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Numerical Performance Evaluation of the Synhelion Absorbing Gas Solar Receiver Under Different Operating Conditions

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Abstract. The thermochemical process of syngas production, exploiting concentrated solar power, requires thermal energy at very high temperature, in the order of 1000-1500 °C, well beyond the maximum operating temperature of actual commercial receivers. The absorbing gas solar receiver, proposed by Synhelion SA, represents a breakthrough in the point focus solar technology allowing to operate at temperature levels higher than 1500 °C. This innovative cavity-type receiver exploits thermal radiation, as major heat transfer mechanism, for directly heating the gaseous heat transfer fluid (water vapor or carbon dioxide). Given the complexity of the physical phenomena taking place into the receiver, a CFD-based approach was followed to accurately replicate its thermo-fluid dynamics behavior under different operating conditions. In detail, a total of three CFD simulations campaigns, assuming the receiver operating at ambient pressure or at 10 bars, were performed with the aim of evaluating the effect of important parameters, such as heat transfer fluid entrance angle, gravity and realistic concentrated solar flux distribution into the cavity, on the receiver performance. An incoming concentrated solar flux on the aperture of 1.2 MW/m^2 (corresponding to 600 kW/m^2 on the absorptive surfaces) was assumed as reference leading to a total input power of 120 MW and 240 kW in the case of unpressurized and pressurized receiver respectively. According to the results obtained, gravity resulted to be the parameter with major influence followed by realistic concentrated solar flux distribution and heat transfer fluid entrance angle. However, a minimum receiver thermal efficiency of 66%, at about 1600 °C outflow temperature, was observed under the worst operating conditions considered indicating the reliability and robustness of this innovative receiver deign.

INTRODUCTION

Solar is among the major renewable energy sources that can be exploited, with proper concentration techniques, to fulfill the needs of applications requiring thermal energy at very high temperature levels, e.g. higher than 1000 °C, such as thermochemical syngas production. However, the operating temperature of commercial receivers, currently lower than 500 °C, has to be increased [1]. The Swiss company Synhelion SA is developing a new generation of cavity-type solar receivers, for large-scale installations, suitable to operate at temperature levels higher than 1500 °C [2]. This innovative cavity-type receiver design can work, in principle, with thermal radiation only as heat transfer mechanism exploiting a heat transfer fluid (HTF) with specific optical properties. The working principle is similar to greenhouse effect; concentrated solar radiation, entering the receiver, is absorbed by highly-absorptive surfaces located at the back of the cavity. As a result, these surfaces start to re-emit thermal radiation that is absorbed by the heat transfer fluid, mostly opaque to this longer wavelength type of radiation, which flows through the receiver. Water vapor or carbon dioxide are among the suitable HTF candidates on the basis of their favorable optical properties. In the first part of the present paper, the computational fluid dynamics model, developed to replicate the behavior of this receiver, is described. The paper then focuses on the presentation of the results of some simulations campaigns,

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finalized at evaluating the effect of important parameters, such as HTF entrance angle, gravity and realistic concentrated solar flux distribution into the cavity, on the receiver performance.

ABSORBING GAS RECEIVER WORKING PRINCIPLE

As already mentioned, water vapor and/or carbon dioxide are among the suitable HTF candidates thanks to their favorable optical properties, i.e. almost transparent to the high-radiation intensity wavelengths of the solar spectrum and mostly opaque (strong absorption bands) in the wavelength range of thermal radiation [2].

Figure 1 shows a schematic of the absorbing gas receiver. The cavity is separated from the external environment by means of a quartz glass window. Concentrated solar radiation entering the cavity is absorbed by specific absorptive surfaces located in the rear part. In a more complex design, these surfaces can be in the form of rings, such as those shown into the picture; or, in the case of basic receiver configuration, the absorptive surfaces are simply the internal surfaces of the cavity. Independently upon the type of absorptive surfaces considered, the key aspect for the receiver working principle is that, by absorbing the incoming concentrated solar radiation, the temperature level of these surfaces increases emitting, as a consequence, energy in the wavelength range of thermal radiation back again into the cavity.

At the same time, the HTF is fed through the receiver from the front flowing through the cavity all the way down to the rear part. As aforementioned, being mostly opaque to the wavelength range of thermal radiation, it absorbs the thermal energy emitted by the absorptive surfaces increasing substantially its temperature as it reaches the outlet pipe located in the rear part of the receiver.

Since the receiver can operate, in principle, with thermal radiation only as heat transfer mechanism, it is important to provide a suitable amount of HTF gas molecules into the cavity to absorb the largest fraction of thermal radiation ensuring hence high thermal efficiency levels. For this reason, the receiver dimensions depends on the operating pressure. In the case of atmospheric (unpressurized) receiver, a 16 m long and 16 m diameter cavity is required; while, if the operating pressure is assumed to be ten times higher, the receiver can be safely downsized by the same factor, or even more, with a negligible effect on the overall performance.

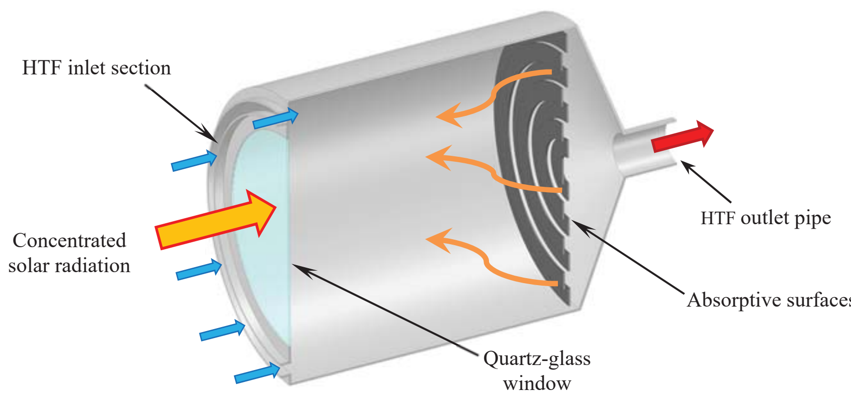


FIGURE 1. Schematic and working principle of the absorbing gas receiver.

NUMERICAL MODEL AND REFERENCE COMPUTATIONAL DOMAIN

A computational fluid dynamics (CFD) model was developed with the aim of deeply understanding the physical phenomena governing the behavior of this innovative receiver concept. For the development of this numerical model, large efforts were devoted to the definition of the most suitable strategy to satisfactorily describe radiative heat transfer in participating media that is among the major physical phenomena occurring into the receiver.

Thermal radiation heat transfer in a flowing participating media is, by nature, a complicated topic that is normally addressed by means of modelling methods which, depending on the desired accuracy, can be computationally very expensive or applicable to very simple and idealized cases only.

Among the four currently available methods for the analysis of radiative heat transfer, the Discrete Ordinates (DO) radiation model was selected to solve the radiative transfer equation [3]. The choice was driven by the fact that it is the only one that allows to model semi-transparent interior or exterior walls, in our case the receiver aperture, and it can be applied for parallel computing without any restrictions in terms of medium optical thickness. The spectral variation of the participating medium radiative properties was accounted for by the weighted sum of gray gases (WSGG) model [3]. However, since the latter was not available in the reference commercial software product selected for the numerical model development, that was ANSYS Fluent 17.1, it was implemented through a purpose-built user-defined function (UDF), i.e. a "C" routine that can be integrated into the solver.

Once completed, since at that time no experimental data were available, the CFD model was satisfactorily validated against benchmark results of another numerical model, developed by Synhelion, exploiting the most accurate method to model radiative heat transfer in participating media: Monte Carlo Line by Line. Details on both the numerical model development and the validation process can be found in [4].

The reference computational domain assumed for the simulations, depicted in figure 2, is 2D axisymmetric with cavity dimensions depending on the receiver operating pressure. The absorptive surfaces, separating cavity domain (wherein absorption of thermal radiation takes place) and rear domain, were modelled as flat surfaces, without thickness, but with the possibility of defining different emissivity values on the two sides (towards the cavity domain and the rear domain). For both the cases, 600 kW/m^2 concentrated solar flux was assumed leading to a total input power of 120 MW and 240 kW in the case of unpressurized and pressurized receiver respectively. The total input power was considered to be evenly distributed on the absorptive surfaces only and hence no ray-tracing was conducted during the simulations.

The HTF under investigation was water vapor which enters the cavity with an inlet temperature of 1000 K (constant for all the simulations performed) and with a reference inclination angle of 27° from aperture (dashed orange arrow in figure 2).

The receiver was assumed to be well insulated with the only source of heat loss occurring from the aperture by means of thermal radiation. Mesh-independent results were achieved with a grid of about 90 000 quadrilateral cells.

The realizable k-epsilon model [5], with enhanced wall treatment [6] as near-wall modeling approach, was selected to account for the effect of turbulence. SIMPLE algorithm [6] was exploited to couple the pressure and velocity fields and to solve the pressure correction equation. 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.

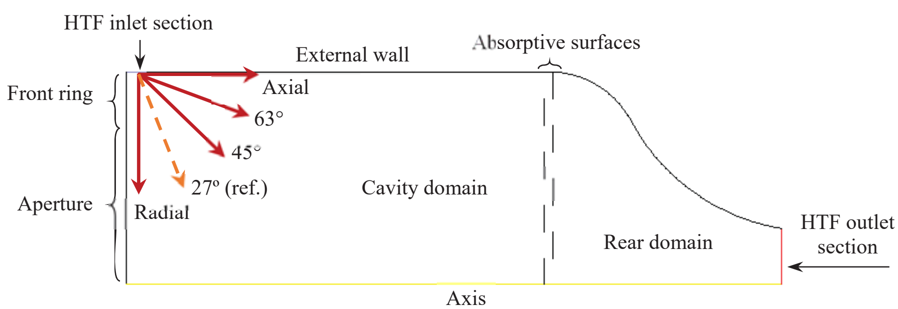


FIGURE 2. Reference receiver geometry – Computational domain.

CFD SIMULATIONS CAMPAIGNS RESULTS AND DISCUSSION

Once validated, the CFD model was exploited to run a series of simulations campaigns with the aim of evaluating how different operating conditions affect the Synhelion absorbing gas receiver thermo-fluid dynamics behavior. The most representative operating parameters evaluated were: (i) orientation of the HTF inlet velocity vector, (ii) gravity (upward- and downward-facing receiver) and (iii) incoming concentrated solar flux distribution into the cavity. Furthermore, two scenarios of receiver operating pressure, ambient pressure and 10 bars respectively, were also considered and compared.

Unpressurized Receiver - Effect of HTF Entrance Angle

Five different orientations of the inlet HTF velocity vector, depicted in figure 2, were proposed and evaluated: radial (0° from aperture), 27° from aperture (reference), 45°, 63° and axial (90° from aperture). For each of these orientations, several CFD simulations were performed varying any time the HTF mass flow rate.

Since the same computational domain was considered for all the HTF inlet orientations proposed, it is worth to mention that at a given HTF mass flow rate, the inlet velocity magnitude changes with entrance angle as a consequence of the constant area of the inlet section.

The resulting receiver efficiency, defined as the ratio of the power removed by the HTF divided by the total input power, is shown in figure 3. As can be observed from the results, reducing the HTF mass flow rate, leads to a decrease of the receiver thermal efficiency due higher heat losses, independently upon the entrance angle. HTF inlet angles lower than 30° from the aperture have a negligible effect on the receiver performance. An inclination angle of 45° has a beneficial effect if the receiver operates at high HTF mass flow rates, i.e. lower HTF outflow temperature. At higher inclination angles, i.e. axial inlet, the receiver efficiency seems to be generally higher. However, the receiver behavior is affected, at the same time, by the combined effect of HTF inclination angle and inlet velocity, since the same inlet section was assumed for all the simulations, and therefore isolating the effect of entrance angle only is not straightforward.

From a graphical standpoint, the temperature distribution into the receiver for some of the cases analyzed and operating with the same HTF mass flow rate of about 51 kg/s, is reported in figure 4. According to the results obtained, it is evident that the temperature distribution is remarkably affected by the HTF entrance angle.

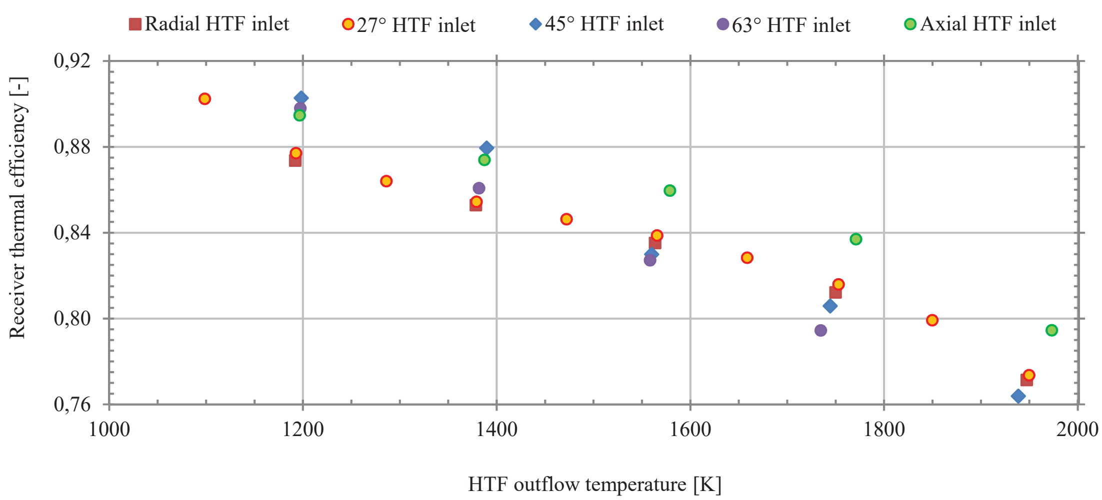
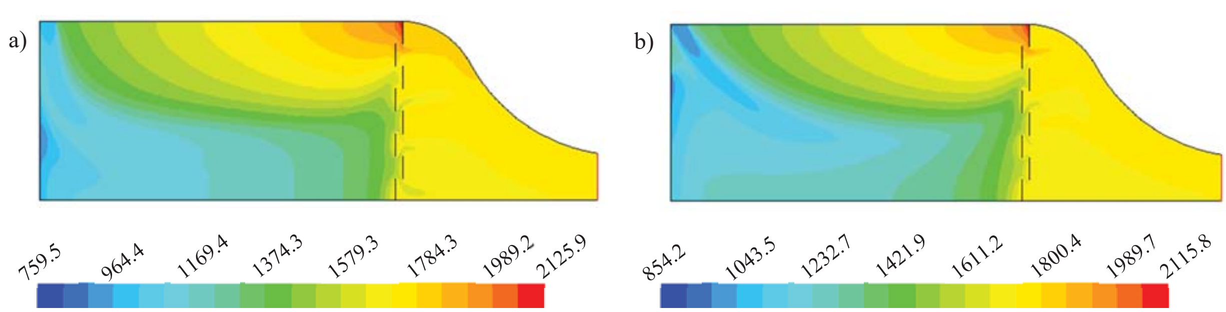


FIGURE 3. Variation of the receiver thermal efficiency as a function of the HTF entrance angle into the cavity.



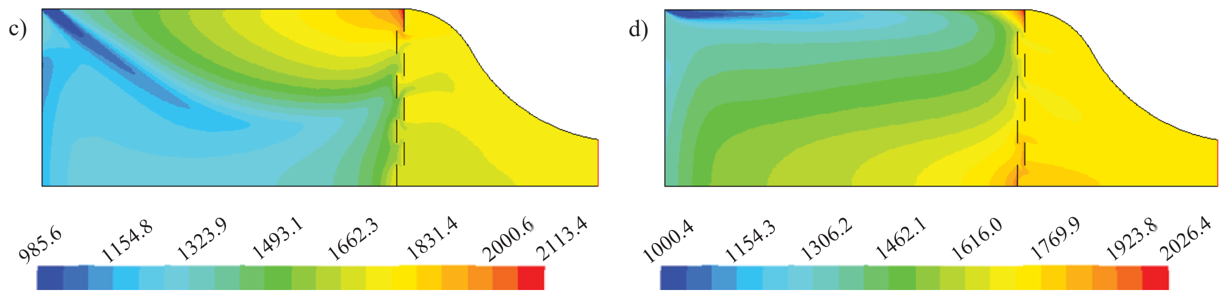


FIGURE 4. Temperature contours of the absorbing gas receiver operating with mass flow rate of 51 kg/s at different HTF entrance angle: a) radial, b) 27° (reference), c) 45° and d) 63°. Temperature values are [K].

Pressurized Receiver - Effect of Gravity

In the case of large HTF density gradients, a gravity-induced buoyancy flow could take place affecting the flow field, and temperature distribution, into the cavity. For this reason, this second CFD simulations campaign was aimed at evaluating the effect of gravity on the receiver performance. To evaluate the worst-case scenario, it was decided to assume the receiver operating at 10 bars as reference. It is well known that 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 resulting higher density of the working fluid. The latter, besides enabling higher piping system compactness and lower insulation material use, it mainly allows for downscaling the receiver of a factor proportional to the pressure increase while maintaining a sufficient number of gas molecules for an effective absorption of thermal radiation.

Therefore, the new cavity considered for this analysis, 0.72 m diameter and 0.72 m length, is sensibly smaller with respect to the unpressurized configuration. The incoming concentrated heat flux (600 kW/m^2) was assumed to be the same as the unpressurized receiver. Therefore, for obvious reasons, the HTF mass flow rate was also reduced with the aim of maintaining the same outflow temperature in the range between 1100 K and 2000 K. To maintain a 2D axisymmetric domain, two different receiver orientations were considered: downward- and upward facing. However, it is worth to mention that this is a pure theoretical investigation since the real receiver will never be subjected to such extreme inclinations.

The results obtained, in terms of receiver thermal efficiency as a function of HTF outflow temperature, are shown in the graph of figure 5 superimposed to those of the reference pressurized receiver wherein gravity was neglected. As expected, the effect of gravity on the receiver performance is more important as the HTF mass flow rate reduces. At the highest mass flow rates evaluated, the effect of gravity is reasonably negligible; conversely, it cannot be neglected for all the other, medium to low, HTF mass flow rates. The downward facing receiver is characterized by higher thermal efficiencies with respect to those of both the reference configuration (without gravity) and those of the upward facing receiver. Concerning the latter, an important performance decay should be expected as the mass flow rate through the receiver reduces.

As shown by the temperature contours plot of figure 6, on the basis of the receiver orientation considered, a completely different flow field, and consequent thermal stratification, into the receiver is obtained. Thanks to the beneficial effect of buoyancy, the downward-facing receiver allows to obtain an ideal condition of thermal stratification along the axial direction leading to very high receiver efficiency values. Conversely, in the case of upward-facing orientation, the colder and denser fluid entering the receiver tends to rapidly reach the outlet section establishing an almost radial thermal stratification into the cavity. The latter is clearly detrimental for the overall receiver performance.

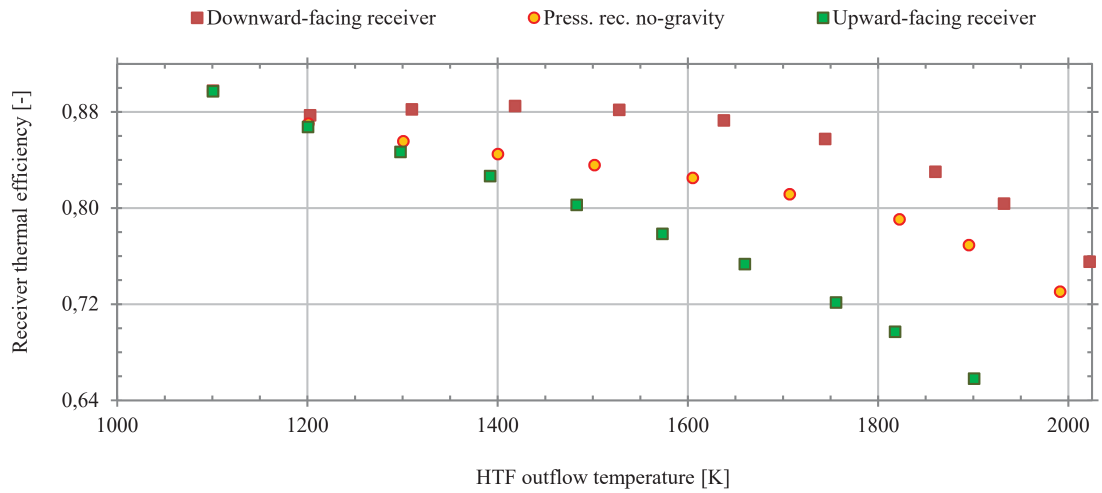


FIGURE 5. Variation of the pressurized receiver thermal efficiency as a function of the HTF outflow temperature for the two receiver orientations investigated: downward facing receiver (red squares) and upward facing receiver (green squares).

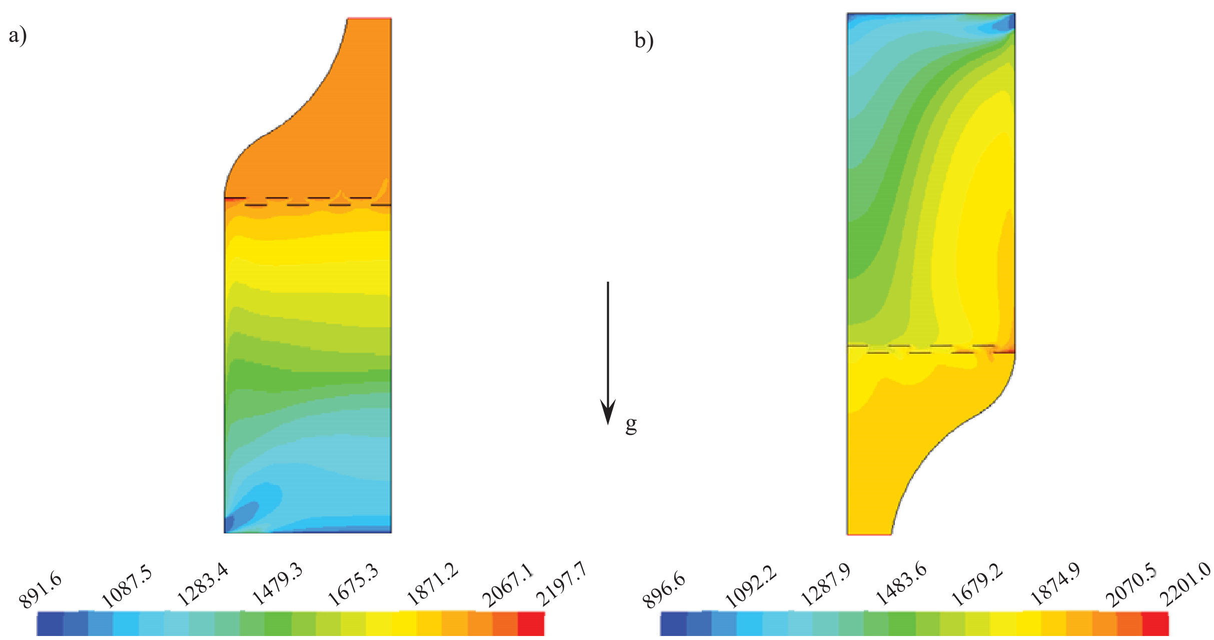


FIGURE 6. Temperature contours of the pressurized receiver operating with the lowest HTF mass flow rate of 0.07 kg/s: a) downward facing and b) upward facing. Temperature values are [K].

Pressurized Receiver - Effect of Realistic Concentrated Solar Flux Distribution

For all the previous cases, it was assumed that the entire concentrated solar radiation entering the cavity was absorbed by the absorptive surfaces only, which then re-radiates thermal energy towards the cavity domain. However, to have a more precise indication on how concentrated solar radiation distributes into the cavity, Synhelion performed a ray-tracing analysis on the pressurized receiver. The results obtained indicated that the majority of the incoming concentrated solar flux is absorbed by the lateral wall (about 65% of the total). In this CFD simulations campaign, the effect of this realistic concentrated solar flux distribution, implemented into the solver by means of a purpose-built UDF, was investigated.

The resulting receiver thermal efficiency is shown in the graph of figure 7. Comparing these results with those of the reference receiver configuration, wherein concentrated solar flux was assumed to be absorbed by the absorptive surfaces only, it is possible to observe that the receiver thermal efficiency follows almost the same evolution as a function of the HTF outflow temperature. However, the realistic heat flux distribution ("Uneven HF" in the graph) leads to slightly lower performance for all the HTF mass flow rates considered. At the highest mass flow rate, the receiver thermal efficiency is about 2% lower than that of the reference configuration; while, if the lowest mass flow rate is considered, a 5% reduction is obtained.

From a graphical standpoint, the resulting temperature contours (shown in figure 8) are compared with those of the reference receiver configuration with the aim of facilitating the assessment of the impact of a different concentrated solar flux distribution on the temperature field into the cavity. In the case of realistic heat flux (uneven HF in the graph), a slightly different thermal stratification into the cavity is obtained with higher temperature levels of the HTF close to the lateral wall due to the increased heat flux in this region.

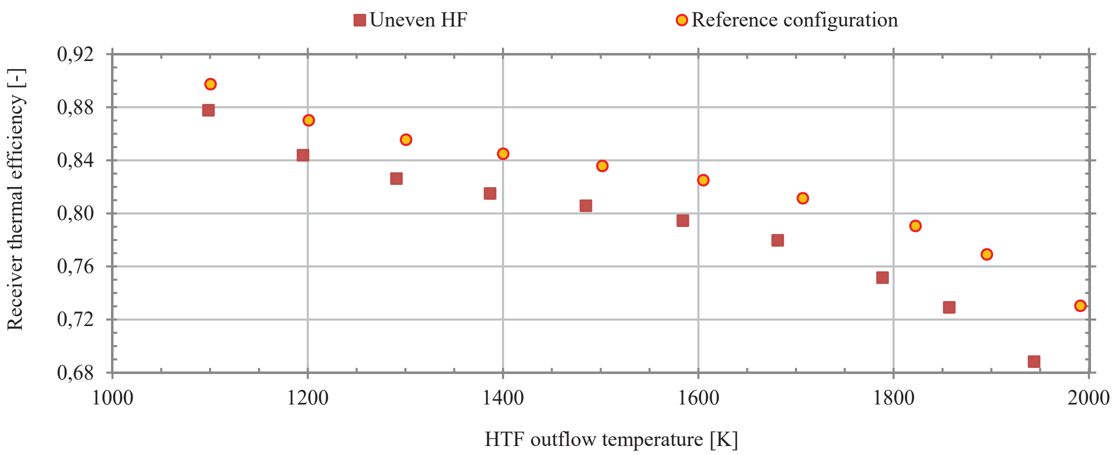


FIGURE 7. Variation of the pressurized receiver thermal efficiency as a function of the HTF outflow temperature assuming a realistic concentrated solar flux distribution into the cavity (red squares).

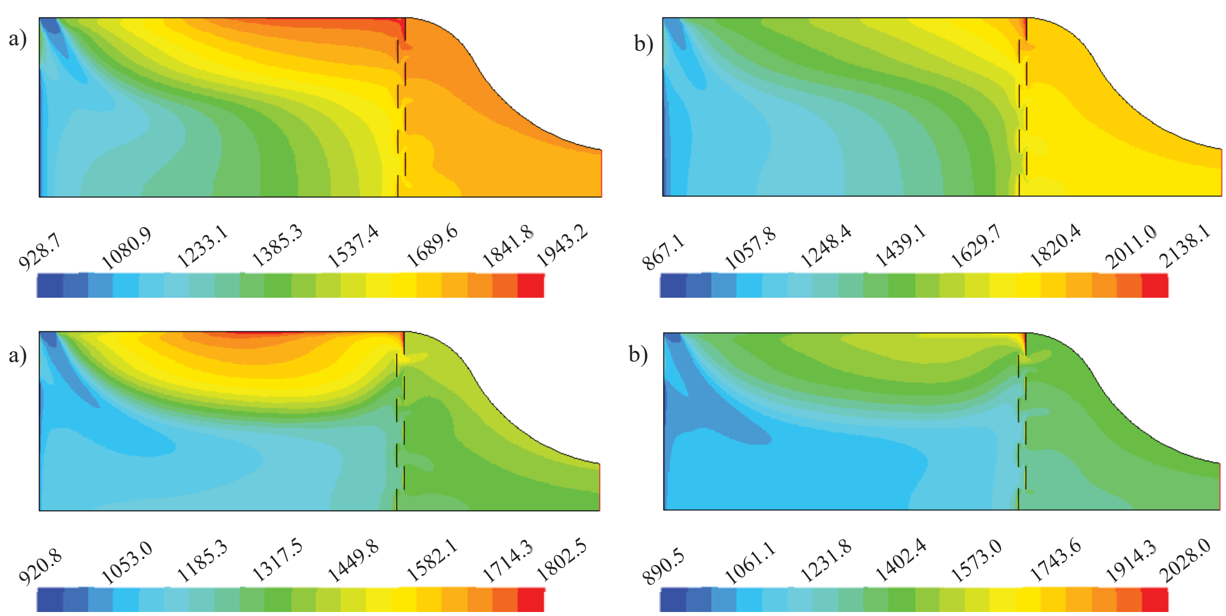


FIGURE 8. Temperature contours of the pressurized receiver operating with 0.09 kg/s (top) and 0.21 kg/s (bottom) assuming: a) realistic concentrated solar flux distribution and b) incoming heat flux on the absorptive surfaces only. Temperature values are [K].

SUMMARY AND CONCLUSIONS

The thermo-fluid dynamics behavior of the innovative absorbing gas receiver, proposed by Synhelion SA, was evaluated exploiting a previously validated CFD model. The latter, developed exploiting Fluent commercial code from ANSYS along with purpose-built user defined functions, solves the governing equations of fluid flow and heat transfer with a special focus on the description of radiative heat transfer in flowing participating media. Discrete ordinates method, for solving the radiative transfer equation, and the weighted sum of gray gases model, for replicating the HTF spectral properties, resulted to be a viable compromise between expected accuracy of the results, computational resources, and computing time.

The CFD model was then exploited to run three simulations campaigns aimed at evaluating the effect of (i) HTF entrance angle, (ii) gravity and (iii) realistic incoming concentrated solar flux distribution into the cavity on the receiver performance.

On the basis of the results obtained, it was possible to observe that the receiver thermal efficiency generally decreases as the HTF outflow temperature increases (i.e., HTF mass flow rate reduces) due to higher heat loss from the aperture.

The HTF entrance angle resulted to have an impact on the evolution of the receiver performance. In detail, HTF entrance angles lower than 30º from the aperture, showed a negligible effect on the receiver performance. Larger HTF entrance angles, up to about 45º, are favorable in the case of high HTF mass flow rates. Best receiver efficiencies were achieved thorough an axial HTF inlet direction.

According to the results of the second CFD simulations campaign, it was possible to observe that gravity has a relevant impact on the receiver performance for both the cases evaluated of upward and downward-facing orientation. On the other hand, the effect of gravity resulted to be negligible in the case of the highest HTF mass flow rates considered.

On the basis of the outcomes of the third simulations campaign, in the case the realistic incoming solar flux distribution is considered, a general reduction, of 5% at most, on the receiver thermal efficiency should be expected.

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