

Active Thermal Insulation – A Possible Option to Reduce Thermal Inertia of Cavity Receivers

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Abstract. An Active Thermal Insulation (ATI) is proposed as suitable option to reduce the transient response of high-temperature cavity-type solar receivers. It consists of a straight tubes bundle, embedded in the insulating material, covering the entire receiver length through which the heat transfer fluid (HTF) is fed prior being injected into the cavity. The implications of adding the ATI to the reference absorbing gas solar receiver were evaluated through a series of 3D CFD simulations campaigns. Two key parameters on the ATI design (i.e., tubes number and radial tubes bundle radial position with respect to the cavity axis) were evaluated assuming the receiver operating at both design conditions (nominal incoming concentrated solar radiation) and part-load (reduced incoming input power). For all the CFD simulations performed, an HTF inlet temperature of 700 °C was assumed with a case-dependent mass flow rate tuned to reach 1200 °C as HTF outflow temperature. The simulations campaign allowed to observe that a HTF pre-heating, between 4% and 6% with respect to the HTF inlet temperature within the ATI, was achieved for all the cases considered. However, despite this, for some cases the receiver efficiency remained unchanged. The ATI resulted to be beneficial on the receiver efficiency if it is operated at full-load and almost irrelevant in the case of part-load.

Keywords: Thermal Inertia, Cavity Receiver, High-Temperature, Absorbing-Gas Solar Receiver, Computational Fluid Dynamics, Thermal Radiation, Heat Transfer.

1. Introduction

In the present study, the topic of thermal inertia and thermal insulation of high-temperature solar receivers is addressed. In detail, a possible solution to reduce the transient response of cavity-type solar receivers is proposed and numerically evaluated through a series of CFD simulations campaigns. The solution under investigation, better described in the next paragraphs, makes use of a straight tubes bundle, embedded in the insulating material, covering the entire receiver length. The receiver heat transfer fluid (HTF) is fed through these tubes prior being injected into the cavity. The foreseen advantages behind the development of this alternative insulating solution were mainly two: (i) to reduce the receiver thermal inertia, having therefore a consequent beneficial impact on the receiver transients, and (ii) to pre-heat the HTF prior entering the cavity by exploiting a fraction of the heat that would have been otherwise lost to the environment. Despite being studied to be integrated in the highly innovative absorbing gas solar receiver developed by Synhelion SA [1], the same concept can be easily adapted for any cavity-type solar receiver.

2. Absorbing gas solar receiver

Figure 1 schematically depicts the working principle of the innovative high-temperature absorbing gas solar receiver developed by Synhelion SA. This receiver exploits the ability of water vapor and/or carbon dioxide to absorb a significant fraction of longer wavelength thermal radiation while being mostly transparent to shorter wavelength thermal radiation (e.g., terrestrial solar radiation). The receiver operation principle is similar to the "greenhouse effect": it relies on a flowing gas volume between an aperture and the black internal surfaces of the cavity, heated by concentrated solar radiation, to absorb the thermal re-radiation of these surfaces and to shield the aperture from it. At the same time, the gas is directly heated by such absorption and acts as HTF. In principle, the receiver works with thermal radiation only as heat transfer mechanism and does not require, a priori, any convective contribution. After being designed, a 250 kW prototype-scale receiver was experimentally tested both indoor, at DLR solar facility Synlight, and on-field demonstrating the capability of this receiver concept to directly capture concentrated solar radiation at a very high temperature level (up to 1500 °C measured) and high efficiency.

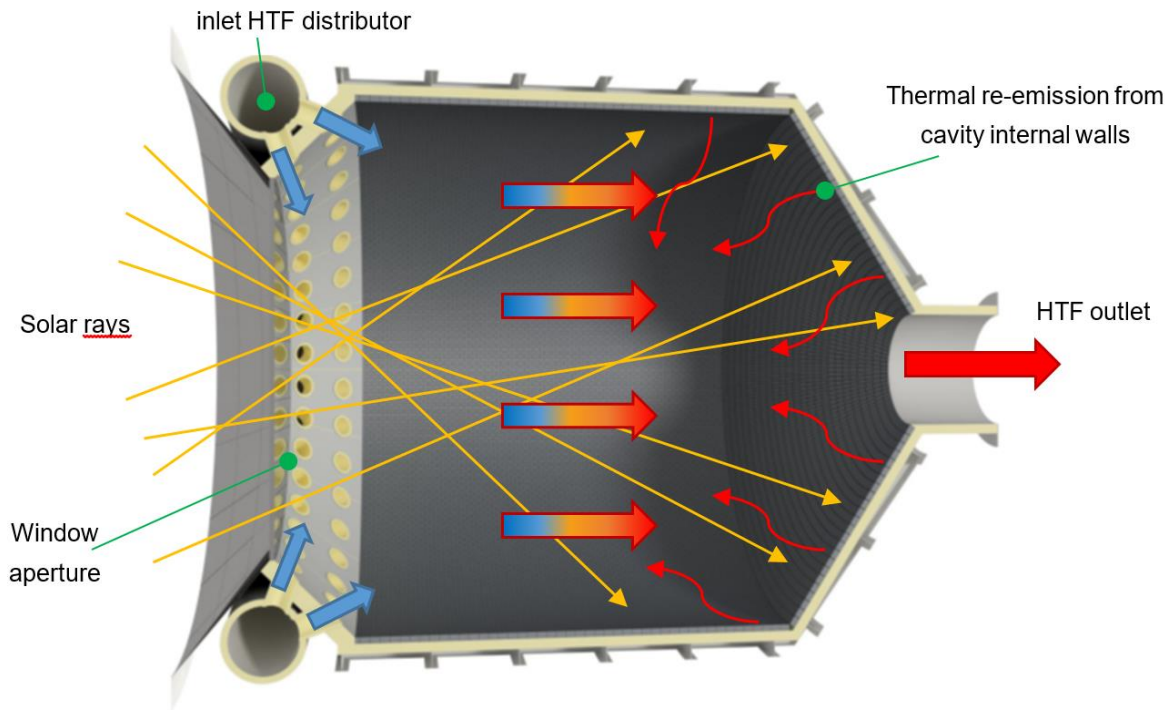


Figure 1. Schematic illustration of the cavity-type absorbing gas receiver concept.
Courtesy of Synhelion SA.

3. Active Thermal Insulation (ATI) system

The proposed active thermal insulation (ATI) solution, depicted in Figure 2, consists of a tubes bundle, integrated into the solid receiver insulating material, located at a predefined radial distance from the internal cavity lateral wall. In the rear part of the receiver, a manifold is exploited to homogeneously feed the HTF through all the pipes. Once in the pipes, the HTF flows from the rear part of the receiver to the front entering therefore into the cavity near the aperture at relatively higher temperature. This HTF pre-heat is achieved by capturing a fraction of the heat that would have been lost from the external surfaces of the insulating material. Furthermore, embedding the tubes bundle into the solid insulating material allows also to reduce the amount of the latter leading hence to a reduction of the receiver thermal inertia. Figure 2 shows a schematic representation of the ATI integrated into the receiver. Referring to that, it's worth to mention that the HTF manifold is only idealized for representation purpose.

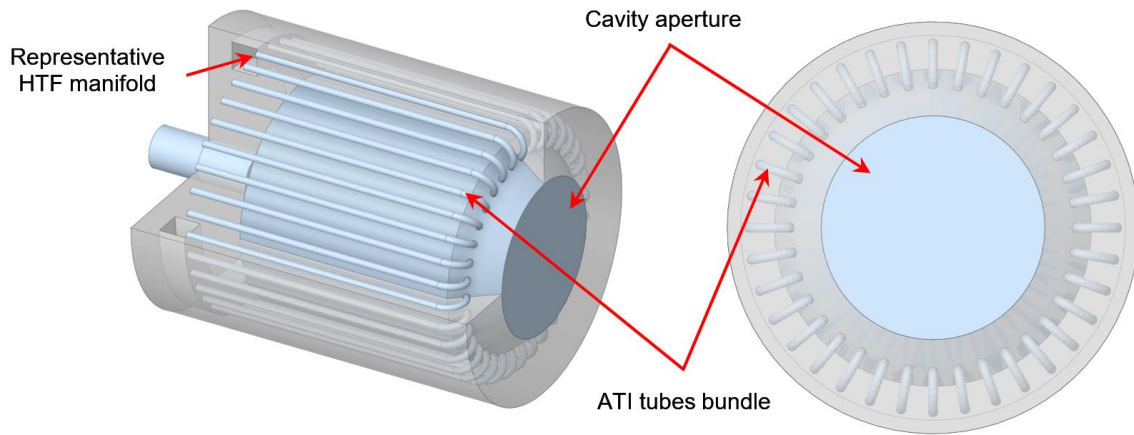


Figure 2. Schematic of the ATI integrated into the receiver.

4. CFD model and simulations campaigns

The implication of integrating the proposed ATI on the absorbing-gas solar receiver behavior was evaluated exploiting a previously-validated CFD-based approach. The numerical model, developed in Fluent code from ANSYS, solves mass, momentum and energy conservation equations along with the transport equations of turbulent quantities. Furthermore, to accurately replicate the absorbing gas solar receiver behavior, special care was devoted to the development of a suitable, and computationally reasonable, strategy to model radiative heat transfer in participating medium. To this purpose, the discrete Ordinates model (DO) with the weighted sum of gray gases (WSGG) method were selected for solving the radiative transfer equation and to account for the spectral properties variation of the participating medium respectively [2]. Further details on the numerical model developed can be found in [3]. Concerning the ATI under investigation, the effect of two relevant parameters on its design were evaluated: (i) tubes number (36 and 64) and (ii) tubes bundle radial distance with respect to the lateral wall of the cavity (1 cm inwards and 1 cm outwards with respect to the reference position). To quantitatively evaluate the impact of the ATI integration, a CFD simulation assuming to operate the receiver without ATI was also conducted. All the CFD simulations performed were steady state considering the receiver operating at full-load (i.e., 544 kW as net incoming concentrated solar radiation) and part-load (i.e., 272 kW as net incoming concentrated solar radiation). The HTF (i.e., H_2O) was considered as ideal gas with temperature-dependent physical properties implemented through polynomial functions derived from [4]. For each simulation, the HTF mass flow rate was tuned in order to reach the desired outflow temperature level of about 1200 °C. A constant HTF inlet temperature, of 700 °C, was considered for all the cases. Heat losses were assumed to occur by radiation only, towards a black-body ambient at 300 K, from the receiver aperture and by conduction and convection from all the other receiver external surfaces. Figure 3 depicts the computational domains considered for the simulations campaigns along with the type of boundary conditions applied. To minimize the computational effort, and since the effect of gravity was assumed to be marginal and therefore negligible for the purpose of this study, a slice only of the receiver geometry was considered exploiting therefore its geometric characteristics. Two different computational domains were realized with slightly different dimensions: 30° slice (l.h.s. of Figure 3) and 22.5° slice (r.h.s. of Figure 3) for the 36 and 64 ATI tubes respectively.

The pressure correction equation was solved by coupling the pressure and velocity fields using the SIMPLE algorithm. The pressure values at the cell faces were interpolated through PRESTO! (PREssure STaggering Option) scheme [5] and the spatial discretization of the transport equations were performed with a second order accurate upwind scheme. Conver-

gence 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.

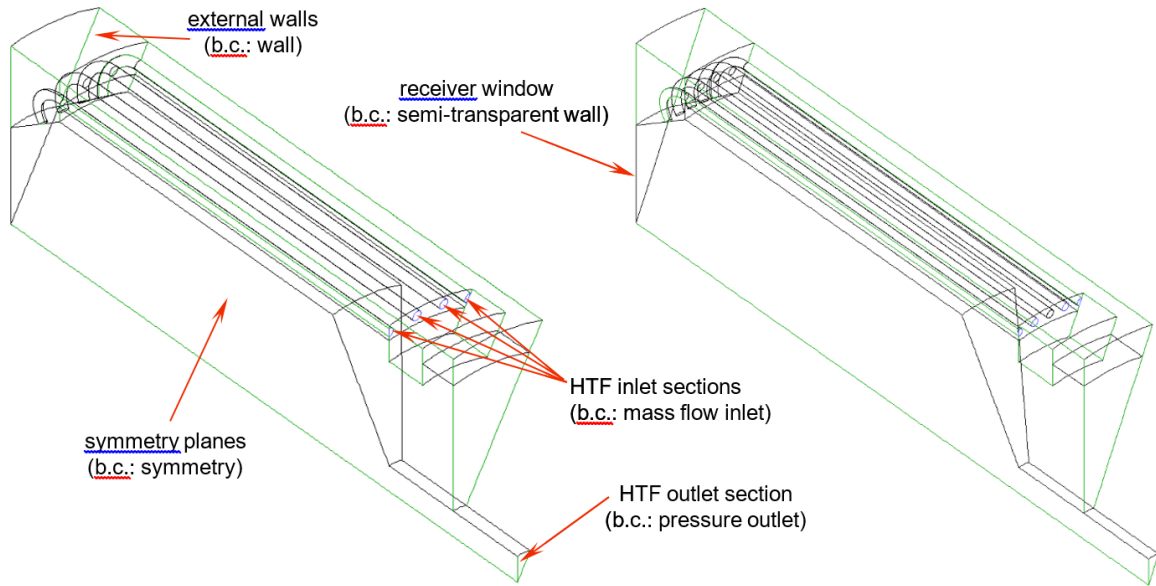


Figure 3. Computational domains, and main boundary conditions, considered for the CFD simulations campaigns: 36 tubes ATI (l.h.s.) and 64 tubes ATI (r.h.s.).

4.1 Effect of tubes number

In this first CFD simulations campaign, the effect of ATI tubes number on the receiver performance was evaluated. Table 1 summarizes the main boundary and operating conditions considered for the CFD simulations, along with some representative results obtained in terms of HTF temperatures, at different receiver locations, and receiver efficiency (calculated as the ratio between the power removed by the HTF, flowing through the receiver, and the net input power entering the receiver). By looking at these results from a macroscopic standpoint, it can be concluded that, operating the receiver in part load has a remarkable detrimental effect on its performance due to a relevant increment of heat loss from the receiver aperture especially. Moreover, still focusing on the receiver subjected to part-load steady operations, it can be seen that the ATI doesn't have a noticeable impact on the receiver behaviour if compared to the conventional design (i.e., no ATI). The situation is different if the receiver is operated at steady nominal condition (i.e., full-load); in this case, the ATI integration shows a beneficial effect on its performance with the 36 tubes configuration that showed a slightly higher efficiency.

Table 1. Summary of boundary conditions and relative results of the receiver operating, in part load and full load, without ATI and with ATI constituted by 36 and 64 tubes respectively.

	Part-load operation			Full-load operation		
	No ATI	36 tubes	64 tubes	No ATI	36 tubes	64 tubes
HTF mfr [g/s]	82.9	83.95	83.2	220.4	244.1	226.4
$T_{\text{HTF,in}}$ [K]	973	973	973	973	973	973
$T_{\text{HTF,out}}$ [K]	1474	1473	1472	1474	1472	1473
$T_{\text{HTF,in,cavity}}$ [K]	//	1022	1031	//	1010	1022
η_{receiver} [-]	0.373	0.377	0.373	0.496	0.545	0.508

4.2 Effect of tubes bundle radial position

An additional CFD simulations campaign was also conducted with the aim of investigating the effect of the ATI radial position on both the amount of energy recovered, and exploited to pre-heat the HTF, and on the overall receiver behaviour. Starting from the 64 tubes ATI, at reference radial position (i.e., the same considered for the previous analysis), two alternative designs were proposed and evaluated. In these designs, the radial position of the ATI was assumed to be 1 cm inwards (closer to the cavity) and 1 cm outwards (closer to the ambient) with respect to that of the reference position. As for the previous analysis, part- and full-load receiver operations were considered.

Table 2 summarizes the main boundary conditions, considered for these simulations, along with relevant results obtained. According to these outcomes, it seems that the 1 cm inwards/outwards variation considered is too small for influencing the overall receiver performance. However, as expected, the closer the ATI with respect to the internal cavity walls, the higher the amount of energy recovered by the HTF. Nevertheless, a slightly higher HTF inflow temperature leads, on average, to an increase of the temperature level in the region close to the aperture. This, in turn, causes an increment in the radiative losses to the ambient that balances the amount of thermal energy recovered by the HTF passing through the tubes bundle. As a result, the overall receiver efficiency remains unchanged. Furthermore, Figure 4 and Figure 5 shows the resulting temperature contours, on various planes along the receiver axis, for the full- and part-load cases respectively.

Table 2. Summary of boundary conditions and relative results of the receiver operating, in part load (PL) and full load (FL), without ATI and with 64-tubs ATI at different radial positions (1 cm inwards and 1 cm outwards) with respect to the reference.

	NO ATI		Reference ATI position		ATI 1 cm inwards		ATI 1 cm outwards	
	PL	FL	PL	FL	PL	FL	PL	FL
HTF mfr [g/s]	82.9	220.4	83.2	226.4	83.2	226.3	83.2	226.2
$T_{\text{HTF,in}}$ [K]	973	973	973	973	973	973	973	973
$T_{\text{HTF,out}}$ [K]	1474	1474	1472	1473	1472	1476	1473	1476
$T_{\text{HTF,in,cavity}}$ [K]	//	//	1031	1022	1050	1033	1014	1013
η_{receiver} [-]	0.373	0.496	0.373	0.508	0.372	0.51	0.373	0.51

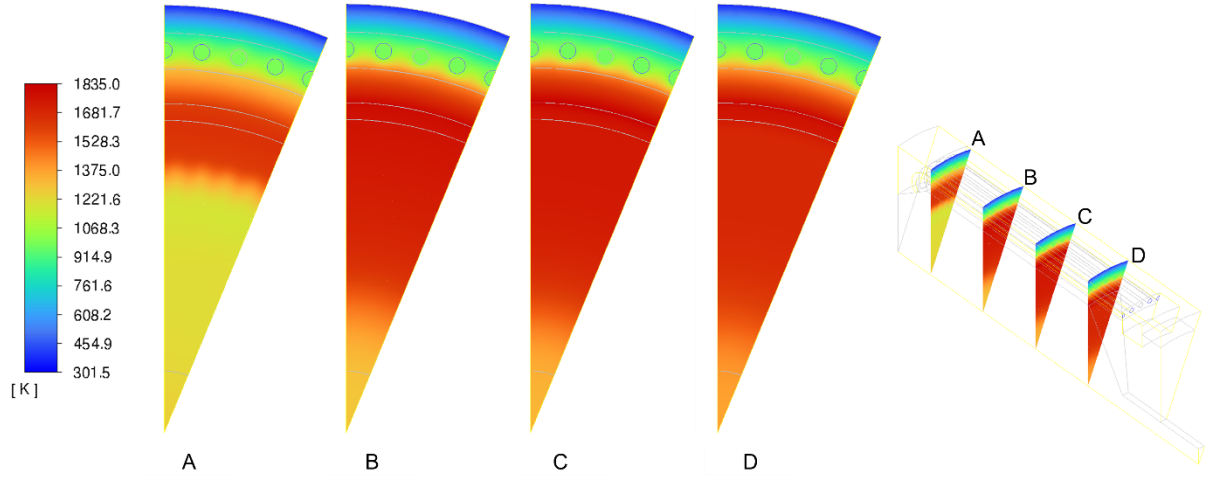


Figure 4. Temperature contours on different planes along the receiver axis (e.g., A: close to receiver aperture window; D: close to HTF outflow pipe) operating at full-load and with 64-tubs ATI at reference radial position.

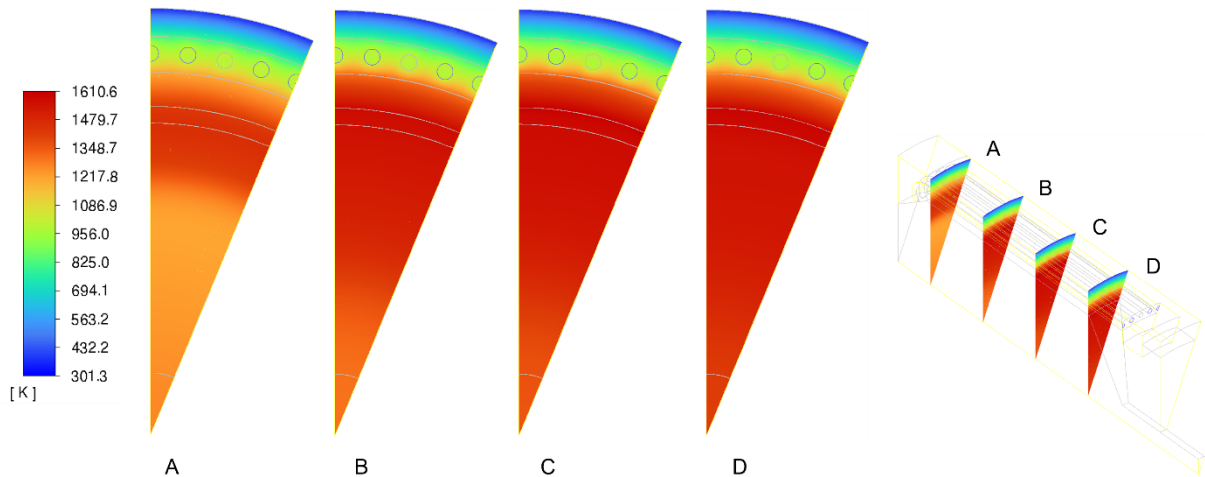


Figure 5. Temperature contours on different planes along the receiver axis (e.g., A: close to receiver aperture window; D: close to HTF outflow pipe) operating at part-load and with 64-tubs ATI at reference radial position.

5. Summary and conclusions

An active thermal insulation system, suitable for cavity-type solar receivers, was proposed and numerically tested. The ATI consists of a tubes bundle, integrated into the insulating material surrounding the cavity, wherein the HTF is flown from the back of the receiver to the front part to be then injected into the cavity. The foreseen advantages given by the implementation of this ATI solution are: (i) the reduction of the receiver thermal inertia and (ii) the pre-heating of the HTF prior entering the cavity by exploiting a fraction of the heat that would have been otherwise lost to the environment.

A CFD-based approach was then followed with the aim of evaluating the effect of integrating the ATI on both the thermo-fluid dynamics behavior, and on the thermal efficiency, of the absorbing gas solar receiver developed by Synhelion SA. The effect of two relevant ATI design parameters (i.e., tubes number and tubes bundle radial position) was investigated allowing to derive some useful guidelines for the eventual ATI development. Based upon the simulations results, the major considerations that can be drawn are:

- For all the cases simulated, the HTF was effectively pre-heated flowing through the ATI between 4% and 6% with respect to the HTF inlet temperature through the tubes bundle at the rear part of the receiver. Despite this, for some cases, the receiver efficiency was unchanged due to the resulting higher temperature of the region close to the receiver aperture which translates into higher losses.
- The ATI system integration resulted to be slightly beneficial only in the case the receiver is operated at full-load (i.e., nominal incoming concentrated solar radiation).
- Concerning the receiver efficiency, the effect of tubes bundle radial position resulted to be negligible in the range considered (i.e., ± 1 cm with respect to the reference position) independently upon the receiver input power (full load or part load). The ATI radial position was only affecting the HTF pre-heating with higher inlet temperature recorded for the case with tubes bundle closer to the cavity wall.
- The effect of tubes number was more pronounced with the receiver efficiency that increased by 2.4% and 9.8%, with respect to the case of receiver operating without ATI, for the full-power cases considering 64 and 36 tubes respectively.

Author contributions

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Conceptualization and investigation: SAZ, PG, GA, MCB; Methodology, data curation and formal analysis: SAZ, PG; Funding acquisition: SAZ, PG, GA, MCB; writing – original draft preparation: SAZ; writing – review and editing: SAZ, PG, GA, MCB; supervision, GA and MCB; project administration, SAZ and PG All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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