Thermal Efficiency of a Concentrating Solar Collector Under High-Vacuum

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Abstract. A new frontier in solar thermal panel technology can be a high vacuum collector, thick enough to be equipped with solar concentrators based on non-imaging optics, such as the Compound Parabolic Concentrators (CPC). The high vacuum technology guarantees higher operating temperatures thanks to the enhanced thermal insulation, which leads to pay particular attention to the absorber radiative emission. In this paper, by means of numerical simulations, we compare the efficiency of a flat selective solar absorber under high vacuum to the efficiency of a CPC under high-vacuum collector.

1. Introduction

Solar energy is one of the best candidates to produce process heat at mid temperatures to satisfy the industrial demand. The shared aim of researchers working about this topic is to improve solar thermal collector efficiencies, in order to take full advantage from this source of energy. In recent years, the research is focusing on the vacuum technology that is the most effective way to thermally insulate the solar absorber. Such technology ensures that both gas convective and conductive losses are reduced to a negligible level, in this way collectors are able to reach high working temperatures (up to 200 °C) [1]. Concentrating Solar Power technology (CSP), combined with high vacuum insulation, could be an alternative to reach higher working temperatures. The sunlight concentration technology splits into two different broad categories: imaging and non-imaging concentration. As regarding Solar Thermal (ST) and photovoltaic (PV) applications, non-imaging concentration has been an interesting option, since mid-1960s [2]. CSP usually uses only direct-beam of the Sun [3], so mirrors require high cleaning standards and tracking systems to efficiently harness solar energy in day-light hours, resulting in high maintenance costs and installation issues. Compound Parabolic Concentrator (CPC) is an example of non-imaging concentrator that could be designed for stationary or passive tracking, even retaining acceptable concentration ratio. Moreover, it can collect both direct solar irradiation and part of diffuse light (only rays within the acceptance angle) [2] and concentrate them on an absorber tube. A new frontier in high efficiency solar collection could be a high vacuum flat solar panel, thick enough to be equipped with CPC. The CPC installed within a high vacuum envelope leads to various advantages: no
need for mirror cleaning, no corrosion due to atmospheric agents, better insulation resulting in thermal loss reduction, possibility to deposit a IR reflective coating on the interior side of the glass to benefit from ‘photon recycling’ mechanism [4]. A pioneering work [5] has experimentally investigated the idea to place a CPC under vacuum to reach the high temperatures needed for methanol reforming, but the small volume of the cylindrical vacuum chamber limited CPC dimensions and performances.

In the present work, the authors carried out numerical simulations to investigate on thermal efficiency of a CPC inserted in a proper vacuum envelope. TVPSolar is a leading company in the field of high-performance solar energy conversion that develops and produces an innovative flat-plate solar thermal collector under high vacuum. The idea of the work is to replace the flat absorber, adopted by TVPSolar, with a properly designed CPC.

The absorber tube of the CPC is supposed to have the same optical properties of the flat absorber (not optimized for mid and high temperatures applications). The CPC dimensions were chosen in compliance with the glass mechanical support of TVP panels. Results were obtained via numerical simulations in Comsol Multiphysics® software, using two different approaches to calculate the thermal radiative losses: the standard diffuse reflection and the specular reflection of the emitted power. Simulation are compared with the experimental data obtained with a flat absorber placed under vacuum.

2. Numerical Simulations

The high vacuum vessel under investigation is equipped with a mechanical supporting structure (Pin Rack) to withstand atmospheric pressure avoiding glass implosion [1]. The presence of this structure gives design constraints to the CPC, in particular the maximum span of the double paraboloid cannot exceed 110 mm in horizontal size. An analysis on several 2D arrangements [2] (shape and dimensions of the absorber and of the parabolic mirrors) has been conducted to find the best compromise between space constraints, working yearly hours and Sunlight concentration ratio. The solution proposed has a cylindrical absorber of 12 mm of diameter and double parabolic mirrors [6], 90 mm wide, with a concentration ratio of 2.4 and 25° of acceptance angle (applicable in high solar irradiance places).

The upper parts of the mirror are almost vertical and they do not influence significantly the concentration of light, the optical losses and the overall width [7]; therefore the parabolic mirrors can be truncated to reduce the panel height. In the present study we reduced the mirror height to 110 mm, however a further reduction to 90 mm would not affect the performance in a substantial way (see [7]).

Simulations have been carried out via Comsol Multiphysics® software adopting Ray Tracing technique for solar rays, whereas for IR radiative emission we used both the standard diffuse emission approach and the perfectly specular IR surface of each component of CPC. Indeed, the specular behaviour of each reflected ray is ensured by the ratio between the roughness of every wall and the radiative electromagnetic wavelength [8, 9]. In particular, in the solar spectrum the parabolic mirrors are designed to perform a specular reflection and to concentrate the solar irradiation towards the absorber, where it is almost totally absorbed (0.95 of absorptivity for the commercial selective coating adopted). In the Infra-Red (IR) region, the roughness of each component (parabolic mirrors, glass and pipe) is significantly lower than the electromagnetic wavelengths. In fact, the root mean square roughness of the less smooth component (the pipe) is approximately 1 µm, whereas the emitted power by each component has radiative wavelengths around 4 µm. For this reason, the Ray Tracing approach for the IR radiative thermal exchange seems to be more adequate.

A further complication to the simulative model is the strong wavelength dependence of the absorber emissivity. The absorber is selective, it means that its emissivity is close to 1 in the solar region of the spectrum (from 300 nm up to 2 µm) and it is close to 0 at wavelengths above 10 µm, with a quite sharp transition from 1 to 0 in the region 2-10 µm.

Since it is not possible to define the spectral emissivity as an analytical function of the wavelength, to reliably reproduce the spectral dependence of the absorber emissivity, a multi-band approach was used. The multi-band study approximates the radiative behaviour of each component as grey body (emittance assumed constant) for every single wavelength interval. In order to keep the computational time reasonable and the simulation accurate, the electromagnetic domain has been split into two broad ranges (Sun and IR spectrum). Furthermore, the IR domain has been divided in 40 wavelength intervals (to accurately reproduce the selectivity behaviour of the absorbing coating on the pipe).
The parabolic mirror adopted for numerical simulations has 0.95 reflectivity in the Sun spectrum and 0.98 in the IR range (it is a commercial mirror produced by ALMECO [10]). The upper glass has 0.95 of transparency in the Sun spectrum (double anti-reflective coatings on the glass) and it is opaque with 0.89 of emittance in IR range. In order to reduce the radiative thermal losses, the vacuum vessel can be covered by the commercial mirror [10].

To validate the numerical apparatus, an experimental set-up has been adopted. It consists of a stainless steel high-vacuum chamber, closed in the upper side by a clear glass, where we can place a flat absorber suspended by four springs of negligible conductive thermal loss [11]. A LED system [12] provides the power to heat the absorber through the cover glass. In figure 1 are depicted the sketches of the experimental arrangement (figure 1a: flat absorber in the vacuum chamber) and of the CPC under investigation (figure 1b: parabolic mirrors and the round tube).

![Figure 1.](image)

**Figure 1.** a) Geometrical sketch of the vacuum vessel with a flat absorber used in the simulation. b) Geometrical sketch of the simulated Compound Parabolic Concentrator (CPC) inserted in a panel under high vacuum.

### 2.1 Solar range: Ray Optics simulations

Ray Tracing technique has been employed to evaluate solar incident power distribution on the CPC walls (i.e. parabolic mirrors, pipe and glass) on the 2D model. To compare the results with flat absorber, the copper pipe was assumed to be coated with a selective solar absorber having the same optical characteristics of the flat absorber (solar absorptance, $\alpha$: 0.95; thermal emissivity $\varepsilon$: 0.05 at 100 °C in air). In the optical simulation, rays are released from a grid placed at the CPC entry aperture, see figures 2a and 2b. The incident angle (with respect to the CPC symmetry axis) for the incoming rays was varied from 0° to 30°. The optical efficiency of the CPC was calculated as the ratio between the power incident on the pipe absorber and the initial total power input on the mirror aperture, without considering the glass cover. The optical efficiency, so calculated, is reported in figure 2c as function of the incident angle ($\theta_i$). It is worth to note that the optical efficiency is almost constant from $\theta_i=0°$ up to acceptance angle. This is due to the balance between two opposite effects. The first effect, that would increase the optical efficiency with the incident angle, derives from the number of reflections on the parabolic mirror walls: at 0° of incident angle (see figure 2a) most rays undergo multiple reflections, whereas close to the acceptance angle a single reflection is sufficient to redirect the rays on the central pipe. The second effect, that would decrease the optical efficiency with the incident angle, leads to a reduction of the effective impinged area by cosine of $\theta_i$ (see figure 2c). Finally, figure 2c shows that above 25° of incident angle the optic efficiency drastically reduces because of the geometrical design of the parabolic mirrors [6].

In order to perform thermal simulations, for each CPC component the corresponding fraction of the input power has been calculated at 0° of incident angle, see table 1. The power fraction absorbed by the pipe can be calculated as the product of the optical efficiency and the pipe solar absorptance (0.95 in
our case). It is worth to note that the rays reflected by the absorber and mirrors are directed to the glass cover and they are mainly transmitted to the ambient (only a small and negligible fraction is reflected back to the vessel according to Fresnel law), see table 1.

![Image](image-url)

**Figure 2.** Ray tracing for solar incoming beams with an incidence angle of: a) 0 degrees, b) 20 degrees. c) Optical Efficiency as function of the incident angle.

| CPC part                  | Absorber | Parabolic Mirrors | Glass   |
|---------------------------|----------|-------------------|---------|
| Absorbed fraction of solar incoming power | 0.813    | 0.096             | 0.091   |
| (transmitted fraction)    |          |                   |         |

2.2 IR range: thermal radiation simulations

Generally, thermal radiation can be easily modelled according to the classical emission and reflection laws, i.e. radiant surfaces emit and reflect radiative energy uniformly in all directions (diffuse surfaces). In this particular case, we are dealing with CPC and the hypothesis of diffuse surface is not verified. The thermal radiation should be treated with ray optics (specular) approach, since the system is composed by mirrors that specularly reflect radiation. Figure 3b and 3c show the difference between the diffuse radiation hypothesis and the specular approach. The diffuse model (figure 3b) assumes that the emitted rays by the pipe are hemispherically reflected by mirror walls. In the specular approach, instead, the infrared rays, emitted by the pipe, reach the glass after one or two specular reflections on the mirror walls. It is clear that in case of diffuse approach, the IR emission of the pipe is mainly absorbed by mirrors, whereas in case of specular reflection the pipe irradiates mainly the glass cover.

We performed numerical simulations in Comsol Multiphysics, using both diffuse radiation and specular reflection models. Geometry of the numerical model mimics a real panel configuration with parabolic mirrors suspended inside the vessel. The flat vacuum envelope can accommodate at least 6 CPCs, but in order to reduce computational time, only one CPC mirror assembly in 2D domain has been simulated.

2.2.1 Boundary conditions and simulation details

The parabolic mirrors are supposed to be aluminium and their back side (see figure 1b) emissivity is 0.05; it is exposed to another mirror back side with the same temperature (in order to simulate one of the inner CPC of the panel). The vessel is stainless steel with surface emissivity 0.15.
Natural convection is imposed on glass and vessel external surfaces. Solar incoming power is modelled as heat flux: every CPC component receives the power fraction calculated by the ray optics analysis in solar range, see table 1.

The efficiency curve is obtained by varying the power subtracted from the circulating fluid in the pipe, from 0 W/m up to the net exploitable power.

In case of the flat absorber, the solar absorptivity and radiative emissivity of the absorber are the same of the pipe of the CPC. In addition, the flat absorber is aluminium and the not coated side has IR emissivity of 0.045.

3. Results

Results are summarized in Figure 4. The efficiency has been calculated as the net exploitable power respect to the solar power incident over the glass (the typical solar irradiation is 1000 W/m²). The experimental data were obtained illuminating the absorber by a calibrated LED illumination system[12] and recording the corresponding absorber stagnation temperature. In such configuration the power losses are equal to absorbed power and efficiency ($\eta$) can be calculated, as reported in equation (1):

$$\eta(T_{Abs}) = \tau_{glass} \alpha - \frac{P_{LED} \tau_{glass} \alpha}{P_{ref}}$$

where $P_{ref}$ = 1000 W/m² is the power density of reference (typical solar irradiation), $\tau_{glass}$ = 0.91 is the glass transparency in the Sun spectrum, $\alpha$ = 0.95 is the absorbance of the adopted commercial coating, $P_{LED}$ is the light power provided by the calibrated LED System and incident over the external side of the cover glass, $T_{abs}$ is the stagnation temperature at a given LED power.

The agreement between the two simulative models (diffuse and specular approach) and between such models and the experimental data is satisfactory, as can be seen figure 4.

The flat absorber case has been further simulated introducing the use of double AR coating on the glass (overall solar transmittance of the glass 0.95) combined with a low emissivity material (emissivity = 0.02) on the inner side of the vacuum vessel. The performance are improved of more than 10% at temperature higher than 200 °C (blue circles specular, blue line diffuse model). The adoption of a more transparent glass (0.95 respect to 0.91 of solar transparency) improves the thermal efficiency of 0.04 and it is highlighted at lower $T_{abs}$-$T_{amb}$ ($T_{amb}$ is the ambient temperature set at 20 °C) as shown in figure 4. At higher temperature, the improvement is also due to the low surface emissivity of the vacuum vessel.

Figure 3. a) Sunlight rays passing through the glass, with 0° of incident angle, impinging on the parabolic mirrors and then on the tube. b) Tube infrared emitted rays impinging on the parabolic mirrors and then diffuse. c) Tube infrared emitted rays experience a specular reflection on the parabolic mirrors, reaching the glass after one or two reflections.
(emissivity of 0.02 respect to 0.15). In this case of planar geometries, the difference between diffuse and specular models are negligible.

Figure 4 reports also simulation results of the proposed CPC configuration for both diffuse and specular models. Due to the increased optical losses, the use of the CPC (in place of the flat absorber) reduces the efficiency at low temperatures from 0.88 down to 0.77. However, as the temperature increases, the reduced emitting area and the presence of a high reflective mirror surrounding the absorber tube allow to obtain efficiency higher than 0.5 at temperature of 300 °C (0.4 at 350 °C, 0.2 at 400 °C). In this configuration, the adoption of the low emitting coating (emissivity 0.02) on all internal surfaces of the stainless steel vessel produces negligible improvements (see straight orange line and dashed black line for diffuse model): most of the power emitted by the absorber pipe impinges on the parabolic mirrors and it is directed towards the glass.

As expected for the CPC configuration, the specular and diffuse models are not equivalent. The diffuse model predicts efficiency higher than the specular one, since mirrors can return to the pipe more of its thermal emission. In order to validate the specular model, an experimental setup is needed and it will be subject of further investigations.

4. Conclusions
In this work the authors have simulated a flat solar absorber and a CPC inserted in a high vacuum vessel (stainless steel envelope closed by a cover glass). In order to validate such simulative models, experimental measurements of the flat absorber architecture have been conducted. A calibrated LED
system irradiated the flat absorber within the vacuum chamber through the glass and the thermal conversion efficiency has been calculated. Two different thermal approaches have been used to perform numerical simulations. The diffuse approach considers that the thermal radiation is reflected diffusely, i.e. every single ray is reflected hemispherically, whereas in the specular approach each ray is fully reflected in the proper specular angle. The two numerical models predict the same thermal efficiency for the flat absorber case and they are in accordance with the experimental results. Additional simulations have been conducted to predict the impact of low emissive internal surfaces of the vessel (emissivity from 0.15 to 0.02) and of the adoption of a double coated AR cover glass (high solar transparency of 0.95 respect to 0.91 for the standard clear glass). The flat absorber architecture sensibly benefits from them.

The CPC architecture has been simulated with both diffuse and specular approach too. Conversely, in this case, the results return a discrepancy between the two numerical models, showing better thermal efficiency for the diffuse numerical model (of the order of 10% above 200 °C). This phenomenon leads to the amount of radiative power emitted by the pipe that is reflected back from the parabolic mirrors to the pipe itself. In the specular approach, such pipe emission is totally focused to the glass because of the geometry of mirrors, whereas in the diffuse model there is part of pipe radiation that is reflected by mirrors and returns to the pipe. Moreover, the use of high reflecting surfaces on the vacuum vessel does not produce any significant change in the thermal efficiency, since the parabolic mirrors shield the pipe radiation. Our simulations indicate that a CPC insert in a high vacuum panel can be an interesting solution to obtain high efficiency at temperatures around 300 °C, whereas the flat architecture has zero thermal efficiency.

5. References

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