum value of 7 °C on 9/09 and a maximum value of 37 °C on 12/09, with a solar irradiance on the tilted plane in the order of 840 W/m² during the cloud-free days. On 8/09 the useful energy produced by the collector was stored in the storage tank and during the first night of the test no thermal energy was extracted from it. During the next 4 days the system operated by collecting and storing energy during the day and delivering energy to the room from the storage tank during the night.

The unloading of the storage tank can be observed through the rise of the indoor temperature during the night hours. The energy provided by the storage tank prevented the indoor temperature in the room from dropping to the minimum values recorded during the first and last night of the test, when no energy was drawn from the storage tank.

On 12 September it was partly cloudy but the system was able to collect and accumulate solar energy while the next day it was completely cloudy and the solar collector did not produce any useful energy. However, during the night, energy was extracted from the storage tank to maintain the temperature inside the room and this prevented it from cooling below 18 °C when the outside temperature was in the order of 10 °C. This indicates that, if the day is completely cloudy and the solar collector does not produce useful energy, the system can still meet the thermal demand of the room during the night due to its high volumetric thermal capacity and its level of thermal insulation.
4.2.2. Solar collector efficiency curve

To determine the efficiency curve of the solar collector coupled to the system, i.e. in a closed circuit, its instantaneous thermal efficiency was calculated using the following equation:

\[ \eta_c = \frac{\dot{m} C_p (T_o - T_i)}{A_c G_p} \tag{1} \]

where:

- \( \eta_c \): instantaneous thermal efficiency of the solar collector
- \( \dot{m} \): air mass flow (kg/s)
- \( C_p \): specific heat of air at constant pressure (J/(kg \(^\circ\)C))
- \( T_o \): output air temperature of the solar collector (°C)
- \( T_i \): input air temperature to the solar collector (°C)
- \( A_c \): solar aperture area of the collector (m\(^2\))
- \( G_p \): solar irradiance on the tilted plane of the collector (W/m\(^2\))

In order for the curve to be representative of the real operation of the collector, the data measured during the hours of the load period on sunny days (8, 9, 10, 11, and 15 September) were selected and the efficiency values obtained with equation (1) were plotted as a function of the variable \( (T_i - T_a) / G_p \), where \( T_a \) is the outdoor air temperature. Figure 7 shows the instantaneous efficiency curve obtained experimentally with a mass flow rate of 0.034 kg/s where the blue points are the efficiency values obtained with eq. (1) and the orange dotted line is the trend line obtained by applying a least-squares fitting (linear regression).

\[ y = -9.2097x + 0.4407 \]
\[ R^2 = 0.9267 \]

**Figure 7.** Instantaneous efficiency curve of solar collector coupled to storage tank and the room to be heated.

According to the correlation in figure 7, with a value \( R^2 = 92.7\% \), the equation for the instantaneous efficiency of the solar collector operating coupled to the system is:

\[ \eta_c = 0.4407 - 9.2097 \frac{(T_i - T_a)}{G_p} \tag{2} \]
This means that the solar collector has a value of $F_R(\alpha) = 0.44$ and $F_RU_L = 9.21 \text{ W/(m}^2\text{°C)}$, where $F_R$ is the heat removal factor, $(\alpha)$ the effective transmittance-absorbance product and $U_L$ the overall heat loss coefficient of the collector. The dispersion of the measured efficiency values with respect to the fitting curve is due to the fact that $F_R$, $(\alpha)$ and $U_L$ are not constant throughout the test.

The collector has a maximum efficiency of 44% for a mass flow of 0.034 Kg/s. This value is not the expected one since the fan used did not meet the expectations in the air flow produced because the motor is inside the pipe, aligned to the air circulation direction, generating turbulences and dissipating heat to the air before entering the storage tank. It is expected that a better designed and more powerful fan will be able to produce a higher airflow and thus increase the efficiency of the collector.

The measured pressure drop across the solar collector was published in a previous paper [16] and, for a mass flow of 0.034 kg/s, its value is 60.2 Pa. This relatively high value is mainly due to the presence of the porous matrix in the lower channel of the collector.

4.2.3. Thermal efficiency of the heat storage unit and the complete system

Based on the results obtained during the test days, the heat transfer rates involved in each process were calculated in order to obtain the daily efficiencies. The equations involved are presented below as expressions of the sensible heat gained or ceded by the air in each element of the system:

- **Solar collector:**
  \[ Q_u = \dot{m} C_p (T_o - T_i) \]  
  (W)  
  (3)

- **Axial fan:**
  \[ Q_f = \dot{m} C_p (T_{ia} - T_o) \]  
  (W)  
  (4)

- **Collector + fan:**
  \[ Q_{u+f} = \dot{m} C_p (T_{ia} - T_i) \]  
  (W)  
  (5)

- **Storage unit (loading):**
  \[ Q_{st,c} = \dot{m} C_p (T_{ia} - T_oa) \]  
  (W)  
  (6)

- **Storage unit (unloading):**
  \[ Q_{st,d} = \dot{m} C_p (T_{oa} - T_{ia}) \]  
  (W)  
  (7)

- **Solar Radiation:**
  \[ Q_{sun} = A_c G_p \]  
  (W/m$^2$)  
  (8)

where:

- $T_{ia}$: input air temperature to the storage unit (°C).
- $T_{oa}$: output air temperature from the storage unit (°C).

The efficiency of each element of the system is calculated by the quotient "energy delivered / energy input". The eq. (1) corresponds to the solar collector. The instantaneous efficiency of the storage unit is calculated by the following equation:

\[
\eta_{st} = \frac{Q_{st,d}}{Q_{u+f}} = \frac{\dot{m} C_p (T_{oa} - T_{ia})}{\dot{m} C_p (T_{ia} - T_i)}
\]  
(9)

In this equation it should be noted that the values of $T_{ia}$ in the numerator and denominator expressions correspond to different times of the day.

The instantaneous efficiency of the complete system is calculated by:

\[
\eta_{sist} = \frac{Q_{st,d}}{Q_{sun}} = \frac{\dot{m} C_p (T_{oa} - T_{ia})}{A_c G_p}
\]  
(10)

Table 2 shows the daily thermal energies (in MJ/day) obtained by integrating eq. (3), (4), (6) and (8) during the storage tank loading period. In the last column, the daily efficiency of the solar collector is included.
Table 2. Daily values of thermal energy produced or delivered by each element of the system during loading periods on sunny days and daily efficiency values of the solar collector.

| Day    | Start time | End time | Charging time (hs) | \(Q_{\text{sun}}\) (MJ) | \(Q_u\) (MJ) | \(Q_t\) (MJ) | \(Q_{\text{st,c}}\) (MJ) | \(\eta_c\) (%) |
|--------|------------|----------|-------------------|-------------------------|-------------|-------------|--------------------------|----------------|
| 09-sep | 10:16      | 17:30    | 7.23              | 47.18                   | 17.12       | 4.03        | 20.57                    | 36.3           |
| 10-sep | 10:19      | 17:30    | 7.18              | 44.99                   | 17.26       | 3.56        | 20.75                    | 38.4           |
| 11-sep | 9:58       | 17:30    | 7.53              | 46.71                   | 18.10       | 3.41        | 22.36                    | 38.7           |
| 12-sep | 10:25      | 17:30    | 7.08              | 33.73                   | 13.16       | 4.44        | 17.59                    | 39.0           |
| 14-sep | 10:30      | 17:30    | 6.72              | 42.35                   | 15.59       | 4.91        | 19.72                    | 36.8           |
| 15-sep | 9:51       | 17:30    | 7.65              | 46.76                   | 15.45       | 4.83        | 20.27                    | 33.0           |

It’s observed in the Table that during the first three days the energy produced by the solar collector, its daily efficiency and the accumulated thermal energy increased due to the increase of the outdoor ambient temperature during those days (see Fig. 6). This contributed to decreasing the heat losses from the collector and the storage tank to the environment. The average daily efficiency of the solar collector during the test period was 37 %.

Table 3 shows the daily thermal energy delivered by the storage unit during the unloading hours and the daily thermal efficiencies of the storage tank and the complete system.

Table 3. Thermal energy values delivered per day by the storage unit during the unloading periods and daily efficiency values of the storage tank and the complete system.

| Day    | Start time | End time | Unloading time (hs) | \(Q_{\text{st,d}}\) (MJ) | \(\eta_{\text{st}}\) (%) | \(\eta_{\text{sist}}\) (%) |
|--------|------------|----------|---------------------|--------------------------|-------------------------|--------------------------|
| 09 to 10| 22:23      | 10:13    | 11.83               | 8.72                     | 41.2                    | 18.5                     |
| 10 to 11| 21:00      | 9:53     | 12.88               | 7.96                     | 38.2                    | 17.7                     |
| 11 to 12| 21:00      | 10:17    | 13.28               | 8.14                     | 36.3                    | 17.4                     |
| 12 to 13| 21:00      | 14:22    | 17.37               | 6.98                     | 39.7                    | 20.7                     |
| 14 to 15| 21:00      | 9:45     | 12.75               | 6.99                     | 34.1                    | 16.5                     |

The average daily efficiency of the storage tank during the 5 nights of unloading was 37.9 % while the overall average daily efficiency of the complete system during the entire test period was only 18.2 %. This is due to the fact that the storage tank delivered very little thermal energy during the unloading periods because could not be reversed the direction of rotation of the fan at nights.

5. Conclusions

This paper presented the design, construction and thermo-energetic evaluation of a solar building heating system composed of a double-pass counter-current solar air heating collector with porous matrix and a water-bed heat storage unit.

The solar collector, operating in a closed circuit with the storage tank and the room to be heated, has a maximum efficiency of 44 % for a mass flow rate of 0.034 kg/s. This value is much lower than expected and is attributed to the fluid dynamic problems produced by the inclusion of the fan motor inside the pipe connecting the collector to the storage tank. It is estimated that the installation of a fan with a better design and more power would be able to produce a higher air flow and thus increase the efficiency of the collector. The maximum air temperature at the collector outlet was of the order of 60 °C during sunny days, with an average temperature increase between the inlet and outlet of 19 °C and a pressure drop inside the collector of the order of 60 Pa. The average daily efficiency of the solar collector during the test period was 37 %.
Analysis of the measured temperature values shows that, during periods of storage tank charging, there is an increase in temperature between the outlet of the solar collector and the inlet to the storage tank, a section of pipework that contains the fan and its motor. This section, being thermally insulated, should not present a temperature increase in the direction of flow but, as a consequence of the heat dissipated by the motor, there is a sensible heat gain in the air that passes in contact with it, which is transported advectively to the storage tank.

During both charging and discharging of the storage tank, the air circulates downwards inside the tank, which is beneficial for stratification during sunshine hours, but is counterproductive during discharge at night and negatively affects the overall efficiency of the system. This mode of operation was due to the fact that the reversible rotation of the installed fan could not be used. Therefore, during unloading, the cold air from the room to be heated enters the upper part of the storage tank where the water is at a higher temperature. There, a convection heat transfer is generated between the hot water and the incoming cold air. The air gains heat, increasing its temperature, and continues its course towards the lower part of the container where it comes into contact with the water at a lower temperature, as the storage tank is thermally stratified. Here the air transfers, by convection, part of the heat gained at the top to the water in the bottles at the bottom before leaving the container. At the end of the inner path, the air leaves the storage tank warmer than it entered, but at a lower temperature than it would have reached if the air had been moving upwards.

On days when the storage tank is discharged, the room temperature curve shows two peaks, one due to the time lag caused by the building envelope, which occurs between 17:00 and 18:00 hours, and the other due to the discharge of the thermal storage tank when the fan is turned on between 22:00 and 23:00 hours. This generates a greater time lag and attenuation in the temperature curve of the room.

During the test period, the night-time discharge of the storage tank allowed the room temperature to be always above 20 °C when the outside temperature was between 10 and 15 °C. Moreover, on sunny days the room temperature exceeded 30 °C at the beginning of the storage tank discharge period. This indicates the need for an automatic fan start-up control system to prevent the overheating of room during sunny periods when the storage tank is fully charged and the outside temperature is higher.

The heat storage capacity of the developed system is able to supply energy to meet the heating demand during a whole cloudy day, keeping the room temperature above 18 °C as shown in Figure 6 for the 14/09.

The average daily efficiency of the heat storage unit during the 5 nights of discharge was 37.9 % while the overall average daily efficiency of the complete system during the whole test period was only 18.2 %. These values can be improved by increasing the circulating air flow rate and by using a reversing fan.

The overall efficiency of the solar thermal system has a quasi-constant behaviour throughout the test period. It presents a direct correlation with the efficiency of the storage tank and its discharge hours, since its maximum value, ~ 21 %, occurred on 12/09 when the discharge was maintained for a longer period of time compared to the rest of the days (approximately 4 hours more).

Analysing the ratio water volume / solar collector area, a value of 151 L/m² is obtained for this system, being 75 L/m² the recommended value for water storage [12]. This indicates that the developed system is undersized in terms of solar collection area and it would be convenient to use 2 solar collectors of the tested type, connected in parallel, for the available thermal storage capacity.

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