DESIGN IMPROVEMENTS AND EVALUATION OF THE NEW CCStaR COLLECTOR

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1. Introduction

The CCStaR project started in 2006 with the aim to bring to the market a solar collector capable of working in the range of 100ºC to 200ºC that could, at the same time, be easily integrable into light building roofs. The two principal target markets for the development were industrial process heat applications and double stage solar cooling.

For the supply of heat in this range of temperatures mainly two designs are currently used: Parabolic trough and Fresnel collectors. Although both designs can be efficiently used on ground applications as well as in flat roofs, capable of resisting moderate to high loads, neither of them are well suited for the light roofs often found in industrial buildings.

Therefore the possibility of using a different approach, based on the concept of the Fixed Mirror Solar Concentrator (FMSC), was explored. The main advantage of this kind of solution is that the largest element of the collector, i.e. the mirror, remains fixed to the building structure thus reducing the wind loads and simplifying the collector integration.

The original geometry of the FMSC, tested during the seventies by the General Atomic Company (Russell 1976), as well as curved mirror alternatives, were thoroughly analyzed using ray tracing procedures (Pujol et al. 2006, Martinez et al. 2006). Comparing the different alternatives, both from the point of view of efficiency and from manufacturing considerations, a reflector based on a single parabolic reflector was chosen.

It is known that a parabola only has a point focus for normal incidence. Nevertheless, given a high enough f/W ratio (where f is the focus distance and W the aperture width) the dispersion of the radiation can be kept in a reduced area for all of the significant (from the energy point of view) sun angles. Furthermore the path described by the area where the radiation is concentrated is a circular path which can be easily tracked with a rotating arm (figure 1).

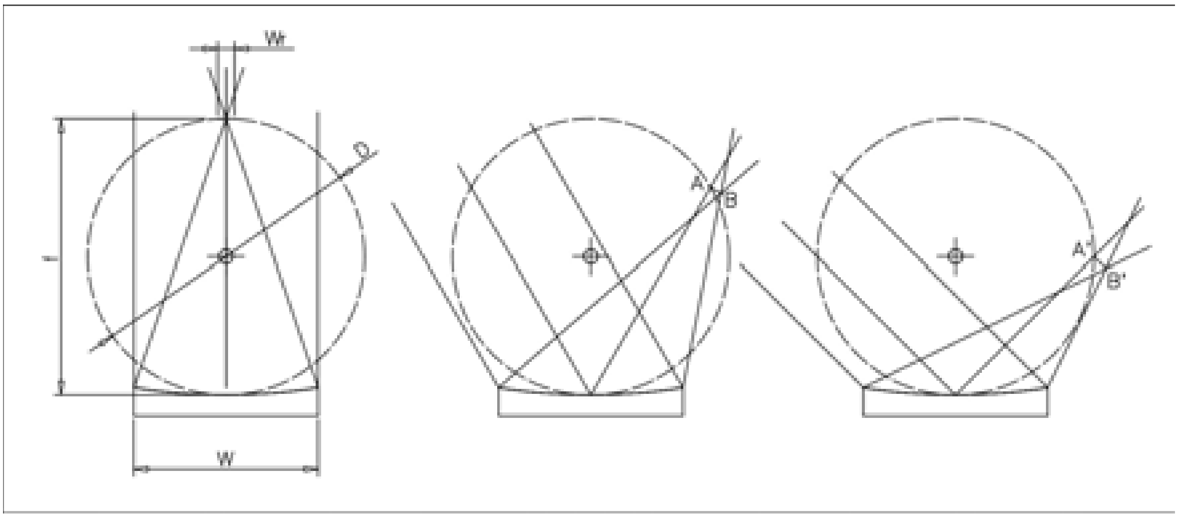

Fig. 1: Geometry of a FMSC based on a parabolic mirror

Although under ideal conditions the f/W ratio should be as high as possible, when the sun size, the mirror errors and the tracking precision are considered, it is found that increasing the f/W ratio over a certain value, can in fact, reduce the averaged collector efficiency. Furthermore, increasing the f/W ratio increases both the cost of the tracking mechanism and the visual impact of the collector. Therefore, it is unlikely that f/W values higher than 1.5 be of practical use in most applications, despite small efficiency improvements could be reached using higher f/W ratios. This fact, on the other hand, limits the geometric concentration ratio to values between 12 to 15 in order to capture most of the incident radiation (figure 2).

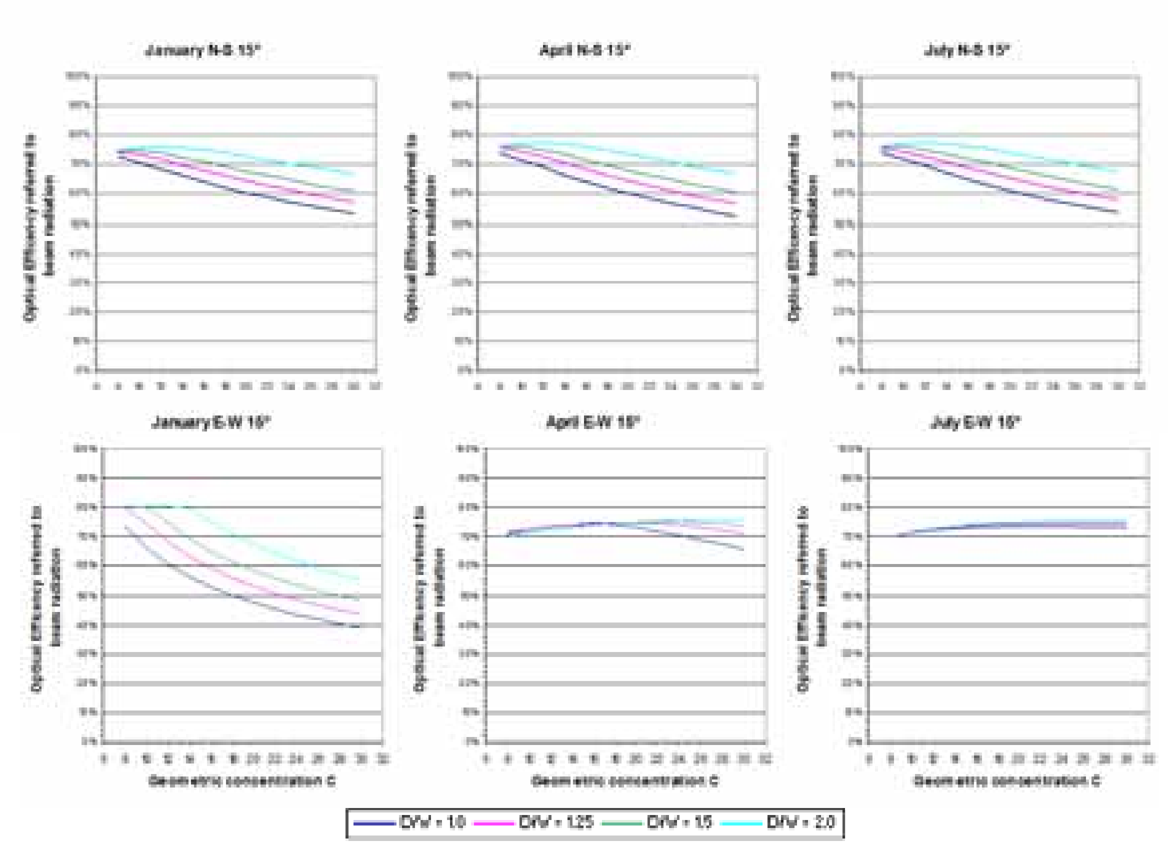

Fig. 2: Variation of the seasonal energy captured at different f/W ratios for collector installed in a south oriented surface with a slope of 15º (the values of D/W and f/W are numerically identical)

2. CCStaR basic design

2.1. Grid structure

It is a common practice for linear concentrators to try build rows of collectors as long as possible in order to minimize the tip loses. That naturally gives to modular designs which are assembled linearly in rows of variable length depending on the space available. Each row (up to a certain limit) shares the same tracking mechanism that usually transmits its action though a torsion element (figure 3).

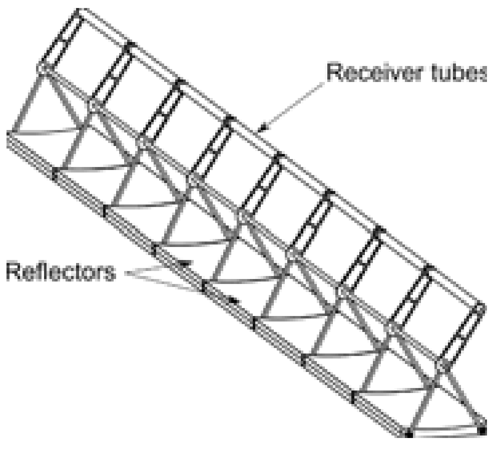

Fig. 3: Linear desging of a FMSC

This basic design, although has been successfully applied to parabolic troughs and Fresnel collectors, can not be easily extended to the CCStaR design, mainly because of the relatively large aperture width to focus distance. This implies that large moving structures should be build to provide precise positioning for an element capturing the energy of a relatively small aperture compared to PT or Fresnel collectors.

Another difficulty found in order to efficiently assemble a set of fixed mirror solar concentrators into a usable collector is that, due to the relatively small concentration ratios, the use of evacuated tubes is mandatory but, again due to the low concentration ratio, expensive tubes with inlet and outlet connections on each tip of the tube are not affordable for such a small aperture. Fortunately, it is possible to adapt conventional U-pipe evacuated tubes to work properly at such concentration levels, but then both inlet and outlet connections lay on the same tube tip, hindering the construction of large receiver rows.

Thus, instead of trying to build large aperture width collectors grouped in rows, a design was chosen with a small aperture of about 0.55 m, combined with standard U-pipe tubes with absorber diameters between 40 to 47 mm. Then, in order to reduce the cost of the tracking mechanism and the assembly times, the tubes were arranged in a grid structure with two hydraulic manifolds and a beam structure responsible for the positioning of 32 evacuated tubes organized in eight rows (figure 5).

2.2. Receiver geometry

In order to efficiently convert radiation reflected from a fixed mirror solar concentrator the absorber should be able to capture radiation coming from a large range of different angles. To accomplish this goal three .(different solutions can be used (figure 4

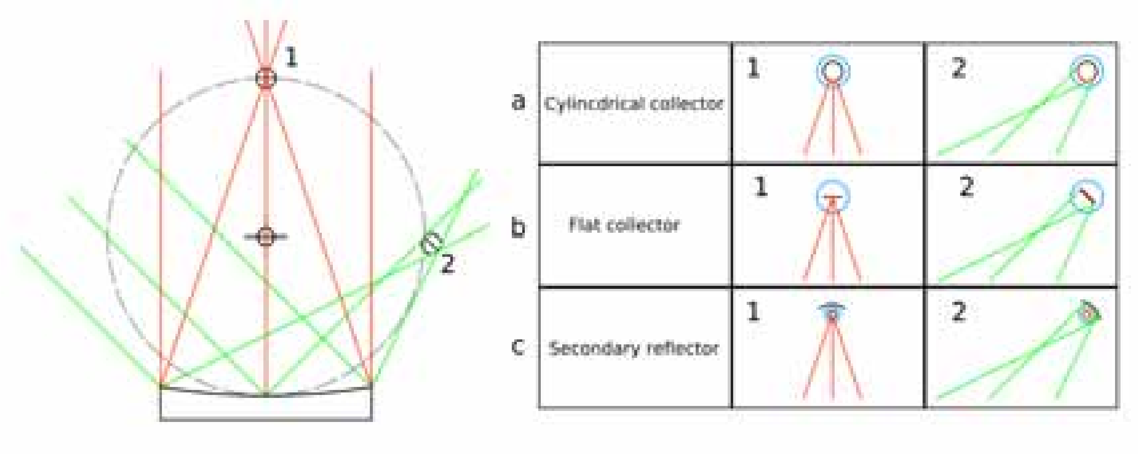

Fig. 4: Receiver geometry

The simplest of the three options, is the use of a cylindrical receiver (option *a* in figure 4) because the second option (flat collector) would require the orientation of the receiver, which would in turn complicate the hydraulic connections, and the third option would require the addition of a moving secondary reflector.

The only drawback of the cylindrical solution consists in its higher radiant surface, about a 60% higher than in the case of the flat plate receiver.

3. First prototype

3.1. Description

From the described general design, a first prototype was built and evaluated in 2008 by the company Tecnologia Solar Concentradora SL a technology development company participated by the University of the Balearic Islands. As shown in figure 5 the overall dimensions of the CCStaR module were roughly 4.5 m wide per 6 m long. The receiver part consisted of 32 standard Sydney U-pipe tubes with an absorber diameter of 47 mm. Sydney tubes where chosen because of its cylindrical shape and its excellent cost to efficiency ratio. The reflector consisted of 16 tiles manufactured as sandwich panels with a reflective aluminum sheet as the top layer, each of the tiles had two parallel parabolic trough surfaces, and measured

1125 mm width per 1500 mm long. The reflector tiles were assembled with fast joints on laser cut steel profiles while the structure supporting the evacuated tubes was manufactured out of standard aluminum profiles. The tracking mechanism consisted in four articulated arms supporting the whole evacuated tube grid animated by two DC motors controlled with on/of switches (Martinez et al. 2007).

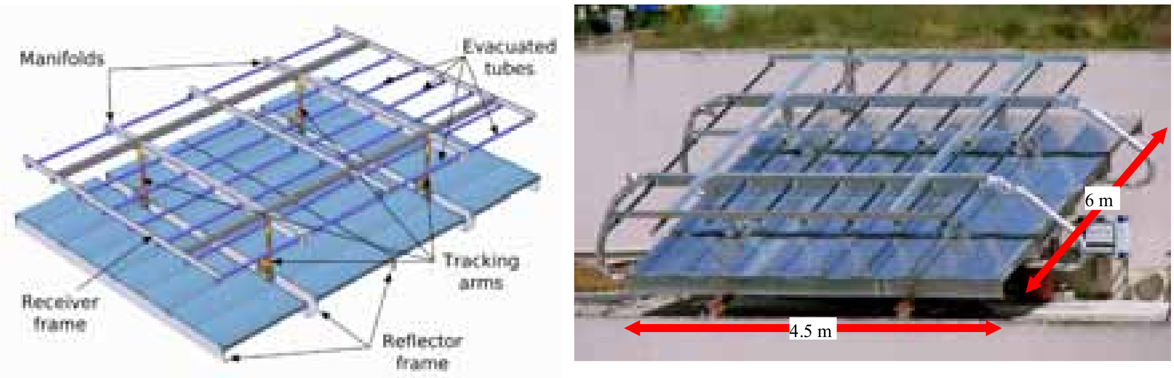

Fig. 5: First CCStaR prototype (2008)

3.2. Prototype testing

The collector started operation in July 2008, after a few tests sudden tube breakings started but, despite those problems, enough operation hours where achieved to accurately measure the efficiency of the system. Due to the large dimensions of the system it was not possible to make measurements at normal incidence, except those made using only one reflector tile and two evacuated tubes, positioned with a two axis tracker, and a special supporting structure for the tubes. These partial measurements, despite its interest, can not be directly extrapolated to the whole collector, except for the optical efficiency, because thermal loses in the hydraulic collector are not taken into account. Even for the optical efficiency, partial results may not be highly accurate due to the fact that the fixed structure used to position the evacuated tubes should not necessarily have the same average precision than the mobile structure of the CCStaR collector.

Therefore the efficiency coefficients had to be evaluated in two steps: First, the IAM curves of the collector were estimated using a ray tracing model of the collector, taking into account, not only the detailed geometry of the collector, but also the geometrical errors measured on the prototype. Then, the efficiency coefficients were obtained comparing the ray tracing results with the actual efficiency points measured in situ according to the quasi dynamic method described in the EN 12975 norm (EN, 2001; Pujol et al, 2010). Table 1 shows the obtained coefficients.

Tab. 1: Efficiency coeficients of the first CCStaR prototype (2008)

η_0 [-]	c_1[W/(m^{2}K)]	c_2[W/(m^{2}K^2)]	c_3 [J/(m^{2}K)]
0,6803	0,6381	0,0054	6490

The figure 6 shows a comparison between the results obtained using those coefficients and the estimated IAM curves.

3.3. Evaluation of the first prototype

Although this first prototype demonstrated the technical feasibility of the CCStaR concept, a series of problems were encountered that should be solved before efficiently using it in practical applications. Despite some of those problems have already been described in earlier presentations, we will now briefly describe them as they constitute the basis for the improved design described in the next sections.

The main problem of the first prototype was no doubt the issue of the tube breakings (Martinez et al. 2008). After some analysis it was concluded that the main factor inducing those breakings were the high temperature gradients occurring in the glass absorber in the zone of the highest radiation flux. It should be taken into account that although geometrical concentration ratio was only about 12, the uneven radiation distribution led to areas with more than 30 suns that lay only a few millimeters from others with almost no radiation exposure. Another possible cause that could be contributing to the problems were the dilatations in the hydraulic collector when the transport fluid increased its temperature more than 100ºC. As the U-pipes of the tubes where directly connected to the 4 m long hydraulic manifolds, its tips would be forced to move several mm while remaining attached to the very precisely positioned (< 1mm) evacuated glass tubes.

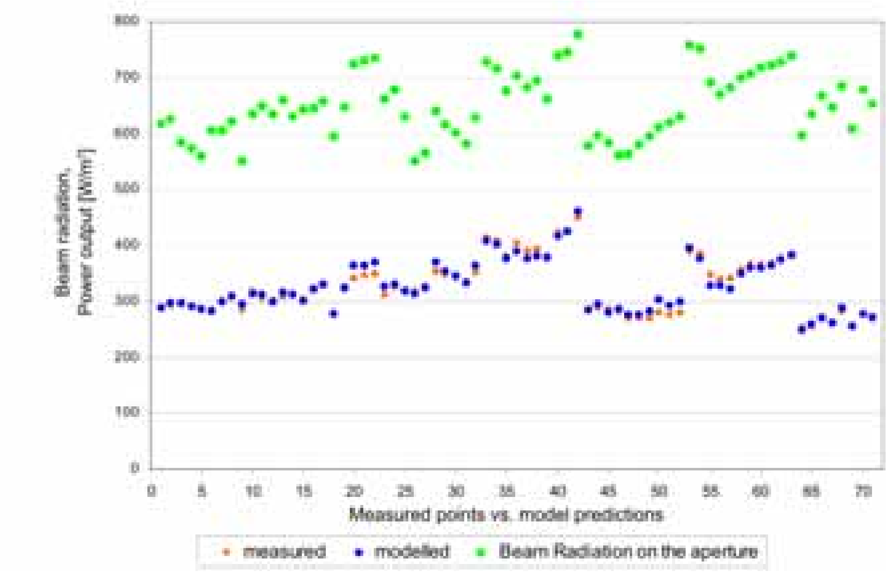

Fig. 6: Measured values vs model estimtations for the first prototype

The second problem encountered is that for low angles in the axial plane (winter time for a N-S oriented collector) the efficiency was lower than expected due to the large shadows casted by the upper structure and by the large space left between reflector tiles of the same row. The later were the spaces occupied by the rotating arms supporting the upper structure and its gearboxes. This spacing had little influence on the collector efficiency for normal incidence because its projection on the evacuated tubes was almost coincident with the area occupied by the manifolds.

Another area that required improvement was that of the mechanical precision of the upper structure. While the positioning of the reflectors and the rotating arms was perfectly under the specified tolerances, the evacuated tubes presented an average absolute horizontal misalignment of 0,9 mm and a vertical one of 3,7 mm. With maximum values of about 4 mm for the horizontal positioning and as much as 18 mm in the case of the vertical alignment. As could be expected the largest errors were found to be at the most external tube tips while the tips connected to the manifolds showed much smaller errors. The causes of the misalignments were both due to poor manufacturing precision and excessive deformations of the supporting structure. Therefore a complete redesign of the upper structure was prescribed.

Both linear and quadratic thermal loses coefficients were larger than expected, after some analysis it was found that the isolation of the manifolds was insufficient and degenerated further due to problems with the water tightness of its external cover.

Finally the tracking mechanism, although was capable of tracking the sun under the specified tolerances, required almost continuous switching of the motors in order to align both couples of arms to each other, what was considered a risk for the durability of both the motors and the control system.

4. Design improvements

When the redesign was started the obvious first step was to avoid evacuated tube breakings. The possibility of continue using Sydney tubes with some design improvements was analyzed. Nevertheless it was found that extreme temperature gradients would still be present even with the best possible designs, due to the low heat conductivity of the glass and to the number of different materials heat should go through before reaching the heating fluid (figure 7). That fact combined with the fragility of glass implied that sporadic and sudden tube fractures were unavoidable under such high and uneven radiation fluxes unless the absorber material was changed.

The alternative to the Sydney tubes were some kind of metal absorber evacuated tubes. The problem there was that typically metal absorber tubes either were designed for apertures in the range of several meters, or they were not manufactured in a cylindrical shape. Eventually, the German manufacturer NARVA developed a specially curved fin U-pipe that fitted perfectly with the specifications of the CCStaR design (figure 7).

The new evacuated tubes overcome the issue of tube breaking because the selective coating is applied on a copper fin that, given it is allowed to expand freely inside the evacuated tube, does not develop the critical stresses that were present in the glass absorber. In addition the copper fin is directly soldered to the pipes containing the heat carrying fluid, shortening the path between the selective layer and the heat carrying fluid, and thus allowing for higher efficiencies.

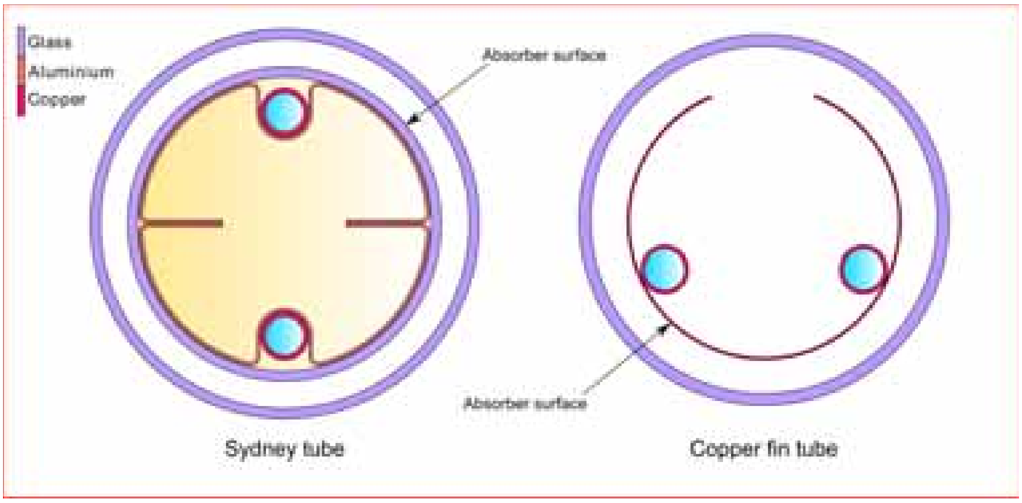

Fig. 7: Change in evacuated tube design

In order to improve the longitudinal IAM curve three measures were taken:

- The separation between reflector tiles of the same row was reduced to the minimum required for the rotating arms to move.
- The structure supporting the evacuated tubes was assembled from steel laser cut “truss like” beams, instead of using standard aluminum profiles. That allowed a lighter and “less opaque” design (see figure 8).
- The overall length of the collector was increased from 6 to 8 m. With this change, first the tip losses were reduced (related to the captured energy) and additionally the larger separation between structural elements produces also a reduction in the shadowing losses.

During the upper structure redesign one of the major considerations was the precise positioning of the evacuated tubes. A detailed finite element analysis of the different structural elements was performed, in order to be able to reduce the element deformations to the required tolerances, or to pre-compensate those unavoidable deformations. This later approach was only used in the case of the two longitudinal beams, due to its length (8 m) and the comparatively large loads they support.

In the first prototype the external cover of the manifold acted as a structural beam. Combining those two functions complicated the tightness of the design and made the hydraulic connections more complicated therefore the two functions were split adding a truss like laser cut beam to support both the evacuated tubes and the manifold itself.

The two DC motors of the first prototype were substituted by a single AC motor driving the four articulated arms. With this solution, at the same time than a cost reduction is achieved, the control algorithms are simplified and fewer adjustment switches are required to correctly track the sun. The only drawback of this solution, is that almost eliminates the possibility of a feedback based fine tracking, that could compensate small misalignments in the transversal direction. Nevertheless this option was already been discarded from the evaluation of the first prototype, after verifying that the kind of corrections that could be induced by moving the evacuated tubes connected to each manifold separately, were not able to correct the main positioning errors found.

Other improvements included special positioning tools and reference marks included in some pieces to reduce assembling times and the division of large elements in subparts to allow an efficient packaging and transportation.

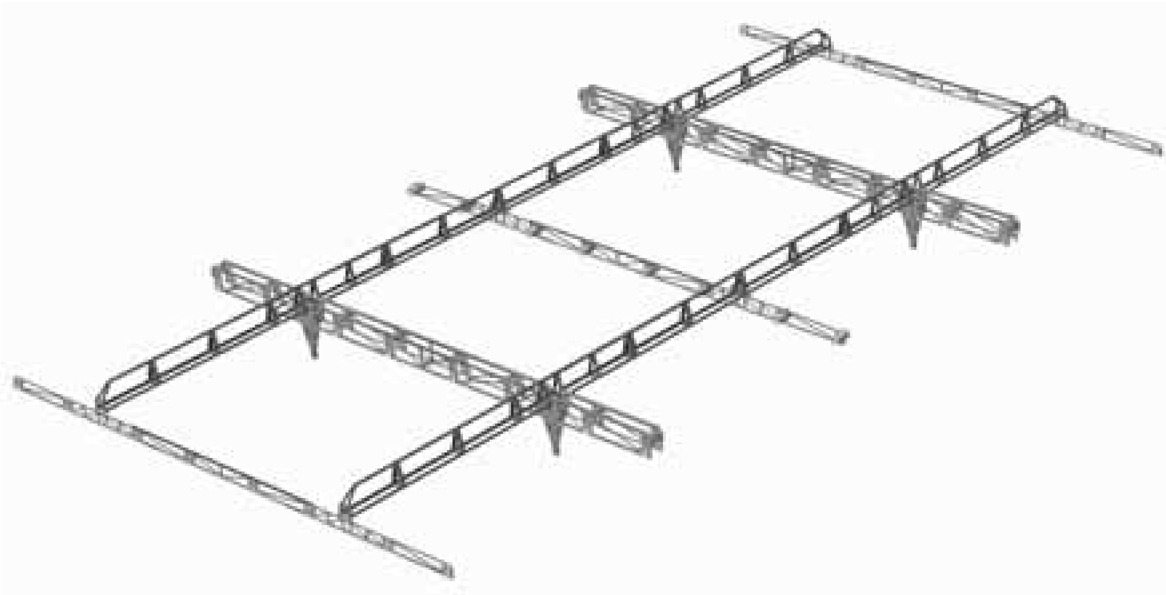

Fig. 8: New upper structure design

4.1 Evaluation

After two years of development, the new prototype was built and started operation in February 2011. In the figure 9 a picture is shown of the collector. As of now, tube breakings have not been observed insofar, neither during the assembling nor during the operation of the collector.

Fig. 9 New CCStaR prototype (2011)

Regarding the collector efficiency, measurements have been done at average temperatures from 56 to 136ºC. Although the complete analysis, combining the efficiency measurements with a detailed ray tracing calculations, has not yet been finished, a direct comparison of the obtained values with the values obtained with the first prototype shows a great improvement in efficiency for every point analyzed (figure 10). In average the measured points show an improvement of a 35% with a minimum of a 16% and a maximum of a

100%. When coming to the energy output, the difference with the first prototype is much higher because of the fact that the neat aperture has grown from 24 to 37 m^2 which combined with the increase in efficiency produces an average increase in the energy output of about a 110% while costs have increased only by a 50% (roughly) compared with the first prototype.

Furthermore it is expected that higher efficiency increments could be achieved, due to the fact that the geometric analysis of the positioning of the receivers in relation to the mirrors revealed a systematic misalignment of about 5 mm in the horizontal direction between the anterior and posterior manifolds. This misalignment comes from the assembly of the motor and the rotating arms and can be avoided by designing a more robust assembling procedure.

Apart from the problem of the rotating arm alignment, and despite the larger dimensions of the second prototype, improvements of the mechanical precision in the vertical direction of the upper structure have been achieved, with an average absolute error value of 2.5 mm. In the case of the horizontal errors an increase in the averaged absolute errors has been detected (even discarding the error in the positioning of the rotating arms). The cause for this increment, apart from the larger dimensions of the collector, is related to the fact that main longitudinal beams can not be manufactured in one single piece due to transportation considerations and should be assembled in-situ. A small redesign of the upper structure is being carried out to avoid this effect in the next facilities.

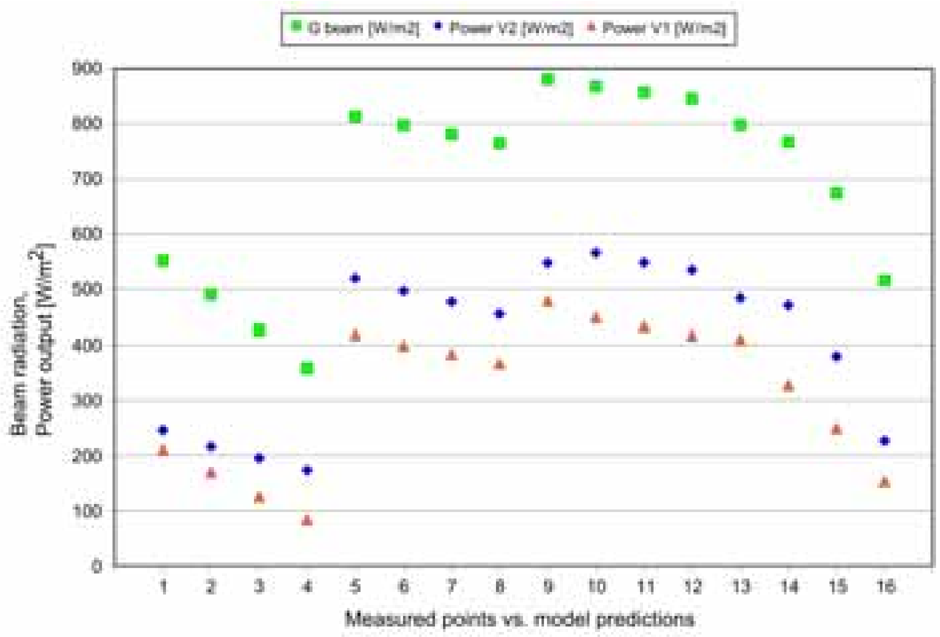

Fig. 10: Compared output (per square meter) of both prototypes.

5. Conclusions

A completely redesign of the CCStaR collector has been completed.

The new evacuated tubes have demonstrated a much higher stability under high radiation exposures. Neither tube fractures have been detected, nor any other kind of degradation, after more than six months of operation.

In most of the cases analyzed the energy output of the new collector more than doubles the one of the first prototype, with an average efficiency improvement of 35%, while costs per square meter have remained in the same level than in the first prototype.

In situ assembly procedures have been greatly improved particularly regarding the pre - positioning of the reflector structure.

After those improvements the viability of the CCStaR concept has been confirmed and the project has reached the required maturity to start demonstration plants that allow evaluating the long term performance and reliability of the collector.

6. Acknowledgements

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