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Performance Evaluation of the Pressurized Synhelion Absorbing Gas Receiver

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Abstract. The pressurized design of the Synhelion absorbing gas receiver concept has been presented. Despite its intrinsic increased design complexity, foreseen advantages such as receiver downscaling and more compact piping and insulation systems were the drivers for the initial development of the 250 kW_{th} receiver design operating at high pressure (10 bar absolute). The latter was driven by the results of specific computational fluid dynamics (CFD) simulations aimed at evaluating the receiver thermo-fluid dynamics behaviour along with the relative performance. This paper shows the results of the two initial CFD simulations campaigns aimed at evaluating the effect, on the receiver performance, of the integration of absorbing inserts (i.e., a series of concentric disks specifically arranged into the cavity to capture the incoming concentrated solar radiation) and the position and shape of the inlet section of the heat transfer fluid. The simulations results allowed not only to evaluate the receiver performance, in terms of thermal efficiency, but also to observe some criticalities related to the motion of the HTF through the receiver.

Keywords: Solar Receiver, High Temperature, Computational Fluid Dynamics, Radiative Heat Transfer, Concentrated Solar Power, Participating Medium.

1. Introduction

An innovative cavity-type receiver concept has been proposed, and it is currently under development, by the Swiss company Synhelion SA. The peculiarity of this receiver, suitable to effectively operate at high-temperatures (>1000°C), is that its working principle rely on thermal radiation as the main heat transfer mechanism as opposed to conventional cavity receivers counting on convection to collect thermal energy. The working principle of the receiver is based on the direct absorption of long wavelengths thermal radiation by a gaseous heat transfer fluid (HTF) with suitable optical properties [1]. The present paper focuses on the development of the absorbing gas receiver for high pressure applications. Pressurized solar receivers are intrinsically more complex than atmospheric pressure receivers especially from the point of view of the pressure-induced mechanical stresses into the quartz-glass aperture window. On the other hand, a relevant advantage of pressurized receivers using gaseous HTFs is the higher density of the working fluid which allows for downscaling the cavity size of the absorbing gas receiver while maintaining a sufficient number of gas molecules for absorption of thermal radiation. While some preliminary studies on the pressurized absorbing gas receiver are already been published by the authors [2], they were based on simplified modeling approaches (typically 2D). Here, the first 3D CFD simulation results, including gravity and the main physical phenomena taking place into the receiver, will be presented.

2. Absorbing gas solar receiver working principle

In the absorbing gas receiver, depicted in Fig. 1, the incoming concentrated solar radiation, passing through the quartz window, located on the receiver aperture, is collected into the cavity and absorbed by the internal walls. This, in turn, causes a relevant temperature increase of these surfaces which start to re-emit longer wavelength thermal radiation back again into the cavity. Simultaneously, water vapor, that is the reference HTF under investigation, is fed into the cavity through a flow distributor and flows from the front, near to the aperture, all the way down to the cavity rear part. Being mostly opaque to the long wavelength thermal radiation re-emitted by the internal walls, the HTF directly absorbs a remarkable fraction of it. As a result, the HTF, flowing through the cavity, increases its temperature and shields, at the same time, the aperture minimizing hence radiative heat loss through the environment. In principle, this receiver can operate with radiation as the only heat transfer mechanism, which is particularly effective in the case of high operating temperatures [1].

An interesting peculiarity of receivers operating with gaseous HTF lays in the possibility, through appropriate design modifications, of operating at high pressure. Despite pressurized solar receivers are intrinsically more complex than atmospheric pressure receivers, a relevant advantage is the resulting higher density of the HTF, which enables higher piping system compactness, lesser insulation material use and lower thermal inertia. Moreover, in the case of the absorbing gas receiver, increasing the operating pressure allows also for downscaling the cavity size while maintaining an appropriate number of gas molecules for absorption of thermal radiation. These foreseen advantages have been the drivers of the analysis described in this paper wherein the performance of the absorbing gas receiver, assumed to operate under high pressure conditions (10 bar absolute), were evaluated through a series of CFD simulations described in the following sections. The 250 kW_{th} receiver under investigation was designed with the aim of realizing a first prototype to be tested indoor as an experimental proof of concept.

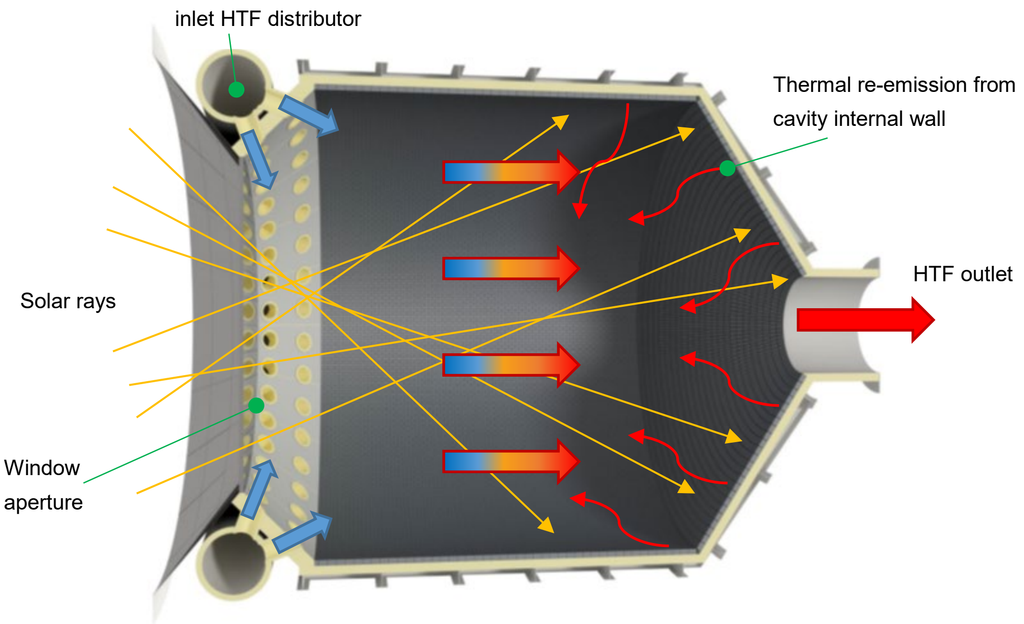

Figure 1. Schematic and working principle of the absorbing gas receiver. Courtesy of Synhelion SA.

3. Reference computational domain

The receiver under investigation has cavity dimensions, both diameter and length of 0.8 m. The favorable receiver topology was exploited to minimize the computational domain by taking advantage of the symmetry plane and, hence, only half of the entire geometry was considered for the simulations. Figure 2 shows a schematic of the computational domains realized. The difference between the two domains lays in the presence of the so-called absorbing inserts. These elements were originally integrated with the aim of focusing concentrated solar radiation directly onto them. However, based upon a preliminary ray tracing analysis, it was observed that the largest fraction of incoming concentrated solar radiation is absorbed by the lateral cavity wall. For this reason, a first CFD simulation, aimed at evaluating the effect of removing these inserts on the receiver performance, was executed. After that, and based on the results obtained, additional CFD simulations were performed to improve the fluid dynamics behavior of the HTF flowing through the receiver. A specific computational grid was constructed for each of the two domains leading to mesh independent results in the case of about 9 and 5 million hexahedral and tetrahedral elements for the receiver with and without absorbing inserts respectively.

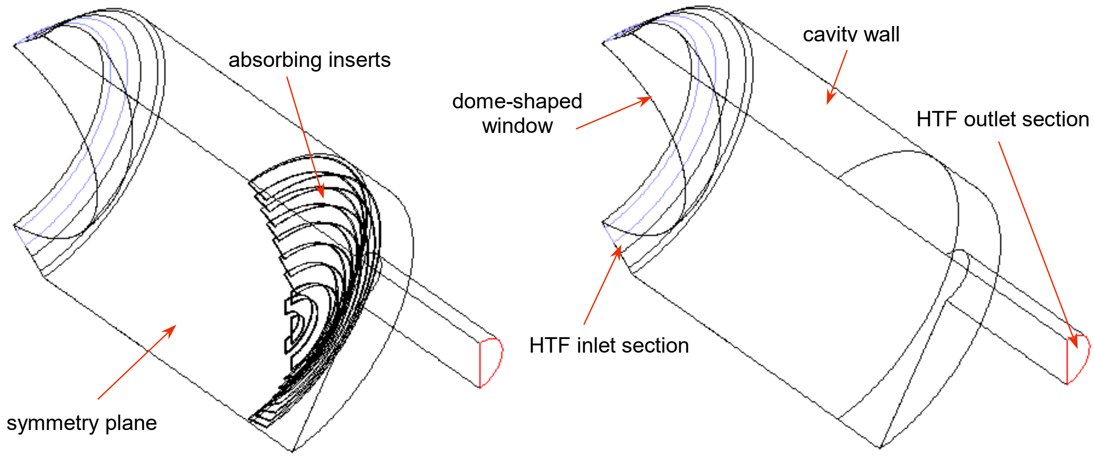

Figure 2. Computational domain of the receiver: with (l.h.s.) and without absorbing inserts (r.h.s.).

4. Numerical model and main boundary conditions

Continuity, momentum and energy conservation equations, along with turbulent transport equations, were solved through ANSYS-Fluent code. Being the major heat transfer mechanism taking place into the receiver, radiative heat transfer was modeled exploiting the discrete ordinates (DO) method coupled with the weighted-sum-of-gray-gases (WSGG) model accounting for the wavelength variations of the participating medium radiation properties. Further details on the numerical model developed can be found in [2]. Temperature-dependent physical properties of the HTF were implemented through polynomial functions derived from tabulated data [3]. Given the relatively low velocity, and low expected pressure variation into the receiver, the HTF was assumed as incompressible ideal gas; therefore, its density was calculated based upon local (variable) temperature values and a fixed pressure value. SIMPLE algorithm was exploited to couple the pressure and velocity fields and to solve the pressure correction equation. The pressure values at the cell faces were interpolated through PRESTO! (PREssure STaggering Option) scheme [4] and the spatial discretization of the transport equations were performed with a second order accurate upwind scheme. Convergence was considered to have been achieved when the mass, momentum and turbulent quantities residuals were below 10^{-5}, the DO and energy residuals were below 10^{-8} and 10^{-9} respectively.

Concerning the boundary conditions, an input power of 250 kW was considered. The latter was directly implemented onto the internal receiver surfaces on the basis of a specific heat flux distribution obtained from a ray tracing analysis. Water vapor was assumed to be fed through the receiver with a mass flow rate of 65 g/s and an inlet temperature of 600 K. The emissivity of the internal receiver wall was imposed to 1 with fully diffused reflection of radiation. The receiver operating pressure was set to 10 bar absolute. Heat losses were assumed to occur from the aperture only, modeled as semi-transparent surface, by means of thermal radiation (blackbody ambient at 300 K). Since the effect of gravity is expected to be non-negligible, it was accounted for assuming the receiver positioned horizontally, replicating the expected orientation during indoor testing.

5. CFD simulations results and discussion

5.1 Effect of absorbing inserts removal on the receiver performance

Figure 3 shows the temperature contours into the receiver operating with and without absorbing inserts. A similar thermal stratification can be observed indicating that the absorbing inserts are not mandatory for the proper functioning of the receiver; the cavity wall can be directly exploited to absorb the incoming concentrated solar energy re-emitting then thermal radiation back again into the cavity. From a quantitative standpoint, removing the absorbing inserts allowed the receiver to achieve a slightly higher HTF outflow temperature, 1’560 K as opposed to 1’546 K, translating into a slightly higher receiver thermal efficiency. The latter, defined as the ratio between the thermal power removed by the HTF and the total input power entering the receiver (i.e., concentrated solar radiation), resulted to be equal to 0.58 and 0.59 in the case of pressurized receiver with and without absorbing inserts respectively. Moreover, the analysis of these results allowed also to observe the relevant effect of gravity on the HTF flowing into the cavity. The colder, and denser, HTF entering the receiver flows downwards accumulating on the lower part of the cavity before being heated up and collected on the outlet pipe.

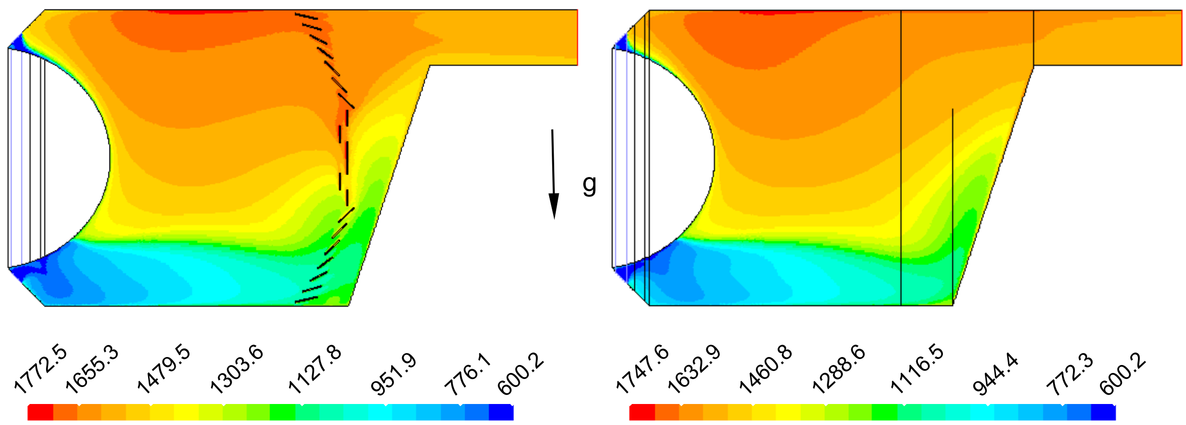

Figure 3. Comparison between the temperature distribution into the receiver with (l.h.s.) and without (r.h.s.) absorbing inserts. Temperature values are in [K].

5.2 Effect of HTF inlet position on the receiver performance

Based upon the results of these first CFD simulations, a non-ideal thermal stratification into the cavity, detrimental for the receiver performance, was observed. The latter was tackled through a redesign of the HTF inlet section with the aim of finding the most promising solution in terms of thermal stratification and thermal efficiency. Three different inlet section designs were then proposed and numerically evaluated. Starting from the reference annular HTF inlet section, the variations proposed were aimed at enhancing the momentum of the incoming HTF to counteract the effect of gravity. In the first solution (case 1 of figure 4), the HTF inlet section was reduced to a quarter only, with respect the original one, located on top of the dome-shaped window (blue area of figure 4). The two additional design modifications were characterized by a further reduction of the HTF inlet section, halved with respect to the previous design, that was firstly located near the dome-shaped window (case 2 of figure 4) and, secondly, positioned closer to the lateral wall (case 3 of figure 4). All the boundary and operating conditions were kept unchanged, with respect to the previous simulation, with the only exception given by the HTF inlet temperature that was increased to 900 K.

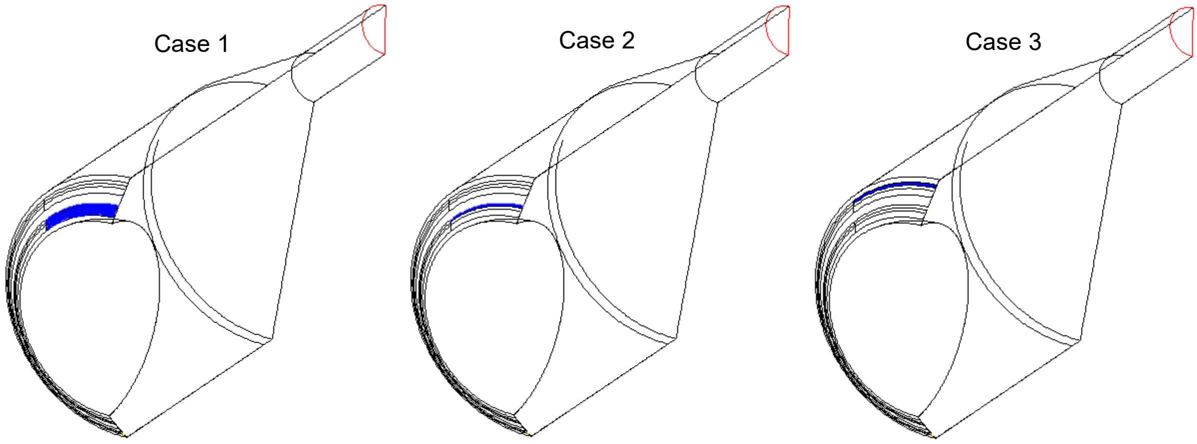

Figure 4. Schematic of the three different HTF inlet section locations proposed (blue area).

Figure 5 shows the results of the three CFD simulations performed in terms of temperature and velocity magnitude contours plots. On the basis of these outcomes, it is evident that the receiver thermo-fluid dynamics behavior is strongly affected by the HTF inlet section considered. For this reason, to maximize the receiver performance, the latter should be carefully designed. The major consideration that can be drawn, based on the results obtained, is that the effect of gravity, as expected, cannot be neglected. The unfavorable receiver orientation (i.e., horizontal) leads to the onset of a strong buoyancy-driven fluid motion into the cavity. As especially visible in the case of low HTF inlet velocity (top of figure 5), the incoming denser HTF tends to sink through the cavity, in a sort of cascade along the domed window, down to the bottom part. The HTF then flows along the cavity, increasing its temperature, until reaching the rear part where it is forced to move through the outlet section. This particular HTF fluid dynamics behavior leads to the development of a relevant recirculation cell covering a large fraction of the internal cavity volume. It is also interesting to observe that, increasing the momentum of the incoming HTF is helpful in mitigating the effect of gravity (middle and bottom contours of figure 5).

Besides the aforementioned considerations on the fluid flow, the effect of the HTF inlet section on the receiver performance was also quantitatively evaluated through the receiver efficiency. The latter, was correlated to the efficiency of the reference receiver configuration wherein an annular HTF inlet section was considered (r.h.s. of figure 2). The resulting chart is reported in figure 6. Besides the receiver efficiency ratio (red dots), the ratio between the HTF outflow temperature and the maximum temperature observed into the cavity, is also reported for each of the receiver configurations evaluated (blue triangles). Based upon these results, the receiver with quarter inlet section located on top of the aperture (case 1), despite having an HTF flow strongly characterized by gravity effects, seems to be the best option showing a 4% higher receiver efficiency and an HTF outflow temperature closer to the maximum temperature into the cavity. Concerning the other two solutions evaluated (case 2 and case 3), the resulting receiver efficiency falls below the one of the reference design. This can be attributed to the fact that, for these receiver configurations, the momentum of the inlet HTF is excessive leading a fraction of it to directly reach the outlet section without collecting a proper amount of thermal radiation (middle and bottom of figure 5).

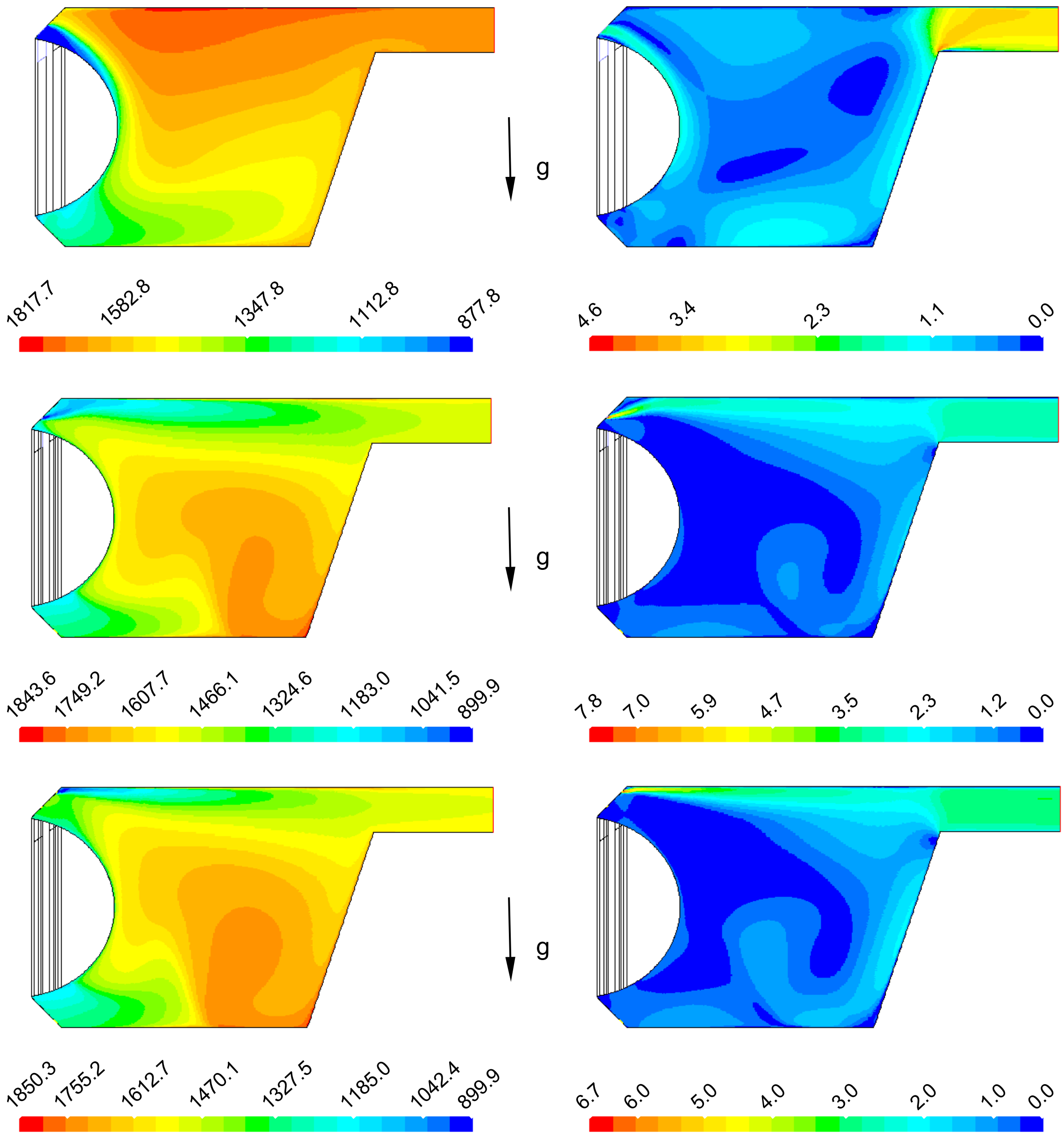

Figure 5. Temperature (l.h.s.) and velocity magnitude (r.h.s.) contours for the three HTF inlet solutions investigated: case 1 (top), case 2 (middle) and case 3 (bottom). Temperature scale is expressed in [K] while velocity magnitude scale is expressed in [m/s].

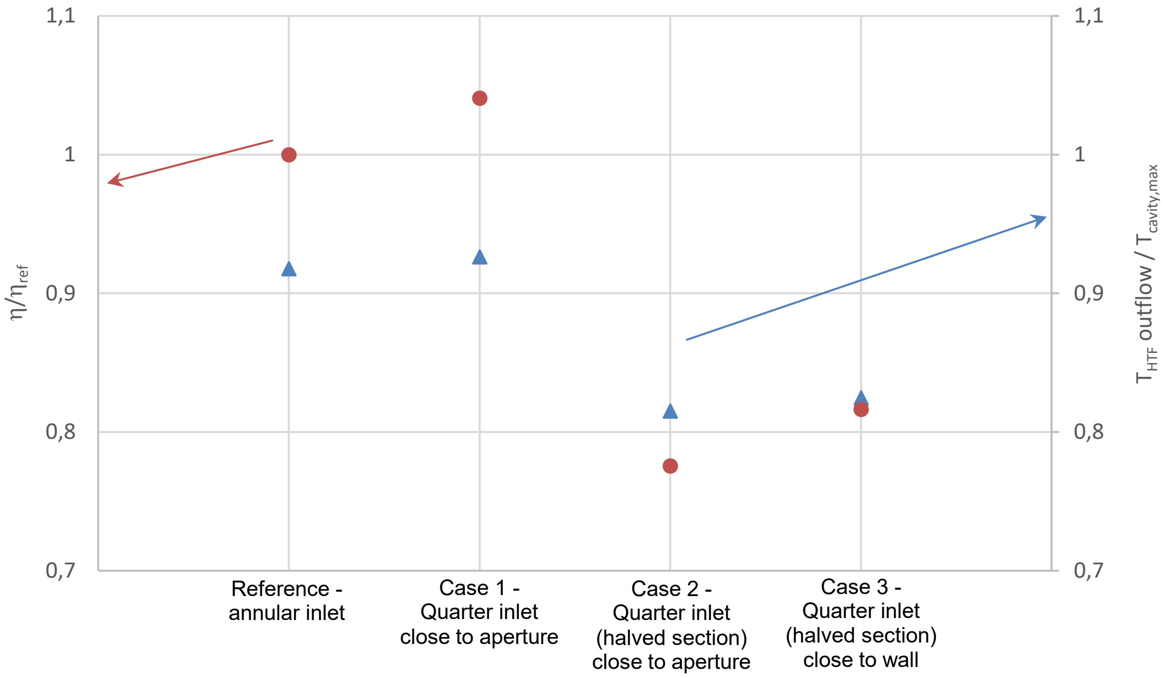

Figure 6. Effect of different HTF inlet section configuration on the receiver performance.

6. Summary and conclusions

The pressurized version of the innovative absorbing gas receiver, proposed by Synhelion and currently under development, has been presented. Despite being more complex than the absorbing gas receiver operating at nearly ambient pressure, expected advantages of higher piping system compactness, lower insulation material use, and possibility of receiver downscaling while maintaining an appropriate number of gas molecules for absorption of thermal radiation, make interesting the development of this receiver design. To this purpose, a preliminary CFD simulation, aimed at evaluating the effect of removing the absorbing inserts on the receiver performance, has been conducted demonstrating that these additional elements are not mandatory for efficiently operate the receiver. Furthermore, the simulation results allowed also to observe a non-favorable fluid dynamics behavior of the HTF which is, highly affected by gravity effect. For this reason, an additional CFD simulations campaign was performed with the aim of evaluating the effects that size and location of the HTF inlet section could have on the receiver performance. Three different receiver design solutions, with variations in the dimensions and location of the HTF inlet section, were proposed and compared to the reference receiver design characterized by a full annular inlet section. The results obtained allowed to observe that, besides the location, the momentum of the inlet HTF stream has a relevant impact on the receiver performance.

Data availability statement

The data supporting the article contribution can be gathered directly from the paper; no additional material is provided.

Author contributions

Conceptualization and investigation: S.Z., P.G., L.G., D.R., R.T., D.M., G.A., M.B.; Methodology, data curation and formal analysis: S.Z., R.T., D.M., M.B.; Funding acquisition: S.Z., P.G., L.G., G.A., M.B.; writing – original draft preparation: S.Z.; writing – review and editing: S.Z.,

P.G., L.G., D.R., R.T., D.M., G.A., M.B.; supervision, G.A. and M.B.; project administration, G.A. and M.B. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

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