PERFORMANCE OF INTEGRAL COLLECTOR STORAGE SYSTEMS OF OVAL SECTION TANKS

Javier H. Garnica, Juan M. Lucchini and Jorge R. Barral

School of Engineering, Universidad Nacional de Río Cuarto, Río Cuarto (Argentina)

1. Introduction

When solar domestic hot water (SDHW) systems are analyzed, it has been proved that consumers rank the environmental benefits very low and most of them make their purchase decisions based on utility bills and saving money (Morrison and Wood, 1999). In addition, just those countries that have implemented promotional politics on the use of renewable energy have achieved good results on the deployment of the technologies and the replacement of fossil fuels (Streimikiene and Girdzijauskas, 2009) (Haas et al., 2004) In this context, many countries, like Argentina, which do not have yet a politics and clear laws to support the renewable energies, need to impose their products based mostly in the low price of them. In contrast, one of the main drawbacks of many solar applications, like is the case of solar domestic hot water, are their expensive initial costs (Hawlader et al., 1987). Then, the use of Integral Collector Storage (ICS) systems in these situations results very competitive, since these systems are composed by just one unit, in comparison with active or thermosyphon systems that require at least to big components, the flat plate collector and the insulated storage tank.

Argentina has a good power electrical network, the cheapest natural gas in the world, and people with not too good ecological and sustainable conscience. But natural gas and inexpensive electricity are fully available just in cities with high population. Then, the solar water heating option seems to be competitive in isolated towns, villages and in country houses. In addition, this problem is in general strongly related to inhabitants with low incomes, which becomes in a social problem that degrade quality of life of these people. Then, the use of ICSs for water heating in these areas would be a possible solution for this problem but only if products at a reasonable price and with small payback periods are offered.

From the simplest systems of one tank in an insulated box, many different kinds of ICS systems have evolved in the last thirty five years (Smyth et al., 2006). The Solar Energy Laboratory of the National University of Rio Cuarto, in Argentina, have been working since 1997 in different types of ICS systems made of cheap non-conventional materials, like tubular systems with plastic absorber (Barral et al., 2002), monotank systems with cylindrical polycarbonate cover (Fasulo et al., 2001), and in the last years with models similar to one of two cylindrical tanks, proposed by Tripanastopoulos et al. (2004).

Although these last models showed to have a good thermal performance, the manufacturing of efficient reflective surfaces is very difficult, and the final volume of the whole system is very large due to the necessity of greater diameters for the tanks to increase the available hot water. Then, a new prototype was developed, following the principles of tanks in insulated boxes with the same aperture area, but aiming to the elimination of the inner reflective surfaces and to the reduction of the system volume. To achieve this goal, a special absorber-storage component was design, based in tank of oval section, which occupies all the inner cavity of the insulated box.

For this new system, structural and thermal considerations were made, which result in the addition of a reinforcement wall that divide the tank in two equal volumes. From the structural point of view, the addition of this reinforcement wall allowed the use of lighter raw materials, which was checked by using a structural finite element software. Regarding the desirable thermo-fluid behavior this reinforcement wall was useful for the stratification maintenance, which is very important in the storage water tanks to avoid the destruction of exergy (Rosen, 2001). The adequate positioning of the inlet and outlet water, bottom and top respectively, contributed also to a proper fluid circulation, making a "piston effect" (fresh water pushing from bottom to top).

Nomenclature			
k	thermal conductivity (W/m K)	ε	emissivity (dimensionless)
M_w	water mass in the tank (kg)	ν	kinematic viscosity (m^2/s)
Nu	Nusselt number (dimensionless)	σ	Stefan-Boltzmann constant (5.67×10^{-8} W/m^2 K^4)
q	heat flux (W/m^2)		
Ra	Rayleigh number	*Subscripts*	
$\dot{S}$	absorbed solar energy (W/m^2)	a	ambient
T	temperature (K)	c	Convection
t	time (s)	$c1$	cover number 1
		$c2$	cover number 2
Greeks		$cond$	conduction
α	thermal diffusivity (m^2/s)	r	radiation
β'	volumetric thermal expansion coefficient (1/K)	s	sky
β_c	ICS tilt angle	t	tank (absorber-storage)

Given the high thermal mass of these systems and the energy source variability, it is not possible to adopt the steady state simplification used in testing of flat plate collectors (Duffie and Beckman, 2006). Therefore, a detailed analysis of absorbed energy and heat losses is necessary. Moreover, at least a complete year analysis is necessary, to evaluate the behavior of the system in all the seasons and the results to be economically useful. Experimental studies for so long periods would result extremely expensive and, for that reason, numerical simulations are highly recommended.

This paper describe the steps followed to design and build the prototype, the instrumentation and measurements performed check its behavior and the results of a physical-mathematical model that resemble the heating and cooling processes of the prototype without water extraction. This new ICS prototype shows a good thermal performance and its advantages are analyzed.

2. Study of Absorber-Storage design

2.1. Geometry, Dimensions and Materials

The study of the new design was started considering first the shape of the absorber-storage and the materials to be used. Since the system is thought receiving the water from an elevated reservoir tank of the house, it is expected that the pressure inside the absorber-storage is not going to be too high, but in spite of this, the shape of this element must be well designed in order to avoid any extra reinforcement. In addition, the external dimensions of the absorber-tank must be adjusted to generate a surface that occupies all the aperture collector area, intercepting all the entering radiation and avoiding in this form the addition of internal reflective surfaces.

The availability of raw materials in the local market and manufacturing requirements was also considered. Then, the absorber dimensions were optimized in accordance to the commercial steel sheets, in order to avoid the generation of scraps. Moreover, the tank materials should resist the corrosion in those parts that were going to be in contact with water. Regarding the manufacturing processes, the geometry was determined in such a manner that just standard tools and small press brakes were required, and no big stamping presses or lathes were necessary.

For the cover transparent system, taking into account the hail, which is normal in the region, an alveolar polycarbonate sheet was thought for the external part; a thin flat piece of glass was prepared for the inner part of the cover system, since glass is opaque to long wave infrared radiation generated in the tank surface, causing in this way a greenhouse effect. Of course, the requirement of durability was also established for all the materials.

Assuming no substantial changes for the conventional insulated box, a parallelepiped of galvanized iron in the external part with wool glass and expanded polystyrene as insulation, the efforts were put in the design of the absorber-storage element. As stated previously, the starting point for the design was the inner pressure in the tank; then, taking into account that these systems would be used in houses of one family, a reservoir tank placed in the roof is considered, which indicates that the system would be under a maximum pressure of 4,00 m of water column.

The determination of the relationship between the surface exposed to solar radiation and water volume inside the tank was made by using the average monthly radiation for Rio Cuarto (Grossi Gallegos y Righini, 2007). Then, for July, the worst winter month, and for a 45º North tilted surface, a rough estimate of 14 MJ per square meter of available radiation in an average day is made. From the experience of the GES team in the study of integral collector storage systems, it is proposed that around a 60 % of this energy would be positively transferred to the water. Then, a relationship of fluid volume to area exposed to radiation of 100 dm^3 per square meter was assumed, which would imply an average water thermal change of 20º for a typical day of July.

Cylindrical tanks do not allow the variation of the volume/surface relationship, from which the absorber-storage could not be of cylindrical section, but taking into account the pressure requirements, the walls of the tank could not be flat neither. Then, limited by the previous considerations, but in order to maintain the construction simplicity it was decided to try a design based on an oval section with cylindrical surfaces spliced with circular sections, as shown in Figure 1.

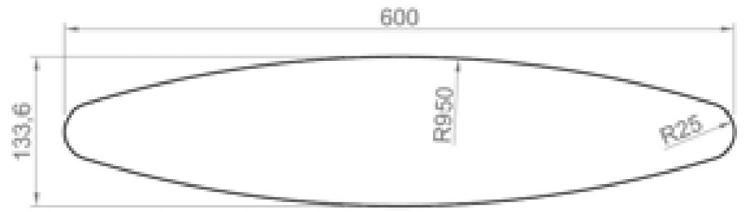

Fig. 1: Section of the absorber-storage tank. Al measures are in millimeters.

The smaller radii of the section tank were selected of 25 mm since it is an easy available tube pipe measure that would facilitate the manufacturing process. The gap between the axes of these smaller circles was selected in such manner that the container insulated box could be built from the standard galvanized iron sheets (1220 mm), which notably reduced the box construction operations, avoiding cutting, drilling and riveting works. After fixing the smaller radii and the space between the circle axes, the bigger circular arc radii were adjusted in order to obtain the volume/surface relationship previously mentioned. The longitude of the tank was defined in 1,2 m, resulting then in a storage capacity of 72 dm^3 and an exposed surface to the radiant energy of 0,72 m^2.

2.2. Structural calculations

After defining the tank section for the ICS and the characteristics of the raw materials, it is necessary to determine the adequate thickness of the walls to support the inner pressure. The classical pressure vessel design theory allows just the calculation of spherical or cylindrical vessels, and in the last case it is not possible to know the stress state at the headers. When the shape of the vessel is different from the previously mentioned, just a few design tools provided approximations with large margins of error; then, since it is difficult to know what happens point by point in the vessel material, there is a tendency to overestimate the vessel walls for safety reasons, which causes greater weights and cost of materials. It is worth mentioning that the fluid to be used is not compressible; then, there is no burst danger and it is possible the use of low security coefficients, which results in less weight and ease for manufacturing.

From the previously stated, a finite element method of structural calculation software was used to determine the sheet thickness to be used in the tank. This determination is in general an iterative process where thicknesses are proposed and for each proposal the stress state for all the model is checked. Adjustments are made until the stress state is satisfactory. In complementary form, some technological aspects have to be covered, like a minimum thickness for the steel in order the welding process to be possible, or a maximum to facilitate the bending of the metal sheets. After this process, a Carbon Steel SAE 1010 of 1,27 mm was selected to form the larger cylindrical surfaces of the tank. For this first prototype, in order to simplify the construction, structural pipe 50 mm diameter was used for the smaller radii parts of the oval tank; although the thickness of this pipe was 1,6 mm, which increased a little the quantity of welding, no especial tools were necessary to curb a sheet metal

After many structural trials and taking into account also the thermal and fluid dynamics of the water, the inclusion of a longitudinal inner wall was considered necessary. This inner wall was welded in all its perimeter dividing the tank in two equal parts. It works as structural reinforcement, since it joins the two cylindrical walls that tend to be opened by the pressure effects (see Figure 2). In addition, considering the movement of the water in the tank when hot water is required, the wall prevents from mixing and helps for the maintenance of the stratification.

It is advisable to use the symmetry of the design to minimize the computer operations required by the finite element method. Then, one fourth of the tank was used to the structural calculation as is shown in Figure 2.

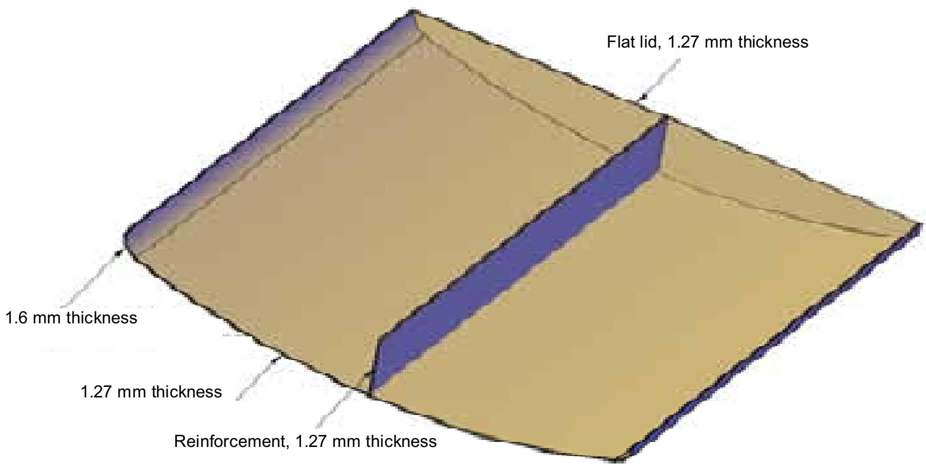

Fig. 2: Model used for the structural finite element analysis.

Applying the symmetry principles, the boundary conditions for the model result simplified. An inner pressure of 39.2 kPa corresponding to 4 m of manometric water column is proposed to run the stress analysis. This assumption responds to the hypothesis that the system would be over the roof of a house for one family, where a conventional reservoir tank is situated in the same roof, and at a maximum height of 2.5 m over the ICS. Then, the use of 4 m water column ensures a safety factor (SF) of 1.6. The SF is fixed for the pressure and not for stresses, since there exist the possibility of non linear effects that could affect the stress state.

When the geometry, the thicknesses of the different parts, the pressure and boundary conditions were known, the software of structural analysis was charged and the stress state was calculated. This is shown in Figure 3, where the stress distribution can be deducted from the label of color code. In the Figure, certain zones of the model are over the failure stress. It is worth noting that failure indicates that the material enters in the plastic region, which does not mean it reaches the steel collapse.

As a SF was established for the charge, a minimum SF equal to one is enough. The parts in red in Figure 3 are below the minimum SF. In order to analyze what happened in the inner part of the most exerted section the SF is represented in Figure 4. This Figure shows that the superficial part of the sheet has a SF less than one, but in the center of the material the SF is greater than one. Then, although there would be zones that would result with permanent deformations, the global analysis indicates that the material would resist the charge without problems. This situation was finally demonstrated by the experimental study.

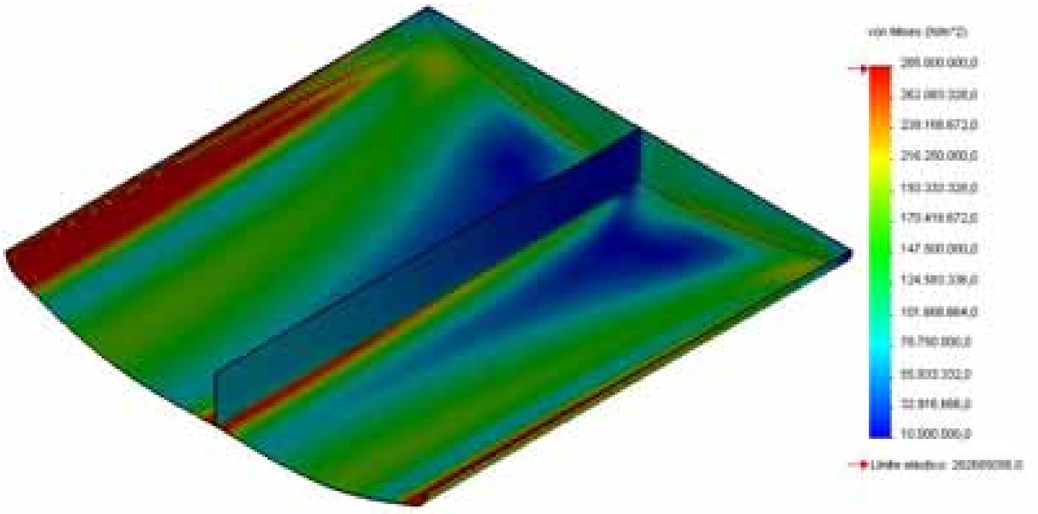

Fig. 3: Results of the finite element structural analysis – Stress distribution.

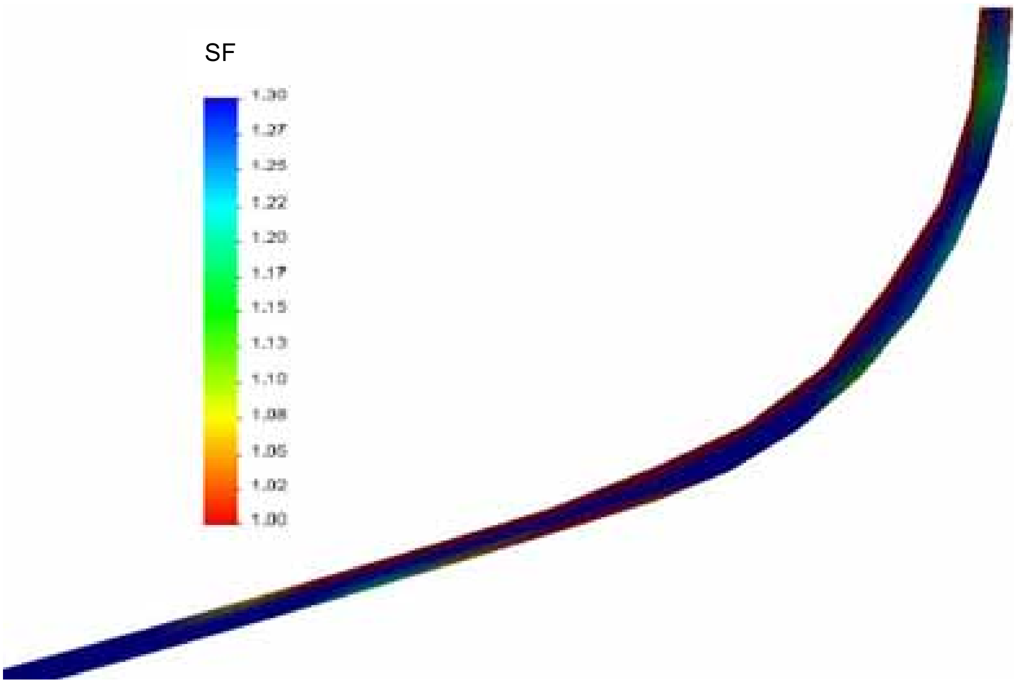

Fig. 4: Safety Factor distribution in the most exerted section.

3. Complete system and its instrumentation

Once the absorber-storage materials and shape were fixed, the whole system design was the completed. The entrance of the cold water was set in the flat lid, in the lower part of the tank, and de hot water outlet in the same lid, in the upper part of it. Commercial ¾ inches threaded nipples were coupled in these inlet and outlet connections. This particular positioning works together with the reinforcement wall in the middle of the tank, to drive the water smoothly in a circuit that makes a "piston effect" and avoids the stratification rupture. Figure 5 shows the inner part of the absorber-storage tank. The cathodic protection is also showed in this Figure. Sixteen thermocouples are distributed in the tank to follow the temperature variation in each part of the system during the day. In Figure 6, the picture shows the tank in its construction process.

The insulation of the unit was composed by two materials: glass wool adjacent to the tank (zone of higher temperatures) and expanded polystyrene. The transparent cover system was made of glass and polycarbonate. The firs cover, the nearest to the tank, was of 4 mm glass, which works as an opaque surface for the long wave infrared radiation and causes the greenhouse effect. The second cover is a multiwall polycarbonate sheet, which has a good hail resistance, effect that have to be prevented in the central region of Argentina. In addition, the polycarbonate provides a good insulation for this kind of systems. The cover system is fastened to the box by and intermediate rubber band and a metal angle. A view of most of the parts of the whole system is shown in Figure 7.

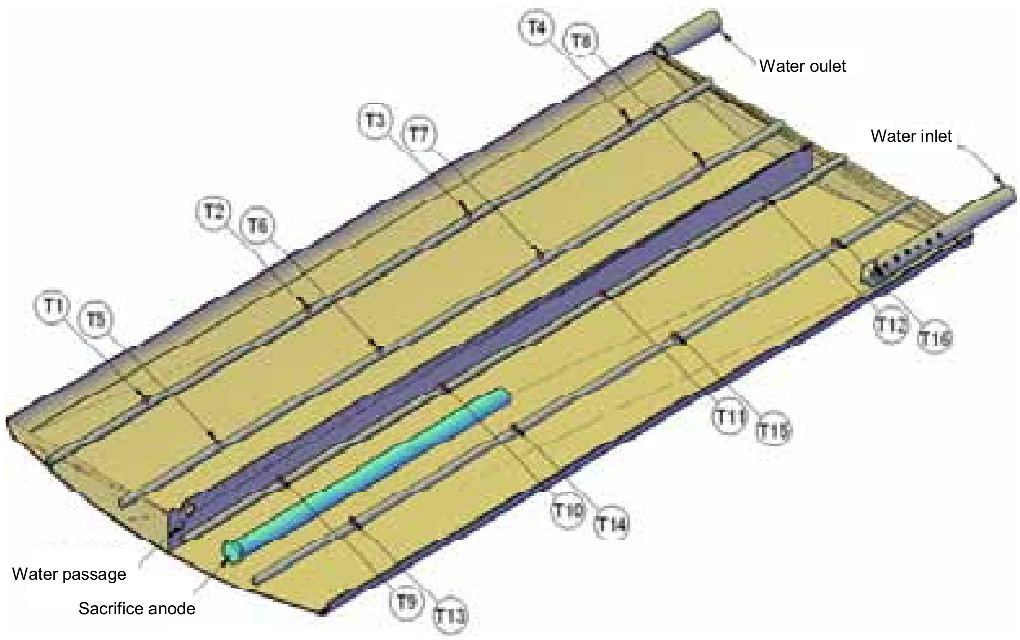

Fig. 5: Inner view of the tank. Identification of inlet, outlet, holes for water circulation, sacrifice anode and thermocouples.

Figure 8 shows a comparison of a system previously studied, cylindrical tanks with internal reflective surfaces, and this new prototype. It can be observed that for the same aperture area, same water volume, and same insulation thicknesses, the new prototype has a volume approximately 40 % less than the system of cylindrical tanks. This results in material economy and better mounting conditions when the system is set in a house roof.

1. Experimental analysis of the unit

The ICS was tested in one of the measurement platforms of the Solar Energy Laboratory of the National University of Río Cuarto, situated at 33.2 S latitude and 64.3 W longitude. The system was mounted facing North with a slope angle of 45 degrees. The experiment was performed during many days and the inner tank temperatures, ambient temperature, solar radiation, wind velocity and relative humidity were recorded every five minutes. The inner thermocouples were able to follow the energy gains of each node, and adding these node gains it was possible to compare the total energy gain of the tank related to the energy of solar radiation over the exterior surface of the cover system. In addition, the stratification process was monitored.

Fig. 6: The absorber-storage tank in construction and the complete system with the thermocouples connected.

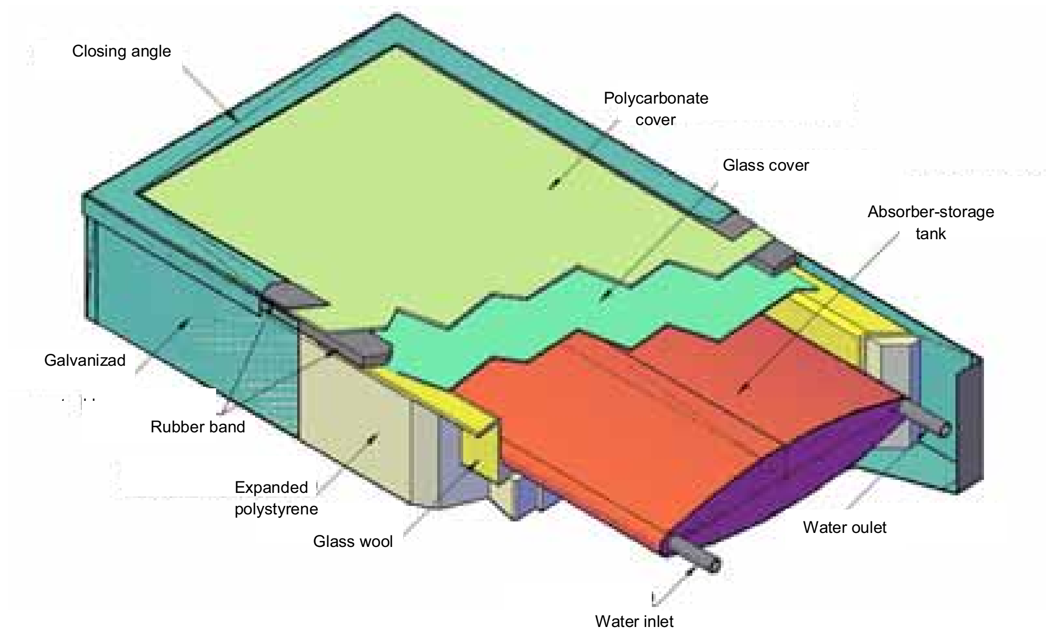

Fig. 7: Parts of the complete system.

The thermocouples were distributed inside de tank in such a way that it was possible to think that each thermocouple tested a small volume equal to 1/16 the tank volume (a node). Then, the evolution of temperatures was followed during the day for each node, and the energy transferred to the fluid was evaluated by integrating all the node temperature increments.

The data were collected and recorded in an Agilent 34970A data acquisition system. A DAVIS Weather Monitor II portable meteorological station was used to measure wind velocity, relative humidity and ambient temperature. The horizontal global solar radiation was measured by a precision pyranometer EKO SBP 801 and the direct solar radiation was measured by a Normal EPLAB firs class W.M.O. Each data was recorded every five minute.

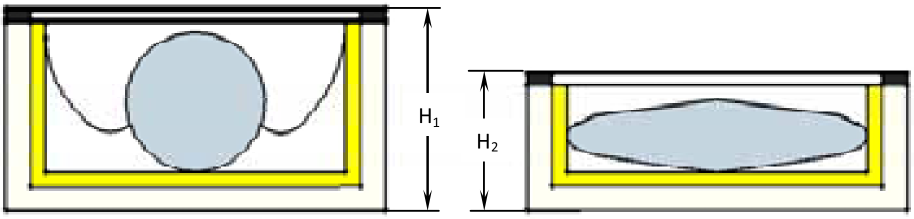

Fig. 8: Global volume systems comparison: cylindrical section and reflective surfaces vs. oval section.

Figure 9 shows the temperature evolution of the each node during a heating process in a day of the month of July. Each small rectangle represents the volume of a node (the drawing is not in scale). The times are in solar hours. By looking at the color code for temperatures, the stratification process is evident, since the lower nodes show a delay in the heating, and at the end of the process have a temperature difference of approximately 20 ºC with the upper nodes.

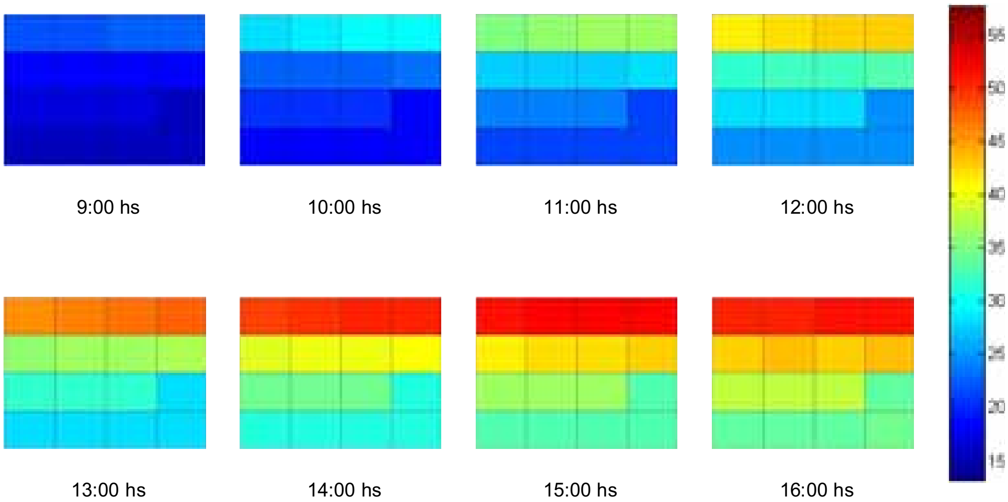

Fig. 9: Thermal evolution of the sixteen volumes of the tank during the heating process of a day.

1. Thermal modeling of the ICS

To understand the processes involved in the functioning of the system and find elements to make improvements in the design, a physical-mathematical model was developed. This model allows also to lower the expensive experimental work, by replacing the experiments by simulations (Nafey, 2005).

The ICS was broken down into subsystems to ease the task choosing control volumes. After that, energy balance equations were posed and the relationships among these control volumes appeared when heat transfer processes were identified between the subsystems.

For the absorbed solar radiation, $\dot{S}$, conventional calculations were used to consider the transmissivity of the glass (Duffie and Beckman, 2006) and a model developed by Barral et al. (2001) was used to considered the influence of the multiwall polycarbonate sheets. An average absorptivity of 0.8 was assumed for the black matte finishing of the tank surfaces. The heat losses were modeled by using conventional heat transfer correlations (Incropera et al., 2006) (Duffie and Beckman, 2006)

Only the thermal mass of the water was considered, neglecting the thermal mass of the tank steel, which is very small compared with the water. Considering the behavior experimentally checked by Figure 9, the tank was divided in four horizontal layers as isothermal nodes, considering the same mass for each node. Figure 10 shows a scheme representing energy gain and losses.

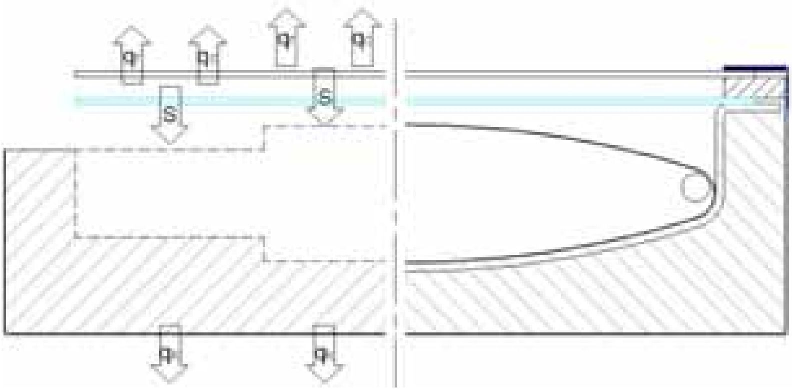

Fig. 10: Energy gain and heat losses of the ICS

Therefore, considering each node as an independent element the following energy balance equation is posed, which includes gains and losses for each time-step.

$$c_W M_W \frac{dT_{(j)}}{dt} = \dot{S} - \dot{Q}_{losses} \tag{1}$$

Where $\dot{Q}_{losses}$ represents all the convective, radiative and conductive heat losses of each section of the surface tank. Just the most representative equations of the model are shown in this paper. The losses from the tank to the first cover is described by equation (2), and from the tank through the back and lateral insulation of the box, by equation (3)

$$\dot{Q}_{losses} = q_{r,t-c1} + q_{c,t-c1} \tag{2}$$

$$\dot{Q}_{losses} = q_{cond} \tag{3}$$

The energy balance equation in the cover 1 is:

$$0 = q_{r,t-c1} + q_{c,t-c1} - q_{r,c1-c2} - q_{c,c1-c2} \tag{4}$$

The linearized radiation heat transfer coefficient between the tank and the firs cover is

$$h_{r,t-c1} = \frac{\sigma\left(T_t^2 + T_{c1}^2\right)\left(T_t + T_{c1}\right)}{\frac{1}{\varepsilon_t} + \frac{1}{\varepsilon_{c1}} - 1} \tag{5}$$

The Nusselt number to compute the convection heat losses between the tank and the first cover or between the two covers is

$$N_u = 1 + 1{,}44\left[1 - \frac{1708\left(sen\,1{,}8\,\beta_c\right)^{1.6}}{Ra\cos\beta_c}\right]\left[1 - \frac{1708}{Ra\cos\beta_c}\right]^{+} + \left[\left(\frac{Ra\cos\beta_c}{5830}\right)^{1/3} - 1\right]^{+} \quad (6)$$

where *Ra* is the Rayleigh number. The convection heat transfer coefficient for heat losses due to the wind is calculated by means of equation 7

$$h_{c,c2-a} = 5{,}7 + 3{,}8V \quad (7)$$

And the radiation heat transfer between the cover 2 (upper) and the sky is represented by

$$\dot{Q}_{c2-a} = \varepsilon_{c2}\, A_c\, \sigma\left(T_{c2}^4 - T_s^4\right) \quad (8)$$

Where T_s is the sky temperature, which is calculated by means of the following equation

$$T_s = T_{amb}\left[0.711 + 0.0056T_{dp} + 0.000073T_{dp}^2 + 0.013\cos(15t)\right]^{1/4} \quad (10)$$

The systems of equations were programmed and processes in MATLAB, using the same climatic data of the experiments, and thermophysical properties obtained from reference bibliography and manufacturers' data. Then, comparisons in temperatures and power were made for series of many days, in order to check the validity of the physical-mathematical model proposed. Figure 11 and Figure 12 show these comparisons

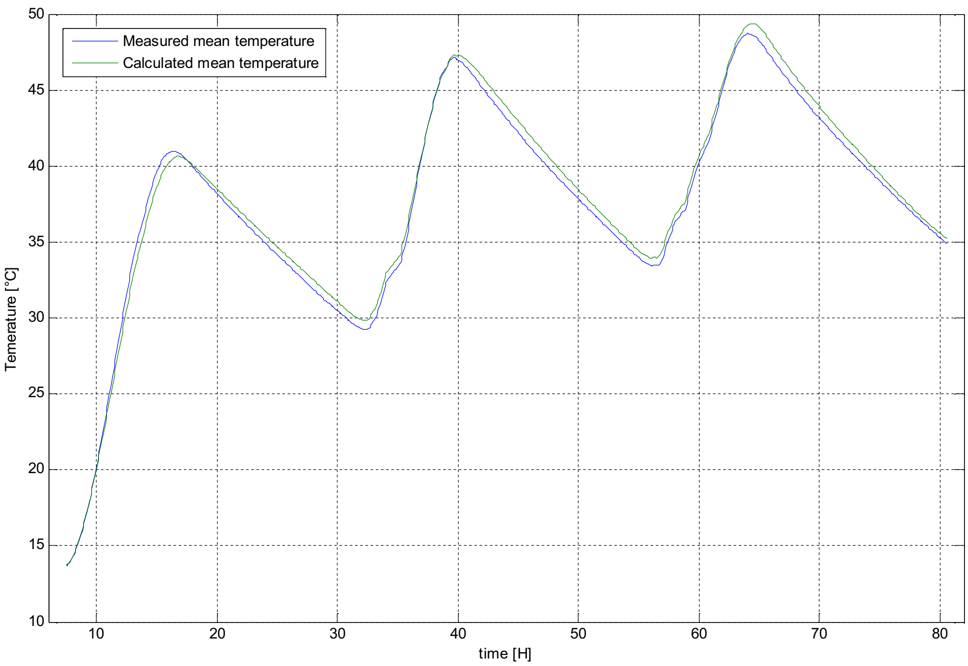

Fig. 11: Comparison between measured and simulated temperature of the ICS

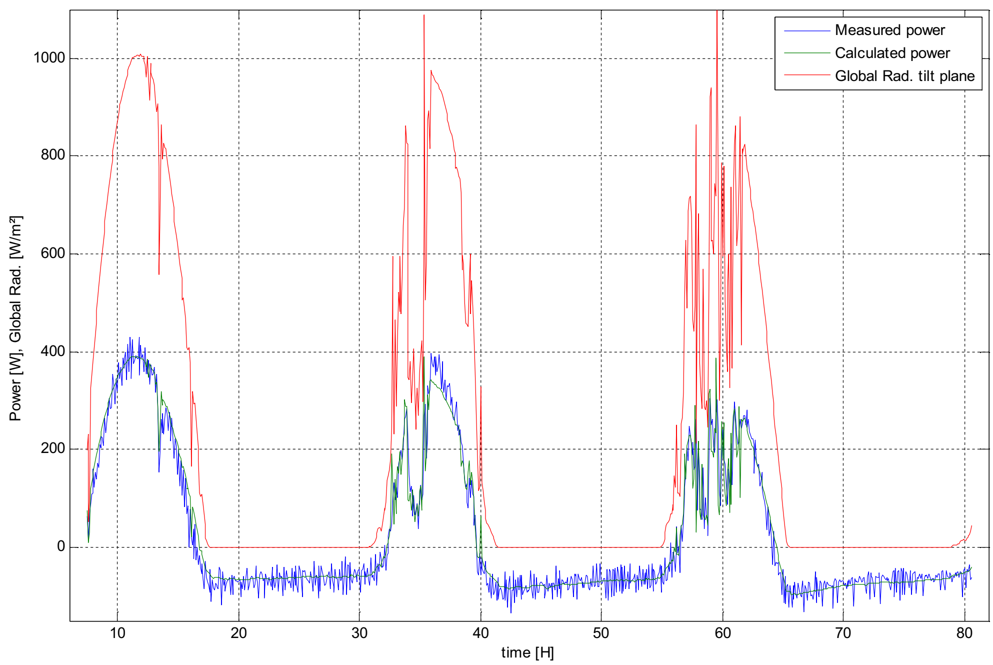

Fig. 12: Comparison between measured and simulated power of the ICS

As is normal in this kind of systems of high thermal inertia, Figure 11 shows that the maximums of temperatures occur at approximately four hours later than the solar noon. This means that this is the best time to perform the water extraction of the system. The model resembles the real system with less than 6 % of error, which can be considered as a good approximation. Regarding the simulation in power terms, the coincidence is also important, and the plot of Figure 12 allows the evaluation the night energy losses by integrating the area under the curves. In summary, this model could be used to estimate the performance of this ICS in different climatic condition. From a calorimetric analysis, this system of one 70 liters tank can be used to cover the hot water needs of two persons per day.

2. Conclusions and future research

It was demonstrated that non conventional vessel shapes can be developed by using structural finite element methods, optimizing the raw material use and given priority to the geometry for the radiant energy absorption, when the vessel is working under low pressure conditions. This calculation tool is today widely available in numerous open code softwares, and easy to use in any personal computer.

The small dimensions obtained with this design facilitate de system installation, and in the same way the effects of wind forces are diminished. The unit does not require a complex infrastructure of special tools for the manufacturing process, and the capacity can be easily changed. This prototype was designed for 72 liters, but a greater capacity unit can be made, just making a longer ICS with the same section.

The thermal performance of the system is similar to those presented by other kinds of ICS, like tubular (progressive) or ICS of cylindrical tanks with inner reflective surfaces. Although the prototype has the typical problem of all the ICSs, high night thermal loses, the cumulative energy acquired after some days without water extraction shows that the system has an acceptable insulation. In other words, for a reasonable sunny day it retains some energy to the following morning day.

Compared with the tubular systems the ICS of oval section has a lower level of complexity (fewer components and connections), and compared with the cylindrical-reflective, the oval section ICS occupies less global volume and avoids the difficult manufacturing process of reflective surfaces. Since this paper shows the development of a prototype, not much effort have been invested to lower the labor hours, but the simplicity of the system, stock management and an economy of scale would allow a notable costs reduction.

An experimental study and modeling for the system with water extractions is necessary to obtain a detailed knowledge of the ICS behavior under different user demands and climatic conditions. In addition, a special standard to test these systems have to be developed because the ISO 9459-2 standard would underestimate its best possible solar fraction. This happens because the maximum energy availability of the system occur approximately between 3 to 4 hours after the solar noon, while the ISO 9459-2 standard establishes a heating process with the water extraction six hours after the solar noon, and by that time the ICS have had important energy losses.

3. References

Barral J., G. Morichetti, P. Galimberti, A. Fasulo (2001) Evaluación de la energía solar absorbida por un colector acumulador integrado monotanque con cubiertas de policarbonato alveolar, Avances en Energías Renovables y Medio Ambiente, Vol. 5, pág. 03.31 – 03.36.

Barral J., Galimberti P., Lema A., Adaro J. and Fasulo A. (2002) Design, construction and simulation Analysis of a low cost Tubular Integral – Collector - Storage System, Proceedings de Euro Sun 2002 - The 4th ISES - Europe Solar Congress. Bologna – Italia.

Duffie J. A. y Beckman W. A (2006) Solar Engineering of Thermal Processes, Third Edition, John Wiley and Sons, Inc.

Fasulo A., J. Follari, y J. Barral. Comparison between a simple solar collector accumulator and a conventional accumulator", Solar Energy , Vol. 71/6, pp 389-401, 2001.

Grossi Gallegos H. y Righini R. (2007) Atlas de Radiación Solar de la República Argentina.. Universidad Nacional de Luján, Buenos Aires, Argentina.

Hawlader M.N.A., Ng K.C., Chandratilleke I.T., Sharma D., Koay, K.H.L. (1987) Economic evaluation of a solar water heating system. Energy Conversion Management 27, 197–204.

Incropera F. P., DeWitt D.P, Bergman T. L. y Lavine A. S. (2007) Fundamentals of Heat and Mass Transfer, Sixth Edition, John Wiley and Sons, Inc.

Morrison G. L. y Wood B. D. (1999) Packaged solar water heating technology, twenty years of progress. Proceedings of the ISES Solar World Congress. Jerusalén, Israel.

Nafey A. S. (2005) Simulation of solar heating systems—an overview. Renewable and Sustainable Energy Reviews, Vol 9, 576–591.

Rosen M. A. (2001) The exergy of stratified thermal energy storages. Solar Energy Vol. 71, No. 3, pp. 173–185.

Smyth M., Eames P.C., Norton B. (2006) Integrated collector storage solar water heaters. Renewable and Sustainable Energy Reviews, Vol. 10, pp. 503–538.

Streimikiene D. y Girdzijauskas S. (2009) Assessment of post-Kyoto climate change mitigation regimes impact on sustainable development. Renewable and Sustainable Energy Reviews, Vol. 13, Nro 1, pág. 129-141.

Tripanagnostopoulos Y., Souliotis, M. (2004) ICS Solar systems with horizontal cylindrical storage tank and reflector of CPC or involute geometry, Renewable Energy Vol. 29, Nro 1, pp. 13-38.