Stratification by Natural Convection directed to improve Energy Autonomy
Development of an integrated collector storage solar waterheater

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Abstract

Development showed in this paper, overcomes the disadvantage presents at the hot water´s tanks, both solar systems and those that use other energy sources, originated in the mixture of cold water coming into the system with hot water contained therein, causing a decrease in temperature.

The integrated collector storage system (ICSS) of three tanks improves stratification by natural convection both inside each tank and between them.

Different aspects of design are discussed, the bases of the simulation program, and the results of the experimental evaluation that allow characterizing the system, validating the simulation program, determining the performance and evaluating the degree of autonomy and the solar fraction. Additional aspects such as frost resistance, tartar formation and others related to installation and maintenance are incorporated.

Keywords: Autonomy, stratification, integrated accumulator collector.

1. Introduction

An important part of the population of Latin American countries is affected by energy poverty, either because they do not have access to the network´s gas distribution, electricity, or the rationing of consumption because of the energy tariffs.

Obviously, the needs of the user who uses solar energy from a certain environmental consciousness, having the possibility of combining it with other traditional energy sources, are different from those of a person who uses solar energy because it is the only one within their reach. In the first case at the time of sizing the system it is tried to reach a reasonable balance between the size and therefore the cost and the fraction of the thermal load that is able to supply (solar fraction), avoiding that it is oversized for a great part of the year. But for the case in which the solar system is proposed as an alternative to the difficulty of access to other types of energy, it is desirable to reduce to a minimum the use of auxiliary energy.

The autonomy of the system, introduces the concept of usable temperature, understood as the minimum temperature necessary to satisfy a certain need. In the extreme case that there is no auxiliary energy source, when the temperature is lower than the usable one, the energy contained in the system cannot be used. The developed system seeks to reduce time to reach usable temperatures and improve the preservation of them, improving the stratification.

The integral collectors are simple in their constructive form and their basic operation is carried out without moving parts, unlike the systems with pumping. With relatively cheaper materials they achieve greater performance than the separate manifold and tank system, tested in different tests. Due to their large volume of water they offer good frost resistance. Its main drawback is that the night losses are greater than in other systems, whose accumulator tank is completely isolated.

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In countries with a tropical climate such as India or Cuba, constructive simplicity and the use of low-cost materials are prioritized, so that the systems are widely accessible to the population. For the prevailing climatic conditions, the integrated accumulator collectors give good results even without a very elaborate design. The strategy adopted to reduce night losses is the use of transparent covers combined with the use of Honeycomb polycarbonate. (Reddy, Kaushika, 1998), (Massipe Hernández et al. 2012) and the English (Chaurasia, Twiddel, 1999). Ahmad et al (2014) compared three different shapes of front absorber plat, flat, wavy, and zigzag shapes seeking to improve collection efficiency.

In order to reach and preserve higher temperatures the Greeks have carried out detailed studies of different configurations with one and several tubes comparing diferent shapes of linear reflectors. (Tripanagnostopoulos et al. 2004.). Madhlopa et al. (2006) investigated systems of several tubes and how in them the stratification depends on the interconnection of them, which was also investigated by Tacchi (Tacchi and Monrós, 2004). The same authors developed different designs with a lid that closes manually or automatically when the radiation is less than a certain established limit value. Kumar and Rosen (2011) develloped a system with an extended storage unit, deviding the total volume in two sections, one exposed to solar radiation and the other insulated on all sides.

The study of the mentioned works, leads to the conclusion that the design details that try to respond to the problem of night losses of integral accumulator collectors, are based on the selection of materials such as selective surfaces, use of concentrators, partial coverings permanent, complete coverings for periods of low radiation and designs focused on stratification.

The system analyzed in this work takes as its starting point the patent (AR040913B1) in the name of Victorio Tacchi entitled "New arrangement of elements that constitute a water accumulator that can also originate from solar energy", which proposes the division of the volume Total water in several overlapping horizontal tanks interconnected with each other seeking stratification. It also contemplates the use of a complete coating for periods of low radiation.

The present study focuses on the detailed analysis of stratification. Although it does not modify the total energy content of the system, it favors the possibility of taking advantage of it. In this sense, systems composed of several tanks located by the collector's own inclination at different heights, largely prevent the degradation of energy at a temperature that is no longer usable. The desired stratification is achieved by the combination of concentrators (which produce a non-uniform exposure to radiation) with an adequate interconnection of the tubes with each other..

2. Design

The prototype was designed to meet the needs of a family of seven members, resident in an area without access to the gas distribution network, and problems of shortage of bottled gas in winter.

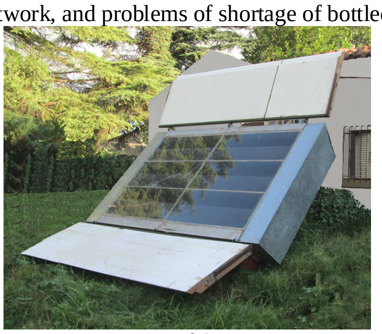

Fig. 2.1 Foto of the prototype

The prototype consists of three galvanized iron and black painted tubes of 256 mm inside diameter and a length of 2500 mm. They are contained in an insulated box with polyurethane in a thickness of 120 mm. The total capacity is 386 liters and the glazed surface that receives the radiation is 3.59 m2 which responds to a volume / surface ratio of 107.5 l / m2.

The inclination of 45º towards the equator perpendicular to the axis of the tubes results in a height difference between axes of 362 mm. The double connection between the tanks favors the thermosiphonic circulation between them, forming three zones of well defined temperatures.

One third of the surface of the tubes - located at the bottom - is in direct contact with the insulator while the remaining surface is exposed to solar radiation, either directly or by receiving it by reflection of asymmetric parabolic cylindrical concentrators.

All the described characteristics were designed and calculated to promote the convection inside each tank and the thermosiphonic circulation between them, in order to improve the thermal transfer to the water and preserve the usable temperatures.

2.2. The connections between the tubes

The design of the interconnection between the three tubes that make up the system has a great influence on its operation, since it affects both, the processes that make stratification and the behavior during extraction that can lead to a degradation of energy below the usable temperature.

Basically we can distinguish three variants of connection (Madhopla, 2004): in parallel, in series and double connection.

This last variant was chosen. The tanks are interconnected with each other through two ducts. Hot water is extracted from the highest part of the system while cold water enters through its lowest part.

The double connection allows the thermosiphonic circulation between the tanks when no extractions are made, since while one of the pipes rises the water at a higher temperature by the other, the one that is at a lower temperature drops. In this way a greater degree of stratification is obtained than in the other systems and is still preserved at times without incoming radiation. In addition the thermosiphonic circulation improves the flow factor and therefore the heat removal factor.

In order to define the exact location of the inlet and outlet pipes, their diameters and the way of connection to the tubes to favor thermosiphonic circulation and stratification, as well as to prevent mixing during extraction, a simulation program was developed from the physical-mathematical model, which was then tested by experimentation. The final design is shown in the figure 2.2.

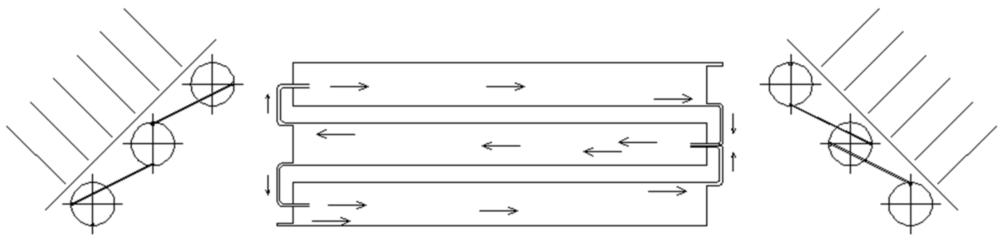

Fig. 2.2 Termosifonic connection

In the design, the ascending tubes leave the upper part of the diameter of the lower tank flush with the lid, and enter the upper tank at half the diameter in the far part of the glass penetrating 15 cm into the tank. The height difference is 36 cm and it is assumed that as long as there is convection inside the tanks there will also be a temperature difference.

The downcomers leave the lower part of the upper tank by penetrating the lid of the lower to middle tank on the face exposed to radiation.

Since the diameters of the ascending and descending tubes are 22.2 mm and 16.6 mm, respectively, it is expected that the effects of countercurrent circulation, which produces mixing with cold water, are small as indicated in Figure 2.17, with the small arrows.

3. Simulation

The objective of the simulation was to help characterize and understand the internal convection processes in each tank, and the thermosiphonic circulation between them, for later - once the results were corroborated by the measurement - to be able to predict the effects of certain changes of the design.
For the simulation the following premises were adopted:

• There are two types of zones: Those that receive radiation and those that do not. This difference leads to internal convection.
• Initially, two internal temperatures are distinguished: one near the illuminated part (Tw1) and another prevailing in the rest of the tank (Tw2 = Tw3).
• A convection process begins between Tw1 and Tw2, transferring heat from the surface to the center. As its temperature rises, water occupies horizontal isothermal layers.
• In the horizontal layer adjacent to the insulator, Tw3, there is a calm zone, excluded from the convection process. Heat is transmitted to it by conduction.

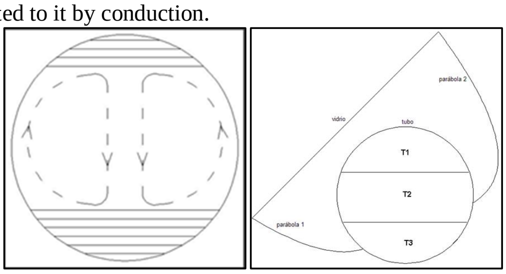

Fig. 3.1. Convection process and temperature evolution

3.1. Water temperature calculation

To calculate the temperature (Tw1) of the illuminated part of the tank, the equation that is suggested by Duffie and Beckmann (1991) was used for integrated accumulator collectors for taking thermal capacity into account.

$$T_w^+ = T_{amb} + \frac{S}{U_t} - \left[\frac{S}{U_t} - \left(T_w - T_{amb}\right)\right]\exp\left(-\frac{A_c U_t t}{M}\right) \qquad \textbf{(3.1)}$$

being T_w the water temperature [ºC], T_w^+ the water temperature in the new interval, Tamb the ambient temperatura, S the global radiation on the collector plane [Jm^{-2}] , Ut the top loose coefficient [$Wm^{-2} \cdot K^{-1}$], Ac the top surface[m^2], M thermal capacity [JK^{-1}] and t the time[s].

3.2. The convection process inside each tank

The stratification inside the tube is due to the fact that two thirds of it receives solar radiation while the other third, which is in contact with the insulator, does not receive it. The process is reinforced by the concentration of radiation in the lower part of the area exposed to light due to the reflectors.

It is then a question of looking for a similar process that has been experimentally tested in order to determine the Nusselt number and from it the convection coefficient. The best fitting analyze found in the literature was the proposal by Mijeev M.A. and Mijeeva I.M. (1979), which includes a variety of internal convection processes in the chapter entitled "Heat emission in a limited space" (fig. 3.7).

They propose to simplify the calculation considering the process as an elementary phenomenon of thermal conduction by introducing the concept of the equivalent coefficient of thermal conductivity, which divided by the coefficient of thermal conductivity of the medium gives a dimensionless number that shows the relative influence of convection and flame convection coefficient h.

This coefficient is a function of the product between the Prandl and Grashof numbers. For the procedure, the thickness δ of the intermediate layer is taken as the characteristic dimension, which in the case studied is equal to half the diameter. The determining temperature is the average fluid temperature.

They show experimentally that, despite the simplification, the different geometries and with different means fit a single curve that relates the convection coefficient to the GrPr product. Finally they obtain the general formula for the convection coefficient as long as $Gr\,\Pr \geq 10^3$:

$$h_c = 0{,}18(GrPr)^{0{,}25} \qquad \textbf{(3.2)}$$

The equivalent thermal conduction coefficient k_{eq} is obtained from the convection coefficient of the cavity taking into account the conductivity of the fluid k_{fl} as follows:

$$k_{eq} = h_c k_{fl} \qquad \textbf{(3.3)}$$

Heat flow is then calculated by Fourier's Law in the usual way:

$$q = \frac{k_{eq}}{\delta}(T_s - T_{int}), \text{ expressed in } Wm^{-2} \qquad \textbf{(3.4)}$$

Once the convection coefficient is calculated, the energy balance is carried out to obtain the temperatures Tw1, Tw2 and Tw3. For this, an iterative calculation is performed assuming that the surface of the tube that receives radiation and the adjacent fluid layers are at the temperature Tw1 calculated with equation (3.1). The inside of the tube is initially at the Tw3 temperature as well as the surface that does not receive radiation.

The termosiphonic circulation between the tubes

Due to the temperature gradient inside each tube, connecting them conveniently, figure 3.9, a thermosiphonic flow will be established between the tubes, allowing stratification and obtaining as many average temperatures as there are tanks. The self-convective or thermosiphon flow works according to the following principle shown in Figure 3.4. (Meinel A. and Meinel M, 1982).

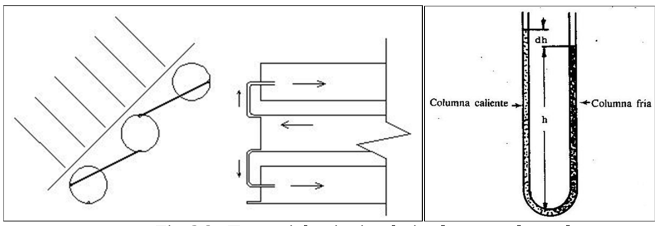

Fig. 3.2. Termosiphonic circulation between the tanks

The expansion of the fluid that is at a higher temperature causes an additional pressure that results in a force that accelerates the fluid in such a way that the higher temperature fluid rises and the lower temperature fluid replaces it. This force is:

$$F = \rho dhAg = ma \qquad \textbf{(3.5)}$$

Being ϱ the density of the fluid [Kgm^{-3}], dh the difference of heigt due to expansion [m], A is the area of the duct [m^2], g the acceleration of gravity [ms^{-2}], m the total mass [Kg]of the fluid to be set in motion and its acceleration. This height difference depends on the coefficient of volumetric expansion β [k^{-1}], on the height h [m]which is the difference in height between the exit and entrance of the duct and the temperature difference.

$$dh = \beta h \Delta T \qquad \textbf{(3.6)}$$

where β can be calculated in the following way

$$\beta = \frac{1}{\rho_m}\left[\left(\frac{\rho_2 - \rho_1}{T_1 - T_2}\right)\right] \qquad \textbf{(3.7)}$$

In this way, the speed of the thermosiphonic flow can be calculated as:

$$v_f \leq (gh)^{\frac{1}{2}} \beta (T_1 - T_2) \qquad \textbf{(3.8)}$$

The flow rate C[Kgs^{-1}] is then calculated based on the internal diameter D[m] of the smaller pipe and the average density.

$$C = v_f \frac{\pi D^2}{4} \rho_m \qquad \textbf{(3.9)}$$

And finally the ascending dQ_s [Js^{-1}]and descending dQ_b [Js^{-1}]heat fluxes are obtained as:

$$dQ_s = CC_p T_1 \qquad \textbf{(3.10)}$$

$$dQ_b = CC_p T_2 \qquad \textbf{(3.11)}$$

3.2. Results and simulation adjustment

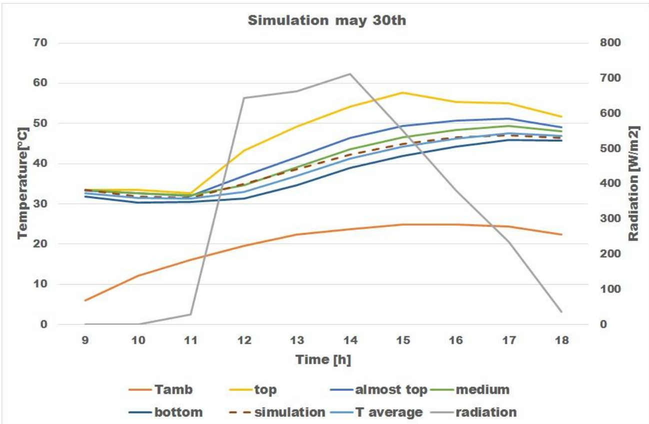

Fig. 3.3. Simulated average temperatura

As can be seen in figure 3.3. the simulated average temperature is located as an average between the temperature measured at the middle of the medium tank and the average temperature calculated based on the measurements. The fact that temperatures in the medium of the tank are higher at the time of radiation is due to the influence of high temperatures in the boundary layer.

However, it was not so simple to simulate the thermosiphonic processes between the tanks. The temperature differences between the tanks were smaller in the simulation than in the measurements made as can be seen in Figure 3.4.

After having made attempts to calculate the Nusselt number with different methods, and to compare the values of measured and simulated flows without finding significant differences, the simulation program was adjusted so that the energy contained in the ascending flows is not delivered to the entire liquid of a tank but only to a stratum of the same. Taking the mass of one third of the tank the .simulated curves fit much better to the experimental values as shown in figure 3.5. It is an achievement to be able to corroborate in this way that the location and shape of the entrances and exits of the tanks match the objective of promoting and consolidating the stratification both inside each tank, and between one tank and the other.

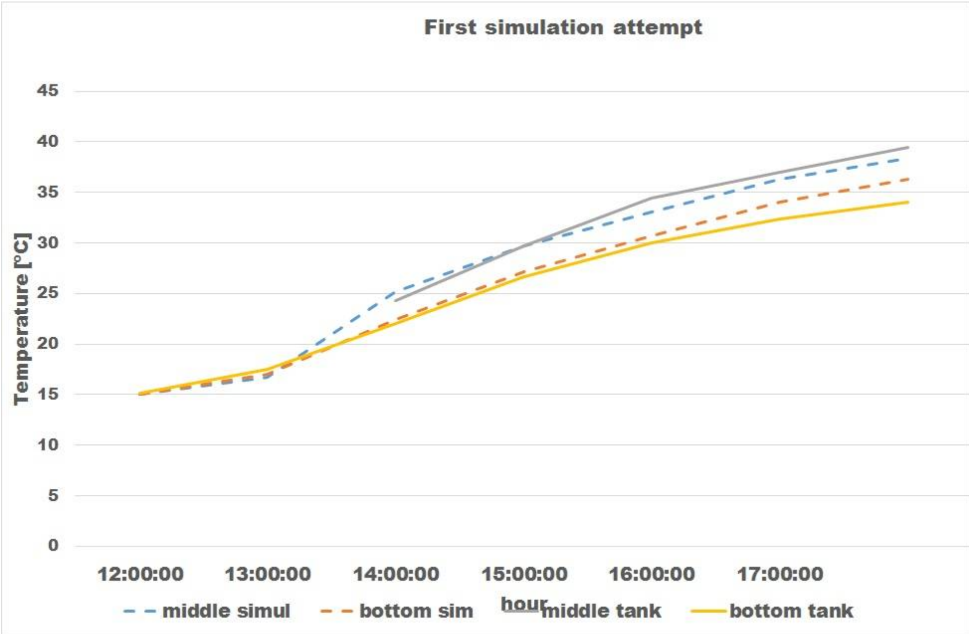

Fig. 3.4. First simulation attempt

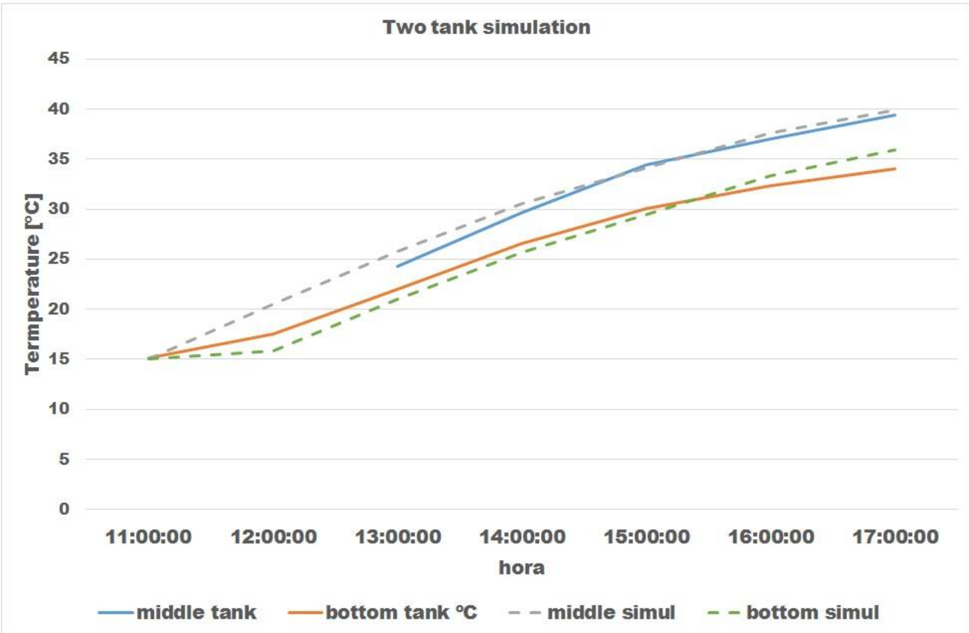

Fig. 3.5. Two tank simulation

4. Experimental evaluation

The purpose of the experimental evaluation was to verify if with the developed constructive form the stratification is achieved inside each tank, the differentiation of temperatures between the tanks and their conservation during the extraction. With a second series of measurements it is intended to confirm that the integrated system obtains satisfactory performance, which combined with greater stratification increases the degree of autonomy of the solar system.

4.1. Experimental setup

Eighteen temperature sensors were installed, according to the scheme shown in figure 4.1. The sensors used are semiconductors of type LM35 connected to a data acquisition system. The radiation was measured with a photovoltaic type pyranometer built and calibrated by the National Atomic Energy Commission. For the measurement of the water flow, a Unimag-Actaris water meter, metrological class B, and suitable for a maximum flow of 3m3 / h was used. in combination with a stopwatch.

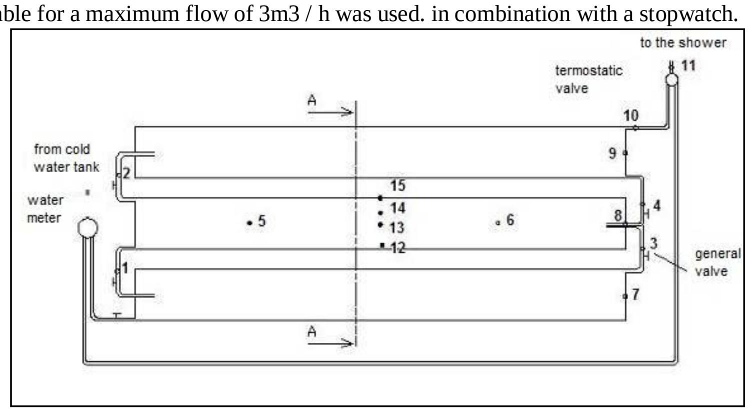

Fig. 4.1. Location of temperature sensors

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4.2 Stratification inside the tank

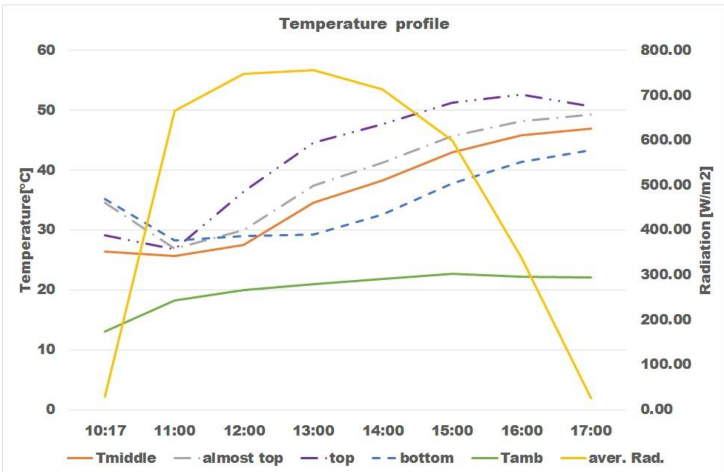

Fig. 4.1 Stratification inside the tank.

Figure 4.1 shows the temperature gradient inside the medium tank. The greatest temperature difference between the upper and lower part of it is 15.25 ° C and is reached at the time of greatest radiation (756 W / m2). Note that this thermal jump corresponds to the strip located in the upper two or three centimetres of the tube belonging to the thermal boundary layer. The "almost up" temperature has the sensor located five centimetres from the top of the tank.

4.3. Temperature difference between the tanks

Figure 4.2. shows the stratification that takes place due to the interconnection of the collection tanks that are at different temperatures The maximum difference between the upper and lower tanks amounts to 9 ° C, somewhat delayed with respect to the maximum radiation. Between the outlet temperature and that of the lower tank there is a difference of almost 16 ° C, which implies that the system is capable of reaching

usable temperatures in very short time intervals, in this case of 2.5 hours, starting with a stabilized system at the inlet water temperature.

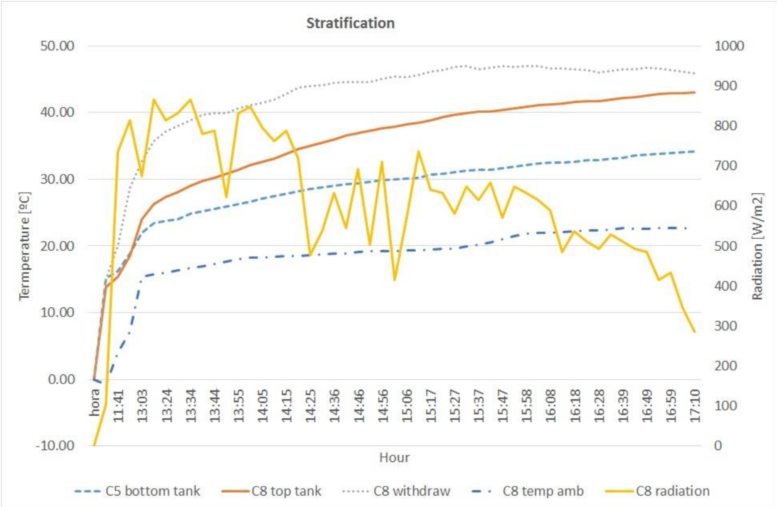

Fig. 4.2. Stratification between the tanks. Temperatures of august 11th.

In turn, in the middle tank, where the sensors are placed at different heights, a temperature gradient of 16.48 ° C is observed. If it is possible to concentrate the radiation in the lower part that is at a lower temperature, heat transfer is promoted.

4.4. Behavior of the temperatures during withdraw

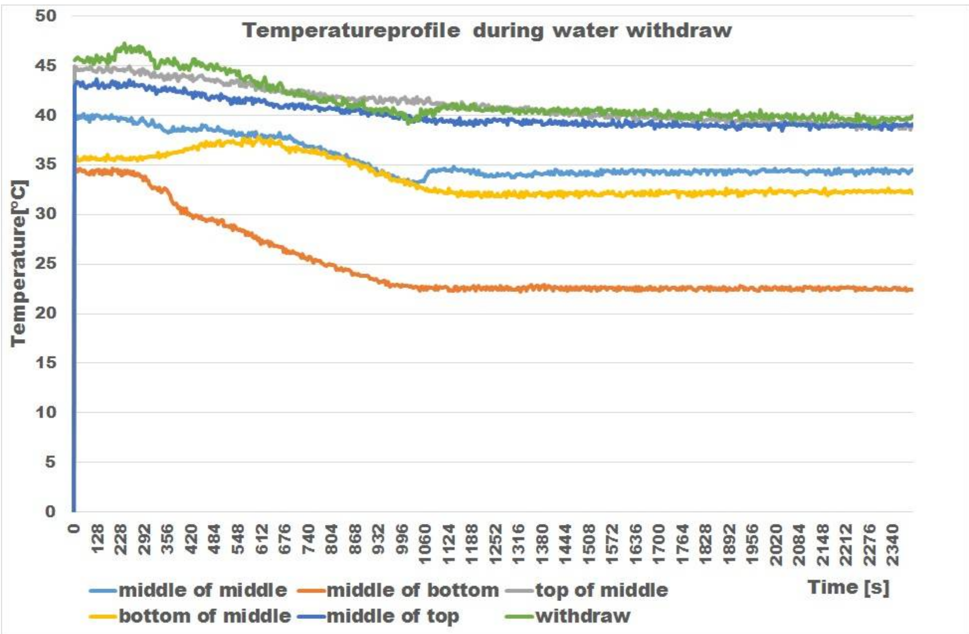

Fig. 4.3. Temperatura profile during water withdraw

When designing exactly the position, the diameters and the shape of the connection pipes between the tubes, it has been proved that the stratification can be maintained even during the extraction, when obviously the tendency is that the replacement water ascends in all possible ways.

The real effect of all these design factors is difficult to simulate, so the information needed to approve or improve it could only be obtained through measurement. Figure 4.3. shows the behaviour during extraction and subsequent night cooling

It is observed that stratification, instead of decreasing, is accentuated during extraction. The causes of this effect are better understood by analysing what happens with the temperature of the lower zone of the middle tank. Figure 4.3. shows that at first it increases and then goes down parallel with the temperature in the middle of the same tank. This is explained by the entry of water at a higher temperature from the lower tank from the middle and upper part of it. The result is that the water that is extracted is always replenished with the water that is at a higher temperature in the system, achieving that, while the temperature in the lower tank drops 12ºC, the temperatures in the upper tanks only decrease between 2ºC and 5ºC. This allows better use of accumulated energy. In other systems with a single tank the mixing effect is similar to that occurring in the lower tank - to a greater or lesser extent -, which reduces the amount of water at usable temperatures, due to the mixing with the replacement water.

4.5. Energy transformation test over a 12-hour period

During these tests, the routine proposed by ISO 9459 -2 (1995) was followed, which consists in balancing the entry and exit temperatures of the system in the morning, before sunrise, exposing the equipment to radiation for twelve hours, and then extract as much water as necessary to reach equilibrium again, if possible at the same temperature as in the morning. Six hours after solar noon, water was extracted at a flow rate of 10 L / min until the stability conditions were reached. The outlet water temperature was measured every 2 s. Average temperature values were calculated every 40 L of which useful energy is obtained by integration. During the 12 hours of radiation exposure internal temperatures, ambient temperature, wind speed and solar radiation were measured. The tables 4.1 y 4.2. show the results of two consecutive measuring days.

Tabla 4.1 Tests according to ISO standard. External factors

Date	H	Average ambient temperature	Water inlet	Tamb - Tinlet	Windspeed
	MJ/m2	ºC	ºC	K	m/s
28/12/2014	20.878.075,89	30,27	21,27	9,00	0,24
29/12/2014	15.406.868,24	31,57	21,46	10,11	0,29

Tabla 4.2. Ensayos según norma ISO. Factores internos

Volume	Average outlet temp.	Tmax extr.	Tmax-Tinlet	Q	Performance
l	ºC	ºC	ºC	MJ	
882,4	32,32	52,99	31,72	41.265.764,24	0,55
818,3	30,57	45,68	24,22	31.965.843,70	0,58

As you can see, the system has a performance greater than 50% on both days. In addition - from the results of day 28 that was characterized by the presence of a lot of cloudiness - it can be deduced that the ICSS has a satisfactory use of diffuse radiation.

3.5 Test with multiple extractions in 24-hour period

If it is desired to evaluate the degree of autonomy of the ICSS, it must be tested under conditions that are as close as possible to a situation of actual use. This is the purpose of a test routine used by the INTI on the solar platform for homologation of solar thermal equipment. It consists of performing three daily extractions, for several consecutive days.

- Stabilization of the system at the inlet temperature.
- Three extractions:
  - 80 litres in the morning, before the radiation hits the system
  - 80 around 2 pm This schedule was chosen because the system is fully illuminated only at 10:25 am by shadows of surrounding trees
  - 100 litres at night, after sunset.

- Extractions were performed with a flow rate of 10 litres / min., Measuring temperatures every 2 s averaging them every 10 litres.
- To calculate the solar fraction, it was assumed that the demand for seven daily baths, two in the morning, two at noon (or dishwashing), and three at night, had to be met.
- The energy per bath was calculated based on a consumption of 45 L at 42 ° C.

Tabla 4.3. Test results with three extractions per day

Date/time	**Extracted energy**	**Volume at 42ºC**	**Solar fraction**	**Radiation on system**	**Radiation on the plane**	**Inlet temperature**
	J	L		J/m2	J/m2	ºC
March 9				4,483,534.6	6,972,376.9	24.5
midday	11,241,741.3	64.0	0.71			
night	Wasn´t done	Wasn´t done	Wasn´t done			
morning (10)	Wasn´t done	Wasn´t done	Wasn´t done			
total	11,241,741.3	64.0				
March 10				13,767,980.7	15,792,886.4	23.3
bath	24,214,073.8	137.8	*)			
night	11,411,408.1	64.9	0.90			
morning (11)	14,106,407.6	80.3	0.89			
total	49,731,889.5	283.0				
March 11				18,039,394.3	18,074,529.5	24.4
midday	19,521,935.9	111.1	1.23			
night	23,395,056.4	133.1	0.99			
morning (12)	15,184,848.9	86.4	0.96			
total	58,101,841.2	330.6				
March 12				15,829,366.7	16,162,930.8	24.9
midday	19,850,128.9	113.0	1.26			
night	23,235,857.9	132.2	0.98			
morning (13)	14,478,673.4	82.4	0.92			
total	57,564,660.3	327.6				
March 13				12,794,330.3	13,366,343.1	24.4
midday	20,359,168.3	115.9	1.29			
bath	9,447,093.3	53.8	*)			
night	12,498,288.6	71.1	0.93			
morning (14)	14,222,019.7	80.9	0.90			
total	56,526,569.9	321.7				

5. Conclusiones

The results of the measurements, lead to the conclusion that the combination of the integrated design, with the parabolic concentrators generates differences of temperatures of up to 16ºC inside the tanks.

The difference in temperatures inside each tube together with the thermosiphonic connection gives rise to a stratification process by placing each tank at a different average temperature and allowing to reach usable temperatures in reduced intervals of time: Starting from a balanced system at the inlet temperature it took two and a half hours to reach 42 ° C in winter. The temperature differences decrease as the equilibrium temperature approaches, making the entire system reach usable temperatures.

During extraction - instead of decreasing as usual - stratification is accentuated due to the location of the water inlets and outlets of each tank. Water is practically moving in isothermal layers from the lower to the upper tanks. In this way it is possible to maintain the usable temperatures and the process of recovery of the temperature begins immediately after the end of the extraction (diurnal) or even during it.

These characteristics allow to reach in the collection yields that are around 55% that were measured with the procedure established by ISO 9459-2. As a complete system - measured in 24-hour periods - the yields of the system with a lid are around 50%. The system meets the expectations regarding thermal behavior and manages to obtain the expected autonomy, is robust, resistant to hard water and frost.

An industrial model is currently being developed, complying with international quality standards and taking into account aspects that are related to installation and maintenance.

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