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CFD optimization of CPC solar collectors

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Abstract

The use of solar energy for industrial purpose at medium-low temperature is receiving attention. As a matter of fact, this temperature range, usually between 80-200°C, requires low cost devices to convert solar energy into useful heat. In particular, the use of CPCs collectors has been suggested in literature because they can be operated without the use of a tracking system, at least within certain limits. The thermal losses of these devices are often reduced by using an evacuated pipe, but this solution increases the manufacturing costs and reduces the reliability and the optical efficiency of the receiver. A series of alternative methods for the thermal losses reduction has been proposed in this paper, for working temperature up to 200°C. Their effectiveness was evaluated by means of a previously validated CFD model. A cylindrical receiver and a concentration ratio of 2 were taken into account. The results were analyzed in terms of temperature contours and thermal efficiency. In particular, the optical efficiency was focused as a key parameter in the performances of a CPC. As conclusion, it was found that a proper arrangement of the absorber with a baffle may entail an improvement of the thermal efficiency without significantly increasing the complexity of the system.

Keywords: CPC design; solar energy; CFD optimization;

1. Introduction

Among renewable sources, solar energy appears gratuitous and inexhaustible even if its main limits are the

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variability and the low energy density. In literature, several solar devices have been proposed to exploit solar radiation. As a whole, the attention is stressed in choosing the proper concentration ratio as a compromise between thermal performances in one hand, and optical efficiency, simplicity and costs in the other. As well known, the higher the required temperature, the higher the concentration ratio [1]. In facts, for a given receiver area, radiative losses increase as T^4, while convection losses are practically linear with T and depend on the Rayleigh number, whose order of magnitude usually is in the range 10^5 - 10^7 [2-3].
However, many industrial processes, as well as other thermal systems such as ORC cycles, desalination, water treatment, heating and steam generation, require a heat source at a temperature which is in the range 350-470K. This is a temperature range in which medium-low concentration ratio compound parabolic concentrators (CPCs) may be employed even without the use of a tracking system, because of their relatively wide acceptance angle. This way the installation and maintenance costs can be reduced [1,4-5]. In addition, these low-profile and lightweight collectors may be placed where bulkier and heavier devices cannot be installed, for instance on the roof of industrial warehouses.
The thermal insulation of CPCs is usually improved by placing the receiver into an evacuated glass pipe to suppress convective and radiative thermal losses, but, reliability, optical efficiency and manufacturing cost are penalized in the meanwhile [1,6]. Consequently, the design of compact CPCs, without evacuated pipe, appears worth of investigation. This issue was already faced by several authors that investigated the effects due to cavity shapes and baffles [7-8] or the introduction of insulating materials [9] and inert gases [10]. Even though similar analyses have been carried out [10], to the authors' knowledge, this paper is the first to introduce the analysis of parametric design criteria for low cost CPCs efficiency increase. This paper also suggests the use of a baffle and of a cavity instead of insulating glasses or evacuated pipes to reduce manufacturing and operating costs. The results were provided by a CFD model that was based on an experimental approach previously discussed in [11] and followed in [2,12]; finally, a comparison with the efficiency of a commercial CPC with evacuated pipe was shown.

Nomenclature		**Greek symbols**		**Subscript**	
C	Concentrating ratio	α	Absorptivity	Opt	Optical
I	Solar radiation [W/m2]	ρ	Reflectivity		
q''	Specific thermal losses [W/m2]	τ	Transmittivity		
T	Receiver temperature [K]	η	Efficiency		

2. Numerical model

A 2D, stationary model was employed to reduce the computational effort without penalizing the results accuracy [11]. The CPC was represented in all its parts, such as the receiver, reflectors, baffle and the glass coverage. The filling air was modeled as an incompressible ideal gas [11]. The physical properties and emissivity of the materials and the modeling of thermal exchanges were provided in [2,12]. As for the boundary conditions, the temperature of the receiver was imposed, because it was assumed that the heat transfer fluid mass flow rate and temperature could be accommodated to keep constant the temperature receiver [2,12]. The external heat exchange was modeled assuming a heat exchange coefficient of $5 W/m^2K$ with an ambient temperature of 300 K. More specifically, a convective heat transfer was assumed for the outer envelope, while a mixed heat transfer, based on both convection and radiation, was assumed for the glass coverage. As suggested in [11], the turbulence was solved considering a k-epsilon model with enhanced wall treatment.
The derivatives were treated with a second order upwind approach, while a body-force weighted approach was chosen for pressure; moreover, the double precision option was set to improve the accuracy. The model was solved by means of the coupled algorithm in which the pseudo transient formulation was enabled; the convergence criteria were fixed up 10e-9. As a preliminary step, a grid independence test was carried out for mesh elements between 25000 and 70000.

2.1. Optical efficiency

Generally, the optical efficiency may be calculated by employing suitable numerical methods, such as ray tracing, with accurate values. Due to the preliminary nature of this work, the optical efficiency was evaluated by means of a simplified approach based on a solar energy balance inside the cavity [2,5,12], based on the following assumptions:

- Solar radiation orthogonal to the coverage glass;
- Sunrays incident on the parabolic reflectors were reflected only one time before hitting the receiver;
- Sunrays were assumed to be in the visible spectra;
- A value of 0.95 was chosen for absorptivity α of the receiver and for the reflectivity ρ of the reflecting surfaces; the transmissivity τ of the glass was assumed to be 0.94 [2,12].

As a result, the calculation provided values similar to other literature results [5,7].

3. Analysis of results

The thermal efficiency of the whole CPC was found as:

$$\eta(T) = \eta_{opt,model} - \frac{q''(T)}{IC} \tag{1}$$

in which the term q(T)” accounts for the receiver thermal losses and I is the radiation intensity, which was assumed to be 850 W/m^2.

3.1. Case study

The CPC collector was assumed to be installed in zones of the central Italy, for latitudes of 43 deg., with the axis aligned in the east-west direction and the coverage faced toward the South. More specifically, a concentrating ratio of 2 and a tilt angle of 35^o were assumed to maximize the solar energy collection. The circular receiver had a diameter of 35 mm, and consequently the height of CPC, evaluated as the distance between the receiver center and the glass coverage, was 225.5 mm. As for the materials, the receiver was built in copper and painted using a selective coating, while the insulation around the collector was made by polystyrene.

3.2. Baseline CPC configuration

A CPC collector with an insulated receiver and without any convection suppression device was chosen as the baseline case for the various comparisons. This configuration obviously showed the worst thermal performance but also the better optical efficiency, since the sunrays are nor blocked neither absorbed by any device put into the cavity. The optical efficiency is given by:

$$\eta_{opt,0} = \tau\alpha\left(\rho + \frac{1}{\pi C}(1-\rho)\right) \tag{2}$$

3.3. Horizontal baffle

The first type of convection suppressor considered in the work was an horizontal baffle (Fig. 1-a) placed between the receiver and the glass envelope.)). The baffle thickness was assumed to be of 4 mm. The effect of the distance between receiver and baffle was analysed and the best thermal performance (Fig.1-b) was gained by using h/H=0.1;

the reason was that the motion of thermal loop was suppressed confining the plume near the receiver as shown in Fig.2.(c). Conversely, the optical efficiency, evaluated by the relation (3), was reduced up to 0.80 because of the interaction of the baffle with the incoming radiation.

$$\eta_{opt} = \tau^2 \alpha \left(\rho + \frac{1}{\pi C} (1 - \rho) \right) \tag{3}$$

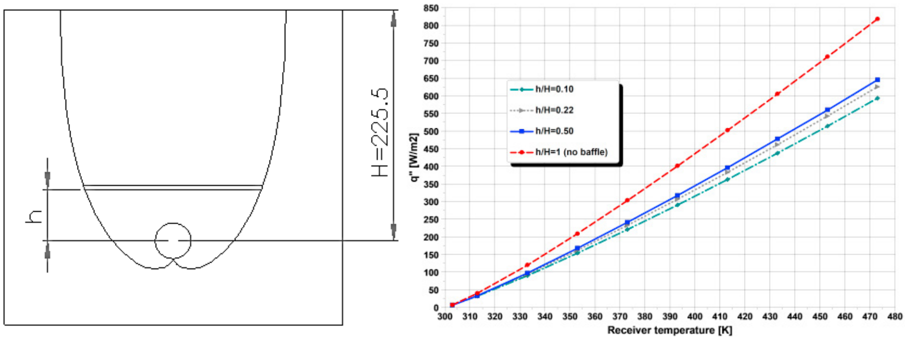

Fig.1. (a) CPC with horizontal baffle; (b) thermal losses trend.

The effect of the baffle length variation was then analysed with the aim of mitigating the worsening of the optical efficiency while increasing the thermal performance. might increase the optical efficiency as well as the insulation: for this purpose, according Fig.1.(b), a minimum height h=22.5 mm was chosen. The thermal efficiency was then expressed as a function of the quantity s/L, named aspect ratio, whose values were between 0.25 and 0.75. For the sake of comparison, also the CPCs with and without baffle, described by an aspect ratio of 0 and 1 respectively, were included. In particular, noting that solar irradiation on the receiver depends on the length s, the calculation of the optical efficiency was reasonably assumed as a weighted average based on the optical efficiencies of CPCs with s/L=0 and s/L=1 (see Eq. (4)):

$$\eta_{opt,\frac{s}{L}} = \eta_{opt,0} + \frac{s}{L} \left(\eta_{opt,L} - \eta_{opt,0} \right) \tag{4}$$

Since the geometry of the collector with a partial width baffle is not symmetrical, the analysis was carried out by considering both baffles placed on the upper and on the lower part of the reflector.

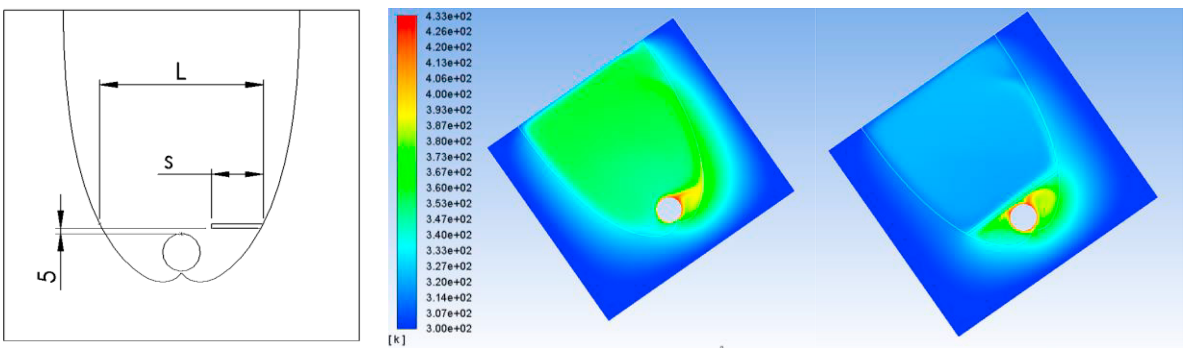

Fig.2. (a) parametric model; (b) Thermal contours for CPC with s/L=0 (no baffle); (c) CPC with s/L=1 (complete baffle) at 433 K.

In both cases, s/L=0.25 did not provide substantial results, since the overall efficiency was comparable or even worse than the baseline case, without baffle. Placing the baffle on the lower or on the upper part of the reflector resulted in a different behaviour of the overall efficiency as a function of the aspect ratio. When the baffle was placed on the lower side of the reflector, the best performance was gained with s/L=0.5 as a result of the balance between optical and thermal losses on the whole investigated temperature range (see Fig.4). When the baffle was placed on the upper side of the reflector, the trend was different, since the best result was obtained with the full width baffle (see Fig.6). Placing the baffle on the upper side, however, provided lower efficiencies than on the lower side. Placing the baffle on the lower side, in facts, proved to be more effective in suppressing the thermal plume, as reported in Fig. 3 (baffle on the lower side) and in Fig. 5 (upper side). As a whole, the baffle is effective above 353 K because the gain in thermal efficiency overcomes the loss in optical efficiency.

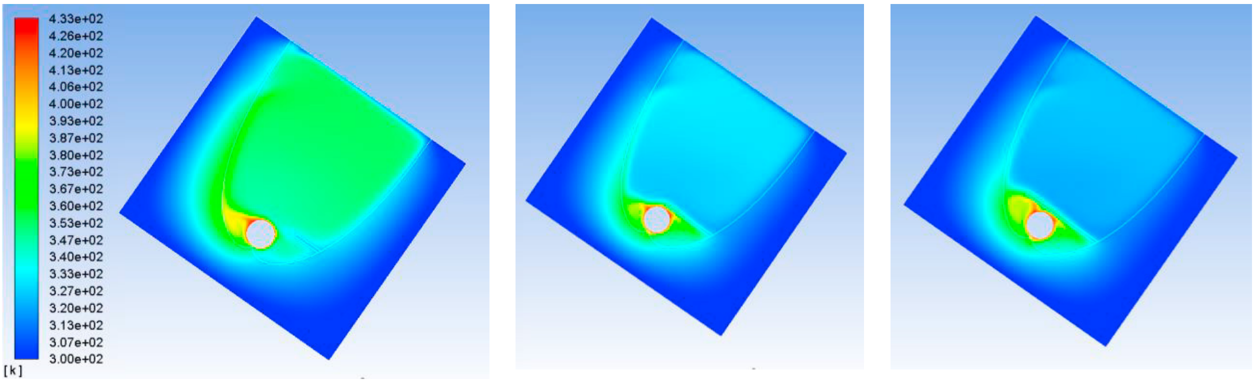

Fig.3. (a) Thermal contours for a baffle placed on the lower side of the reflector with s/L=0.25; (b) s/L=0.5;(c) s/L=0.75 at 433 K.

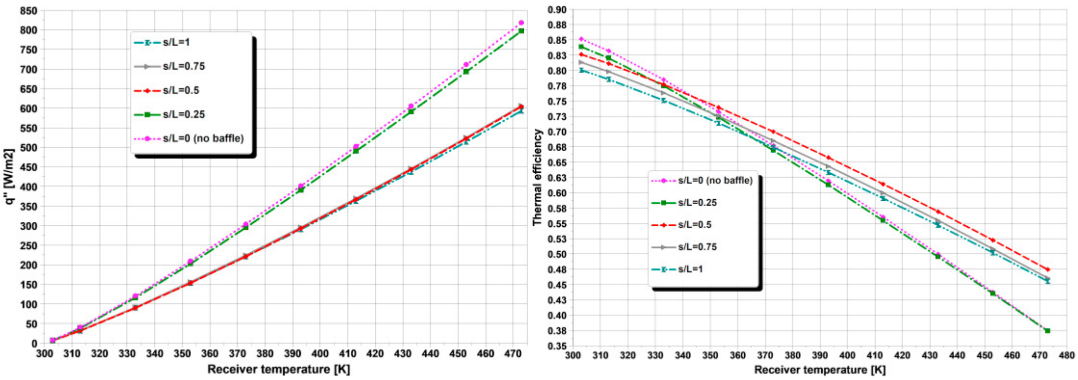

Fig.4. (a) Trend of the specific thermal losses and of the thermal efficiency for a negative tilt angle (b).

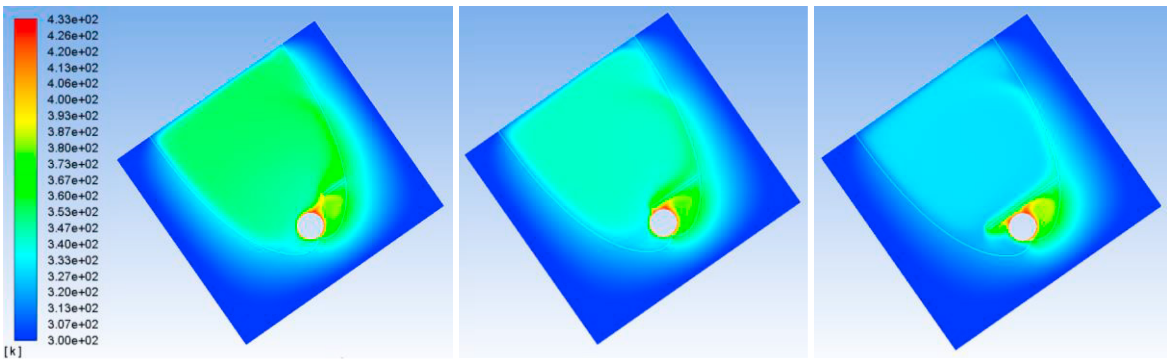

Fig.5.(a) Thermal contours for a baffle placed on the higher side of the reflector with s/L=0.25; (b) s/L=0.5;(c) s/L=0.75 at 433 K.

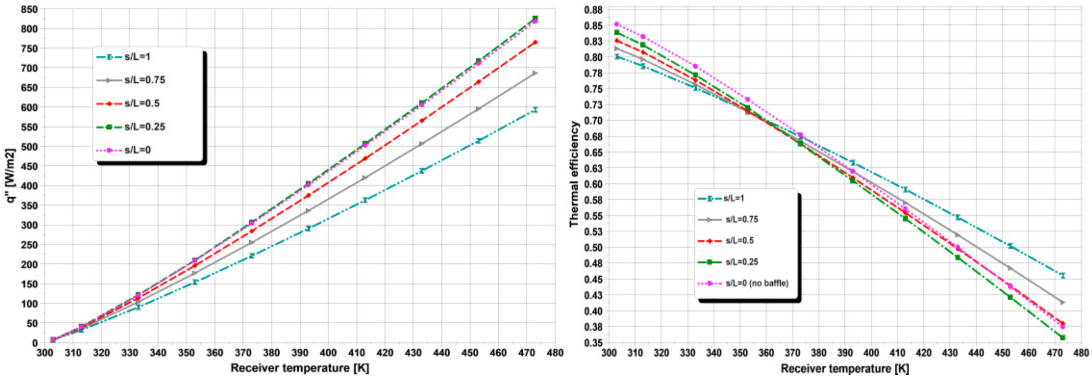

Fig.6. (a) Trend of the specific thermal losses and of the thermal efficiency for a positive tilt angle (b).

3.4. Vertical baffle.

Similarly to Eames [7], the effect of a vertical baffle was investigated, taking into account the influence of the aspect ratio. Differently from the horizontal baffle, the reduction of the thermal losses was negligible and never overcame the reduction of the optical efficiency (Fig.7-a) for any value of the aspect ratio. The vertical baffle, in facts, did not provide a sufficient obstacle to the air movement inside the enclosure and its effect as a convection suppressor was very limited (Fig. 8).

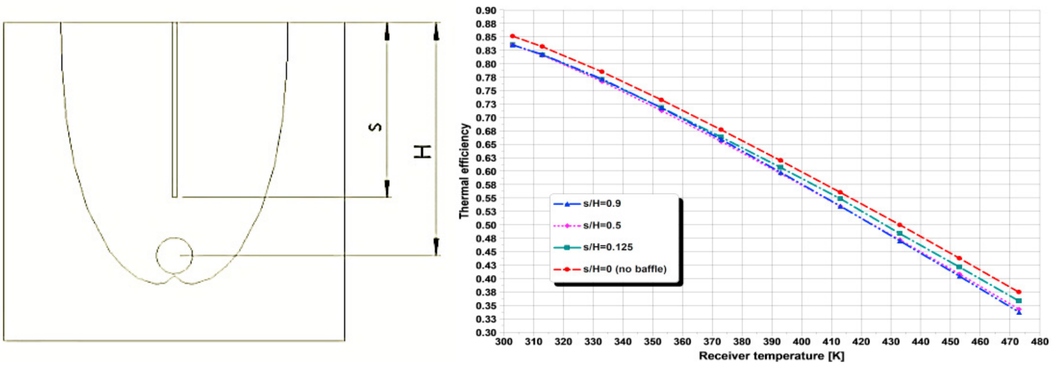

Fig.7.(a) CPC with vertical baffle; (b) trend of the efficiency for different value of term s/h.

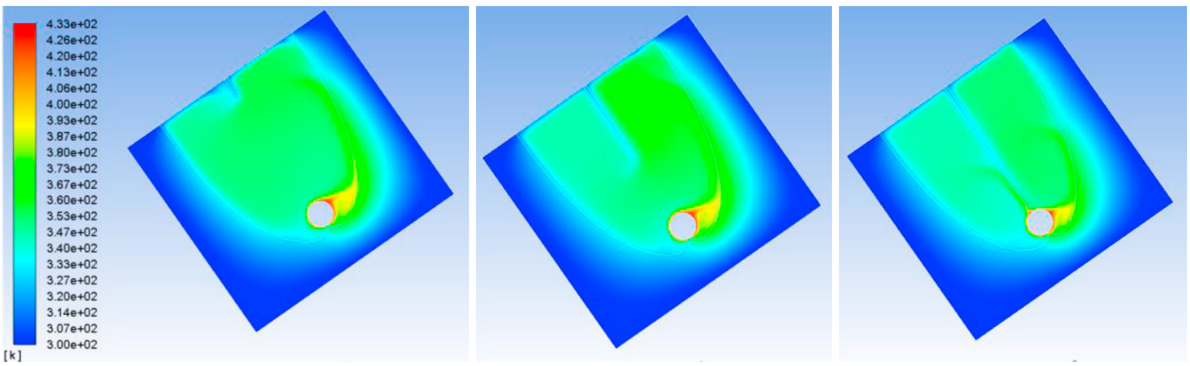

Fig.8. (a) Contours of static temperature for vertical baffle at 433 K.

3.5. Suppressing cavity.

The use of a suppressing cavity was proposed by Rabl for a flat absorber to prevent the thermal loop [1]; consequently, in this work, the original CPC was modified to accommodate a cavity for the circular receiver (see Fig.9(b)). Assuming an average number of reflections of 3, the optical efficiency, evaluated by Eq. (5), was 0.77 and the thermal efficiency at 473 K was practically 0.44 (see Fig. 9(a)). This value was lower than the efficiency of a CPC based on a horizontal baffle with s/L=0.5 and negative tilt. Consequently, the suppressing cavity appeared as an expensive solution due to the larger surface of the reflector [1].

$$\eta_{opt,cavity} = \tau\alpha\rho^3 \quad (5)$$

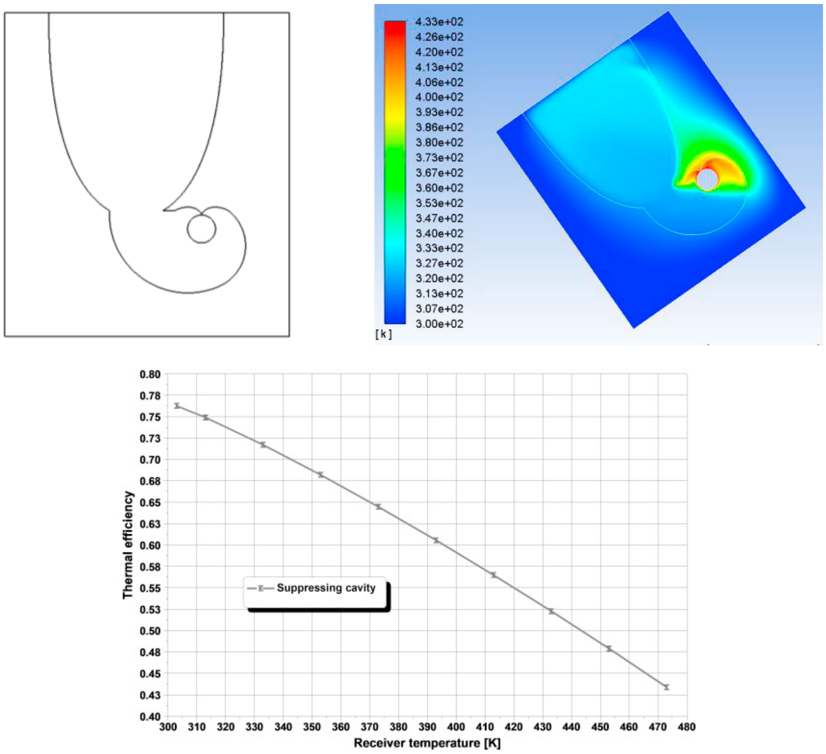

Fig.9. (a) Cavity sketch; (b) Contours of static temperature for CPC with suppressing cavity at 433 K; (c) Trend of thermal efficiency.

3.6. General comparison

If we compare the above reported results (Fig. 10), the following considerations can be drawn:

- the baseline configuration is able to provide the better efficiency below 340-350K because of the largest optical efficiency;
- between 350 and 440K, the best performance can be gained by employing a partial baffle placed on the lower side of the reflector, because this configuration provided the best balance between optical and thermal losses;
- above 440K the use of the evacuated pipe provides the largest efficiency because the thermal loss rapidly becomes the prevalent loss;
- the suppression cavity is effective only from the point of view of the thermal losses, because the optical loss is too large and this results in a not satisfactory performance at least in the investigated temperature and concentration range;
- Generally, when the receiver was at 473K, the resulting glass coverage temperature was 30K higher than the environment value, while for medium values the difference was reduced up to 15K.

4. Conclusions.

The work presented in this paper allowed comparing the effectiveness of different techniques for the convection suppression inside a compound parabolic collector with a circular receiver and a concentration ratio of 2.
The various techniques proved to be effective in different temperature ranges. Below 350K there is no need of any suppressor because the most relevant loss is the optical one. Between 350 and 440K the evacuated pipe is not necessary and a simple transparent baffle, placed transversally to the collector axis, is sufficient to reduce the thermal losses without entailing a relevant optical loss. Above 440K, the best solution from the thermodynamic point of view is the evacuated pipe, because the thermal loss is the most relevant one. These considerations relied on the optical efficiency value, that was found using a simplified approach. In particular, the optical efficiency strongly affected the thermal performance, resulting a key parameter in the design of the CPC. Consequently, a further development of this research might be the optical characterization of the proposed insulating systems.

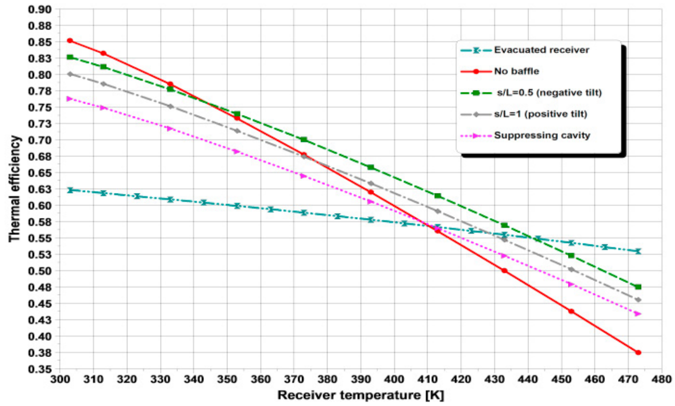

Fig.10. Comparison of efficiency of CPCs with baffle and with evacuated pipe.

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