ANALYSIS OF A SOLAR THERMAL COLLECTOR DESIGNED FOR ARCHITECTURAL INTEGRATION.

Rodríguez Sánchez, David.(1*); Belmonte Toledo, Juan Francisco(1); Molina Navarro, Antonio(2); Almendros Ibañez, José Antonio(2);Izquierdo Barrientos, María(3)

(1) Renewable Energy Research Institute, Section of Solar and Energy Efficiency, Avda de la investigación s/n, 02071, Albacete

(2) Castilla – la Mancha University, Campus Universitario s/n 02071 Albacete

(3) Thermal and Fluid Engineering Department, Universidad Carlos III de Madrid, Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain

*Correspoding author e-mail:david.rsanchez@uclm.es

1. Abstract

The main objective of this work is to develope a theoretical model of a solar collector specifically designed for architectural integration. The main charasteristic of the solar collector is its curved absorber.

As a previous work [1], a curved prototype collector performance was compared with a conventional collector in order to prove that the curved geometry thermal losses were acceptable in cases of architectural integration. That work demonstrated the possibilities of using a curved collector in facades and roofs in certain positions, achieving big architectural integration possibilities.

As a different topology of solar collector, it would be useful to find a theoretical model that allow technicians to know the theoretical performance of the collector in order to find the most interesting architectural integration positions in their buildings. In this way, a mathematical model that analyses the ratio between the energy received by the curved solar collector and the energy received by a conventional one, is developed and compared with experimental measurements.

Once the model is implemented, the geometry of the curved collector can be optimized, looking for the highest thermal performance of the curved collector.

2. Introduction.

Since 2009, it is obligatory in Spain the installation of solar thermal collectors for domestic water heating in all the new buildings. This situation has created a conflict between architect's wishes of obtaining a 'pleasant' aesthetical view on their buildings and the law compliance of having a percentage of domestic water heated by solar energy. In fact, the law admits certain performance losses in the installations in case the collectors would be 'integrated' in buildings, as, for example, being integrated in the building roof.

Architectural integration is a subjective concept, it’s hard to tell when the aesthetical aspect of an installation is 'correct', but is possible to see that, normally, it exists a disagreement between the technical part or 'objective' of designing a installation where the performance is optimized and the artistic or 'subjective' part of finding a pleasant architectonical building for the user view. The previous works made about solar thermal collectors’ integration in buildings had not

been able to find a solution accepted by most of people [1].
From this problem, the idea of building a solar thermal collector that made its architectonical integration easier is born, assuming its performance will be theoretically lower compared with a conventional solar thermal collector. But its aesthetic characteristics allow the thermal collector being easily integrated in facades and roofs.

The main objective of this work is to present a patented design about a solar thermal collector prototype that can be used as an 'active' component in a facade and to make some preliminary tests, theoretical and experimental, that allow to conclude that the performance obtained by a aesthetical aspects collector designed can be acceptable in comparison with a conventional flat plate collector performance.

3. Prototype description

As previously commented, this design of solar collector tries to offer a pleasant aesthetical solution when integrating a solar collector in facades and roofs. Also, the prototype design allows a semi-automatic installation in different configurations, carrying with a compromise between its ornamental purpose and his very really purpose, domestic water heating, offering an acceptable thermal performance. Figure 1 shows schematically the absorbers' composition and figure 2 shows a possible facade integration configuration.

Figure 1: Absorber and complete collector sketch

Figure 2: Photographic editing of an installation of curved collectors in a real facade

The proposed solution, as it can be observed, is a curved collector in a quarter cylinder shape, which allows obtaining architectonical integration solutions in horizontal or vertical positions by composing a quarter or half (combining two collectors) cylinder columns. These topologies would have a low visual impact or even a positive one in certain situations. Another possibility that the cylinder shape offers is to be mounted as a cornice trimmer. Also, in a roof installation, the collector could be easily 'camouflaged', making it almost invisible from the outside of the building.

In order to achieve a complete aesthetical solution, the installation has to be completed with non-active elements 'dummies' that add the whole column a visual aspect of an unique large collector, offering an architectonical 'coherence'. These elements purpose is to hide the collector's connections giving the user the impression of viewing a unique collector, not the combination of several smaller ones [1].

Once the problem and the prototype are defined, it is necessary to check the collector's thermal performance and compare it with a conventional solution (flat plate collectors). To achieve this goal, the equations have been developed that allow finding the direct solar energy which a curved collector is able to collect. This allows calculating the energy losses of the curved topology in comparison with a conventional one. Which is more, preliminary experiments will be made, and comparing two identical absorbers, with the only difference that one of them is curved, forming a quarter cylinder shape.

Due to complications in building a complete curved collector, that first phase of design-demonstration of the collector has been made with naked absorbers, that is, without glass, box or insulating layers. It can be expected that the obtained performance is, logically, very low, but being both absorbers under the same test conditions it is possible to compare their performance, the main purpose of this work.

Each tested absorber consists in 4 copper pipes welded to a selective flat aluminum sheet of 360 x 1900 mm and 0,5 mm thickness. These are two selective commercial absorbers, but smaller than usually, and they are provided by Sunstrip, its main characteristics are showed in table 1.

Table 1. Parameters of the Aluminum/Copper absorber.

Flange efficiency at 20 L/min	0,94
Flange efficiency at 60 L/min	0,98
Emissions value/ratios	5%±2%
Absorption value	94%±2%
Surface tested to IEA task X	Ok

4. Solar energy picked up by a curved surface

The first task to make is to build a theoretical model that offer us a preliminary analysis of the prototype behaviour and a comparison with a flat solar collector, from the point of view of the direct solar energy captured by a curved surface an a flat one of the same dimenssions. For this development Duffie & Beckman [2] equations about radiation capturing of a flat surface are used, and then they are modified to be adapted to a curved surface case.

From figure 3 it can be deduced that the direct radiation captured by a horizontal surface is related with the earth direct radiation by the θ angle as:

$$G_{b,t} = G_{b,n} \cos\theta \quad (1)$$

θ angle can be related with declination δ, latitude φ, surface tilt β, azimuth angle γ, and time angle ω as,

$$\begin{aligned}\cos\theta &= \sin\delta\,\sin\phi\,\cos\beta - \sin\delta\,\cos\phi\,\sin\beta\,\cos\gamma + \cos\delta\,\cos\phi\,\cos\beta\,\cos\omega \\ &\quad + \cos\delta\,\sin\omega\,\sin\beta\,\cos\gamma\,\cos\omega + \cos\delta\,\sin\beta\,\sin\gamma\,\sin\omega\end{aligned} \tag{2}$$

In previous equations, replacing β=0, the equations for a horizontal surface depending on azimuth angle θz are obtained.

$$\cos\theta_z = \cos\phi\,\cos\delta\,\cos\omega + \sin\phi\,\sin\delta \tag{4}$$

If both expressions are divided, the ratio between the captured radiation by a tilted surface with a β angle and the same surface horizontally place is obtained Rβ.

$$R_b = \frac{G_{b,t}}{G_b} = \frac{G_{b,n}\,\cos\theta}{G_{b,n}\,\cos\theta_z} = \frac{\cos\theta}{\cos\theta_z} \tag{5}$$

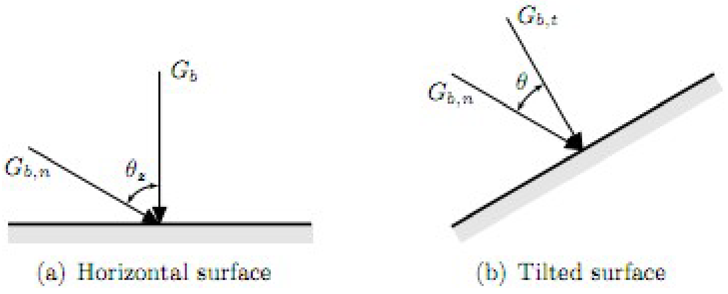


Figure 3: θ angle in a horizontal and a tilted surface.

In a similar way, it can be developed the equations that allow us to obtain the radiation captured by a curved surface. Unlike a flat surface, in a curved one β angle changes along the surface. Next main case is developed, the corresponding to a curved surface south oriented and with its longest dimension in an East-West axis placed.

From figure 4 geometry, an arch differential can be extracted and related with β angle, observing that α= (π/2)-β.

$$dl = r\,d\alpha = -r\,d\beta \tag{6}$$

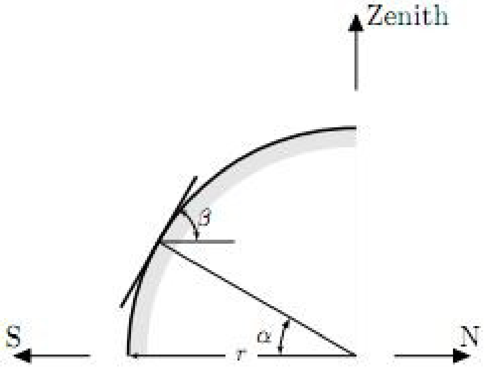


Figure 4. dl definition for a tilted surface

Integrating the intercepted radiation by a curved surface along all of it, the solar radiation captured by area unit is obtained as:

$$\bar{G}_{b,c} = \frac{\int_{\alpha_1}^{\alpha_2} G_{b,n}\cos\theta\, r\, d\alpha}{\int_{\alpha_1}^{\alpha_2} r\, d\alpha} = \frac{-G_{b,n}\, r\int_{\pi/2-\alpha_1}^{\pi/2-\alpha_2} cos\theta\, d\beta}{-r\int_{\pi/2-\alpha_1}^{\pi/2-\alpha_2} d\beta} \qquad (7)$$

where integration limits will be $\alpha_2=0$ and α_1 and they will depend of the sun position from the curved surface. If the plane containing the sun (α_p) is lower than $\pi/2$, the sun is always in front of the collector and $\alpha_1=\pi/2$. However, if $\alpha_P>\pi/2$, a collector part is not receiving direct sun radiation and then $\alpha=\alpha_{p.}$ This last situation could happen in the sunrise and the sundown of a summer day in southern latitudes.

Replacing equation 5 in last equation it can be easily obtained the ratio of solar energy obtained by a surface unit of a curved surface and the sane surface horizontally placed.

$$R_{b,c} = \frac{\bar{G}_{b,c}}{G_b} = \frac{\bar{G}_{b,c}}{G_{b,n}\cos\theta_z} \qquad (8)$$

5. Theoretical results.

With the mathematical development made, several typical day simulations are run in order to know the expected behavior of a solar collector in comparison with conventional topologies.

In this way, it is decided to simulate the longest and the shortest day of the year (June 21th and December 21th) as relevant days (the day with the highest solar angle and the highest sunny hours and the day with the lowest solar angle and sunny hours). It is studied for each day two main positions. First of them, with the curved surface south oriented and the second one East orientated. It is compared both positions with a 45º tilted flat surface and south orientated and the theoretical solar radiation and energy capture of each surface estimation are extracted estimating a mean atmosphere values based in historical data and solar angles typical of the city of Albacete, placed in the south-east of Spain (latitude 39ºN).

First simulation, with both collectors south faced on June 21th shows as a curved surface will work during more hours, capturing the available radiation, but it will capture less radiation (a 15% of highest difference) than a flat surface in the middle hours of the day. When making an energetic estimation, that different behavior can be observed and it makes that during a day the flat absorber achieves more energy, due to the hours the curved surface is the only one working, the solar resource is not high enough to compensate the losses during the main hours of the day. Figure 5a shows that results.

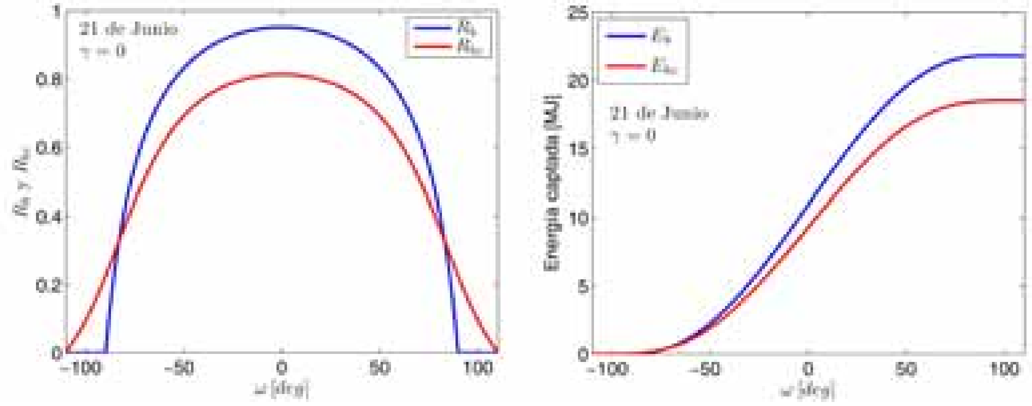


Figure 5a. theoretical capture on June 21th South faced.

When the curved surface is East faced the performance change of the curved collector is easily appreciated. It captures most of the radiation in the first half of the day, and during the second half it almost does not work. In this case, the favorable orientation in this particular day of the collector makes to compensate the daily energy caption with a flat surface. Making the daily performance difference lesser than in the previous simulation. The behavior of the collectors during the simulation is showed in figure 5b.

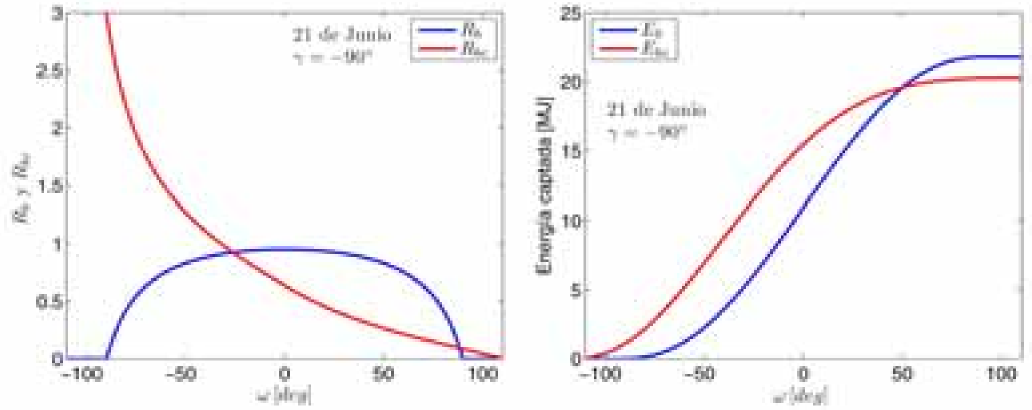


Figure 5b. theoretical capture on June 21th East faced.

In winter simulations big theoretical influences in the variation of the position of the curved absorber can be observed. When this is South faced, its behavior is very similar to the flat surface one, with a thermal loss practically zero. However, fully East faced the curved surface works better than the flat one during the first half of the day, but its performance gets lower very quickly making the foreseen performance losses respect a flat surface would be very significant. That drives to assume that an East faced installation will not be an especially interesting option in buildings that are mostly occupied in winter. Figures 6a and 6b show the results of simulations carried out for December 21th.

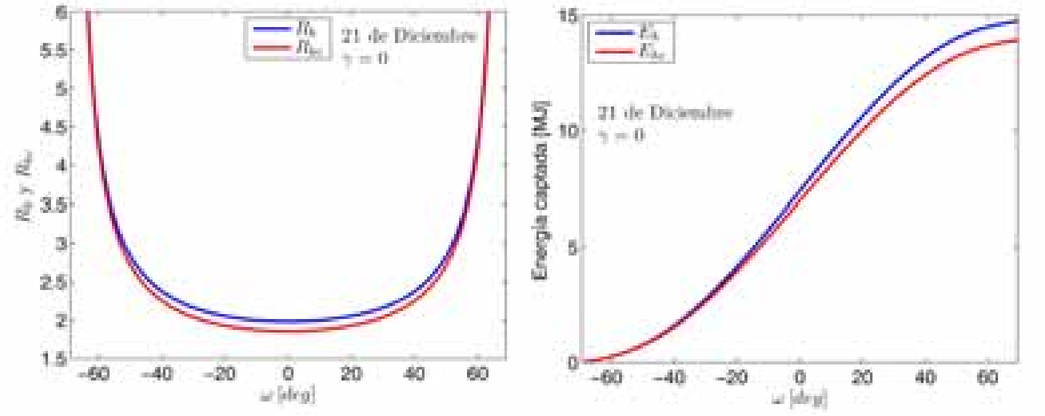


Figure 6a. theoretical capture on December 21th South faced

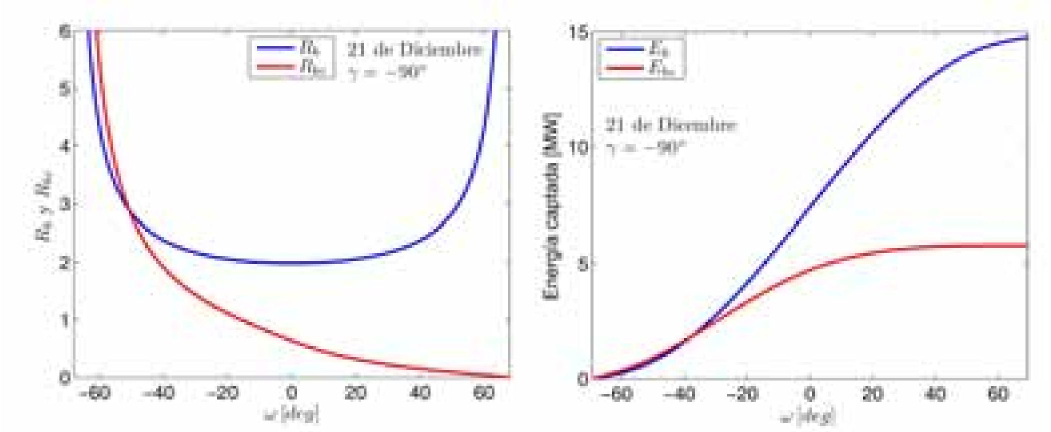


Figure 6b. theoretical capture on December 21th East faced.

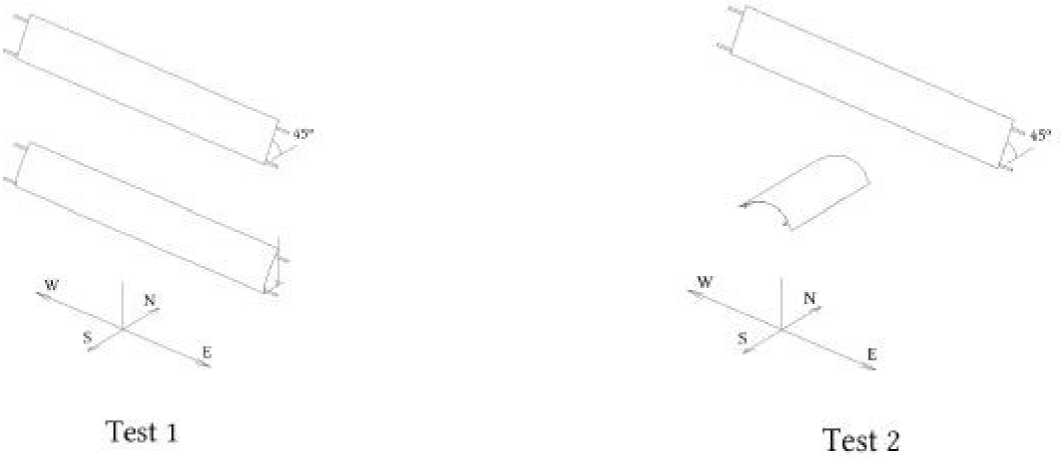
6. Experimental results.

Due to validate the previous theoretical model, several comparison tests between two identical absorbers are carried out. The only difference between them is that one of the absorbers will be bended in a quarter cylinder shape. Tests are made, as said previously, with naked absorbers, not with real complete collectors (there is not glass, box, insulating...). Obviously, the performance obtained will be low if compared with real solar thermal collectors, but as same test conditions are applied to both absorbers, the performance change in a collector due to a geometry change could be analyzed, ignoring any other influence.

First step must be to validate theoretical models. With this objective, two experiments in an experimental facility instrumented with LabVIEW [3] are carried out. Summer tests are chosen to compare with the theoretical models.

Flat absorber comparison is made always with a 45º tilt angle, mainly for two reasons. As tests are made in the Renewable Energy Research Institute of the Castilla – la Mancha University, in Albacete, latitude 39ºN, a 45º position will be a possible position for a real domestic water heating installation. Second reason is that in the first test, the curved surface will describe a curve between a 0º and a 90º angles, and a 45º angle is the mean angle that will be the angle of a projected surface of the curved surface. Second test could be made comparing the curved collector with a horizontal flat one, but the position of the flat collector is maintained because the first reason here exposed, in order to estimate the performance losses of the prototype in this position with a conventional collector in its optimal position.

Figure 7 shows schematically adopted positions by absorbers during the tests.



Test 1

Test 2

Figure 7. Sketch of the absorbers' positions during the tests.

The first test was carried out during 24 hours of a typical summer day in Spain. Due to the high exterior temperature, it was difficult to maintain constant the absorbers inlet temperature. During the higher sunny hours this temperature was controlled between a maximum variation of 7 ºC.

Figure 4a shows the results obtained in the first test. The flat absorber presents a small increment in its outlet temperature in comparison with the curved absorber in the middle of the day, although they have similar outlets temperature during the rest of the day This is caused because the flat absorber has is optimal position during the central sunny hours and the curved absorber will have an opening area smaller than its real area and 45º tilted.

The performance curves, represented in Figure 8, show a similar behavior to outlet temperature curves, i.e. during central hours the performance of the flat absorber is higher than the one of curved absorber, being the difference significant. The instantaneous performance is calculated as:

$$Eff = \frac{\dot{m}\, c_p \left(T_{out} - T_{in} \right)}{I\ A} \tag{9}$$

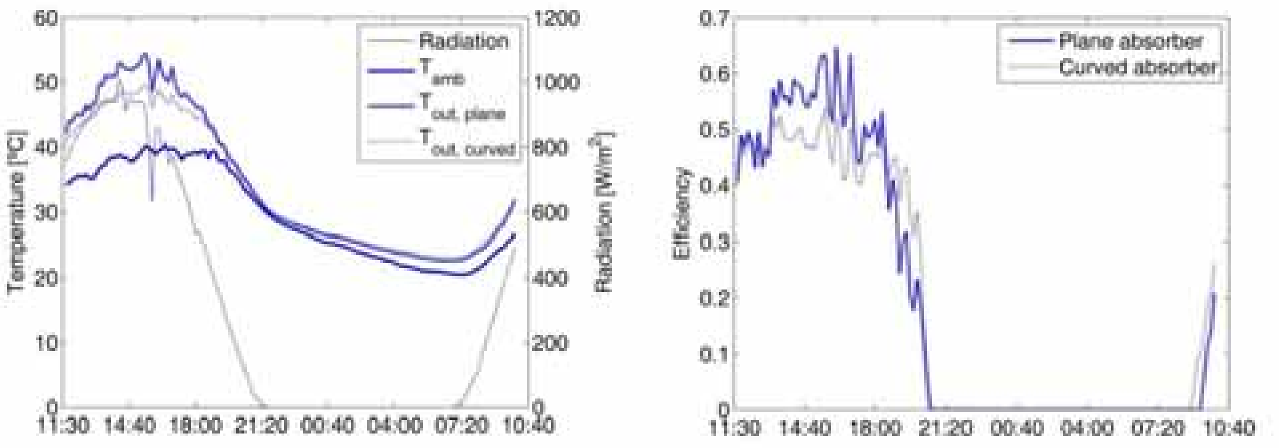


Figure 8. South faced test.

The maximum difference in the performance of both absorbers is 14%, which results in a difference of 5ºC in the outlet temperatures. As the solar radiation decreases, the curved absorber shows a better performance than the flat one because the projected area of the curved one receives more solar radiation during the sunrise and the sundown. At optimal positions, the curved absorber gives a maximum performance difference of 15%. The mean global efficiency during the period showed in Figure 4 is 0.43 for the flat absorber and 0.41 for the curved one.

Once both absorbers have been compared in the "optimal" position, we are going to vary the position of the curved absorber. Other different configuration has been analyzed: in a horizontal position, being its largest length north-south oriented. The flat absorber is maintained with the same orientation. In the horizontal position, due to its geometry, the curved absorber will receive very low sun rays, thus we can expect a higher thermal performance during the sunrise and the sundown. Figure 9 shows this phenomenon. The flat absorber has the same heat capacity as the curved one at central hours, but the second is able to achieve higher temperatures on extreme hours. In the horizontal north-south position the curved absorber offers a more linear and higher performance along the day than in its optimal position, being even higher than the one of the flat collector. Nevertheless, note that the tests have been carried out during summer period and the curved absorber is horizontally positioned, where as the flat absorber is 45º tilted. The performance of the flat absorber will be higher if it were horizontally situated. The global performances in this case were 0.24 for the flat absorber and 0.40 for the curved one.

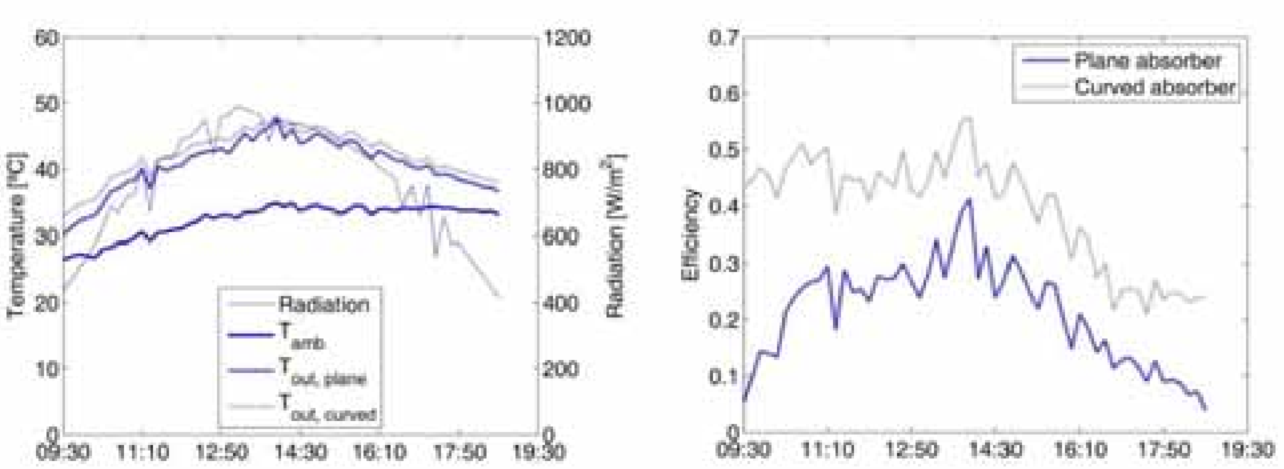


Figure 9. Horizontal position test.

7. Conclusions and future works

That first design phase compares theoretically a curved surface with a flat one. This analysis shows that the main idea of integrate curved surfaces in facades could be very promising in South faced positions but very hard to justify when lateral mountings due to high performance losses that will be make impossible to achieve the main purpose of the thermal installation. It can be observed that, during summer, the curved collector installed in lateral positions starts working very early in the morning comparing it with a flat collector South faced, fact this that perhaps could offer a chance for curved collectors in installations very attached to certain time schedules.

In the second phase, a curved and a flat absorber are compared. Due to difficulties building complete collectors, and being this work a preliminary demonstration work, it is done without any other element than the absorbers, but this fact makes that the high external losses produced when exterior temperature is very low make winter tests not possible.

These preliminary studies are considered acceptable according the expected results and show as a curved collector South faced can be competitive with conventional collectors. The fact that the thermal losses in summer will be higher than winter ones could be positive, due it allows building higher thermal installations, which will offer a higher thermal power in winter (when there is a higher demand) without risking the installation in summer due to overheating. If that occurs, the annual performance of the installation will be increased comparing with a conventional facility.

About architectural integration positions, it is only showed in this work the one where the collector is completely East faced in a roof. theoretical results tell us that mounting that kind of installations searching a pleasant aspect of the installation could be hardly defended because of the poor performance offered by the installation when comparing with an optimal performance one. Nevertheless this position is only one of the several integration positions this geometry can offer.

Because of it, is believed necessary to make a development of chapter 3 equations for adapting them to vertical surfaces, due to, at first, a curved surface mounted as a vertical column will capture a lot of radiation more in winter than in summer and it could offer a mounting positions in facades that use a high percentage of the building facade, making this a high value aesthetical configuration.

In the experimental tests, it is observed a very high atmospherics conditions influence when naked absorbers are tested. For future works, wood non-commercial boxes are being developed. These boxes will offer high possibilities of testing a complete collector with a similar behavior than a commercial one, due the wood box influence comparing a commercial one is not relevant [4].

8. Mentions and gratitude.

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9. References.

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