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Solar Energy at High Temperature

Final report

FUELREC

Solar receiver for the production of solar fuels from water, carbon dioxide and methane

Synhelion
solar fuels

University of Applied Sciences and Arts
of Southern Switzerland
SUPSI

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Contents

Project goals

This project is aimed at the modelling, design, fabrication, and experimental demonstration of one of the core components of a solar fuels plant. Namely, a 200 kW high-temperature solar receiver for delivering process heat at temperatures higher than 1’000°C for the thermochemical conversion of $H_2O/CO_2/CH_4$ into syngas, the precursor to liquid hydrocarbon fuels. The experimental validation of the receiver at pre-commercial scale will advance the technological readiness level and its industrial implementation.

Summary

Environmentally friendly petrol, diesel and paraffin is the key to climate-neutral mobility. Synhelion uses solar thermal energy to convert CO2 and water into synthetic fuels - so-called solar fuels. Solar radiation is reflected by the solar field with a multitude of mirrors, concentrated on the receiver and converted into high-temperature process heat. In commercial solar tower power plants, tubular receivers are usually used for direct water vapour generation or with molten salts as the heat transfer medium, reaching temperatures of up to 600°C. In contrast, the conversion of CO2 and water into synthesis gas requires 1,000°C and more. For this purpose, Synhelion has developed a novel receiver technology that takes advantage of the properties of greenhouse gases such as water vapour and CO2 and uses them as a heat transfer medium. The receiver structure consists only of a cavity with black, thermally insulated walls and a window for the concentrated sunlight to enter. The operating principle is based on the greenhouse gas effect: concentrated solar radiation enters the cavity through the window, penetrates the heat transfer medium, which is transparent in the solar spectrum, and is absorbed by the black walls. This heats up the walls and they in turn radiate back into the cavity. However, they emit radiation with longer wavelengths (infrared radiation). This infrared radiation is largely absorbed by the heat transfer medium as it flows backwards through the cavity from the inlet opening immediately behind the window, thus heating up to the desired outlet temperature. Exploiting the greenhouse gas effect enables heat losses due to back radiation to be minimised, allowing concentrated solar radiation from solar trunk systems to be converted into process heat at temperatures of up to 1,500°C with high efficiencies. As part of the FUELREC project, a 250 kW receiver prototype was built and successfully tested in Synlight - the world's largest solar simulator at DLR in Jülich, Germany. Exit temperatures of up to 1550°C were achieved, 350°C more than with any other receiver ever built. The receiver technology enables the use of solar heat in thermochemical processes for the production of solar fuels (including hydrogen), for example by reforming natural gas or biogas, up to thermochemical water and CO2 splitting by means of two-stage redox processes. The solar heat can also be used to decarbonise energy-intensive high-temperature processes, for example in the steel industry or cement production. In addition, the receiver can be used in solar thermal power plants to generate electricity, which enables high efficiencies well above the state of the art.

Zusammenfassung

Umweltfreundliches Benzin, Diesel und Kerosin ist der Schlüssel zu klimaneutraler Mobilität. Synhelion nutzt Solarthermie zur Umwandlung von CO_2 und Wasser in synthetische Treibstoffe – sogenannte solare Treibstoffe. Die Sonnenstrahlung wird vom Solarfeld mit einer Vielzahl von Spiegeln reflektiert, auf den Receiver konzentriert und in Hochtemperatur-Prozesswärme umgewandelt. In kommerziellen Solarturm-Kraftwerken werden meist Röhren-Receiver zur direkten Wasserdampferzeugung bzw. mit geschmolzenen Salzen als Wärmeträgermedium verwendet, wobei Temperaturen bis zu 600°C erreicht werden. Demgegenüber werden für die Umwandlung von CO_2 und Wasser in Synthesegas 1‘000°C und mehr benötigt. Dazu hat Synhelion eine neuartige Receiver-Technologie entwickelt, die sich die Eigenschaften von Treibhausgasen wie Wasserdampf und CO_2 zu Nutze macht und diese als Wärmeträgermedium einsetzt. Der Receiver-Aufbau besteht lediglich aus einem Hohlraum mit schwarzen, wärme-

isolierten Wänden und einem Fenster für den Eintritt des konzentrierten Sonnenlichts. Das Funktionsprinzip beruht auf dem Treibhausgaseffekt: Konzentrierte Solarstrahlung tritt durch das Fenster in den Hohlraum ein, durchdringt das im Solarspektrum transparente Wärmeträgermedium und wird von den schwarzen Wänden absorbiert. Hierdurch werden die Wände aufgeheizt und strahlen ihrerseits zurück in den Hohlraum. Allerdings emittieren sie Strahlung mit größeren Wellenlängen (Infrarotstrahlung). Diese Infrarotstrahlung wird vom Wärmeträgermedium größtenteils absorbiert, während es von der Eintrittsöffnung unmittelbar hinter dem Fenster durch den Hohlraum nach hinten fließt und sich so auf die gewünschte Austrittstemperatur aufwärmt. Die Ausnutzung des Treibhausgaseffekts ermöglicht eine Minimierung der Wärmeverluste durch Rückstrahlung, wodurch konzentrierte Sonnenstrahlung von Solartrum-Anlagen mit hohen Wirkungsgraden in Prozesswärme bei Temperaturen bis zu 1’500°C umgewandelt werden kann. Im Rahmen des FUELREC-Projektes wurde ein 250 kW Receiver-Prototyp gebaut und im Synlight – dem weltgrössten Solarsimulator am DLR in Jülich, Deutschland – erfolgreich getestet. Es wurden Austrittstemperaturen bis 1550°C erreicht, 350°C mehr als mit jedem anderen jemals gebauten Receiver. Die Receiver-Technologie ermöglicht die Nutzung von solarer Wärme in thermochemischen Prozessen zur Erzeugung solarer Kraftstoffe (auch Wasserstoff) zum Beispiel durch die Reformierung von Erdgas oder Biogas bis hin zur thermochemischen Wasser- und CO2-Spaltung mittels zweistufiger Redox-Prozesse. Die solare Wärme kann auch zur Dekarbonisierung energieintensiver Hochtemperatur-Prozesse beispielsweise in der Stahlindustrie oder Zementherstellung verwendet werden. Darüber hinaus lässt sich der Receiver in solarthermischen Kraftwerken zur Stromerzeugung einsetzen, was hohe Wirkungsgrade deutlich über dem Stand der Technik ermöglicht.

Résumé

L'essence, le diesel et le kérosène écologique sont la clé d'une mobilité climatiquement neutre. Synhelion utilise l'énergie solaire thermique pour convertir du CO2 et de l'eau en combustibles synthétiques – les combustibles dits «solaires». Le rayonnement solaire est réfléchi par un grand nombre de miroirs, concentré sur le récepteur et converti en chaleur de processus à haute température. Dans les centrales solaires à tour commerciales, on utilise des récepteurs tubulaires qui emploient de la vapeur ou des sels fondus comme fluide caloporteur pour atteindre des températures allant jusqu'à 600°C. En revanche, des températures à partir de 1000°C sont nécessaires pour la conversion du CO2 et de l'eau en gaz de synthèse. À cette fin, Synhelion a développé un récepteur solaire novateur qui exploite les propriétés des gaz à effet de serre, tels que la vapeur d'eau ou le CO2, et les utilise comme fluide caloporteur. Le récepteur est composé d'une cavité avec des parois noires thermiquement isolées et d'une fenêtre qui permet à la lumière solaire concentrée d’entrer. Le principe de fonctionnement est basé sur l'effet de serre: le rayonnement solaire concentré entre dans la cavité par la fenêtre et passe par la cavité sans être absorbé car les gaz à effet de serre sont transparents dans le spectre solaire. Finalement, le rayonnement solaire est absorbé par les parois noires. Cela réchauffe les parois, qui à leur tour émettent des rayonnements de plus grande longueur d'onde (rayonnement infrarouge) vers la cavité. Le fluide caloporteur circule à travers la cavité depuis l'ouverture d'entrée située derrière la fenêtre et absorbe le rayonnement infrarouge issu des parois pour se réchauffer jusqu'à la température de sortie souhaitée. Grâce à l'exploitation de l'effet de serre, les pertes de chaleur sont minimisées, ce qui permet de convertir le rayonnement solaire concentré en chaleur industrielle à des températures allant jusqu’à 1500°C avec un rendement élevé. Dans le cadre du projet FUELREC, un prototype de récepteur de 250 kW a été construit et testé avec succès au Synlight – le plus grand simulateur solaire du monde – au DLR à Jülich, Allemagne. Des températures de sortie allant jusqu'à 1550°C ont été atteintes, soit 350°C de plus qu'avec tout autre récepteur jamais construit. La technologie innovante de récepteur permet d'utiliser la chaleur solaire pour produire des combustibles solaires (également l'hydrogène) par le bias de processus thermochimiques, tels que le reformage de gaz naturel ou de biogaz, ou bien la séparation thermochimique d'eau et de CO2 par une réaction d’oxydoréduction en deux étapes. La chaleur solaire peut également être utilisée pour décarboner des processus à haute température gourmands en énergie, par exemple dans l'industrie sidérurgique ou la production de ciment. En outre, le récepteur peut être utilisé dans les centrales thermiques solaires pour produire de l'électricité, ce qui permet d'obtenir des rendements élevés bien supérieurs à l'état de la technique.

Sommario

La benzina, il diesel e il cherosene ecologici sono la chiave per il futuro di una mobilità neutrale per il clima. Synhelion utilizza l'energia solare per convertire CO2 e acqua in combustibili sintetici - i cosiddetti combustibili solari o “solar fuels”. Il concetto studiato da Synhelion si basa sulla concentrazione della radiazione solare. Infatti, quest’ultima viene riflessa da un campo solare formato da un gran numero di specchi, concentrata in un ricevitore e convertita in calore di processo ad alta temperatura. Nelle centrali solari a torre commerciali, vengono utilizzati soprattutto ricevitori tubolari per la generazione diretta di vapore acqueo o che adottano dei sali fusi come fluido per il trasporto del calore. Questi sistemi raggiungono temperature del fluido non più alte di 600°C. Tecnicamente però, per la conversione di CO2 e acqua in gas di sintesi, precursore dei combustibili sintetici, sono necessarie temperature superiori a 1.000°C. A questo scopo, Synhelion ha sviluppato una nuova tecnologia di ricevitore solare che utilizza le proprietà dei gas ad effetto serra come il vapore acqueo e la CO2. La struttura del ricevitore consiste in una semplice cavità con pareti nere, termicamente isolate verso l’esterno, e una finestra trasparente alla luce solare concentrata. Il principio di funzionamento si basa proprio sull'effetto serra: la radiazione solare concentrata entra nella cavità attraverso la finestra, penetra attraverso il fluido, che è trasparente nello spettro solare, e viene assorbita sulle pareti nere. Le pareti si riscaldano e, a loro volta, irradiano di nuovo nella cavità. Queste onde elettromagnetiche vengono però riemesse con lunghezze d'onda più lunghe (radiazioni infrarosse) rispetto a quelle caratteristiche dello spettro solare. Questa radiazione infrarossa è in gran parte assorbita dal fluido che scorre nella cavità del ricevitore muovendosi dai getti di ingresso, posti immediatamente dietro la finestra, verso l’uscita posta sul fondo del ricevitore. In questo percorso, il fluido si scalda fino alla temperatura di uscita desiderata. Lo sfruttamento dell'effetto serra permette di minimizzare le perdite di calore dovute alla “back radiation”, cioè alla fuga di energia radiante attraverso la finestra, consentendo di convertire con elevata efficienza la radiazione solare concentrata in calore di processo con temperature fino a 1.500°C. All’interno del progetto FUELREC è stato costruito un prototipo di ricevitore da 250 kW che è stato testato con successo presso il Synlight, il più grande simulatore solare del mondo che si trova presso il DLR di Jülich, in Germania. In questi esperimenti, per il fluido in uscita dal ricevitore sono state raggiunte temperature fino a 1550°C, ben 350°C in più rispetto a quanto ottenuto con qualsiasi altro ricevitore mai costruito. La tecnologia del ricevitore Synhelion permette l'uso del calore solare in processi termochimici per la produzione di combustibili solari (anche idrogeno), per esempio il reforming del gas naturale o del biogas, fino alla scissione termochimica dell'acqua e della CO2 per mezzo di processi redox a due fasi. Il calore solare del ricevitore Synhelion può anche essere usato per abbattere le emissioni di CO2 in processi ad alta temperatura ed alta intensità energetica, come per esempio quelli che si incontrano nell'industria dell'acciaio o nella produzione del cemento. Inoltre, il ricevitore può essere utilizzato in centrali solari termiche per generare elettricità, consentendo valori di efficienza ben al di sopra di quanto oggi offra lo stato dell'arte.

List of abbreviations

CFD	Computational fluid dynamics
HTF	Heat transfer fluid

Work undertaken and findings obtained

1 Introduction

In the framework of the completed BFE-funded project ReceiverSIM (SI/501618-01), a computational fluid dynamics (CFD) approach, suitable to replicate the thermo-fluid dynamics behaviour of the innovative absorbing receiver concept proposed by Synhelion, has been developed and successfully validated with numerical results obtained by Synhelion exploiting the most accurate numerical models available to model radiative heat transfer in participating media.

The validated CFD model was further developed, during the first part of the FUELREC project, and it was extensively used to carry out specific CFD simulations aimed at clearly understanding the physical phenomena occurring into this innovative receiver concept, along with their mutual interactions. Furthermore, the CFD model was also exploited to run several simulations campaigns which allowed to conceptually design on a step-by-step basis the first absorbing gas receiver prototype.

In the final part of the FUELREC project the activities, detailed in the present report, were mainly focused on the final engineering design of the receiver prototype, its realization and on the execution of several experimental tests, performed at the DLR Synlight facility, which allowed to demonstrate the feasibility and effectiveness of this innovative receiver design.

2 Receiver prototype final design and experimental tests

2.1 Effect of important parameters on the receiver performance

A CFD-based approach, suitable to accurately replicate the thermo-fluid dynamics behaviour of the innovative absorbing gas receiver [1], was developed and validated through both the BFE-funded ReceiverSIM and FUELREC projects [2]. This CFD model was extensively exploited to assist the design phase of the receiver prototype. In particular, several CFD simulations campaigns were performed with the aim of evaluating how different operating conditions affect the receiver thermo-fluid dynamics behaviour. 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.

The reference computational domain assumed for the simulations, depicted in figure 1, 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 1’000 K and with a reference inclination angle of 27° from aperture (dashed orange arrow in figure 1).

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.

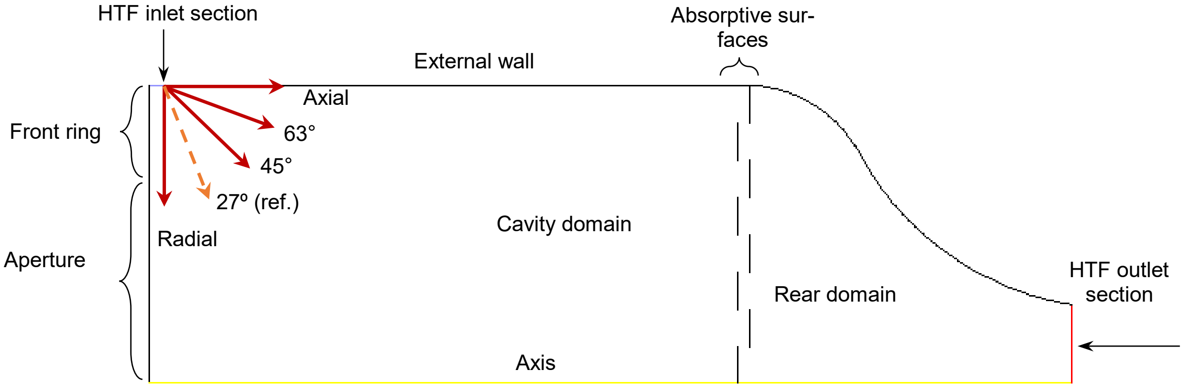

Figure 1: Reference receiver geometry – Computational domain.

2.1.1 Unpressurized receiver - Effect of HTF entrance angle

Five different orientations of the inlet HTF velocity vector, depicted in figure 1, 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 2. 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 3. According to the results obtained, it is evident that the temperature distribution is remarkably affected by the HTF entrance angle.

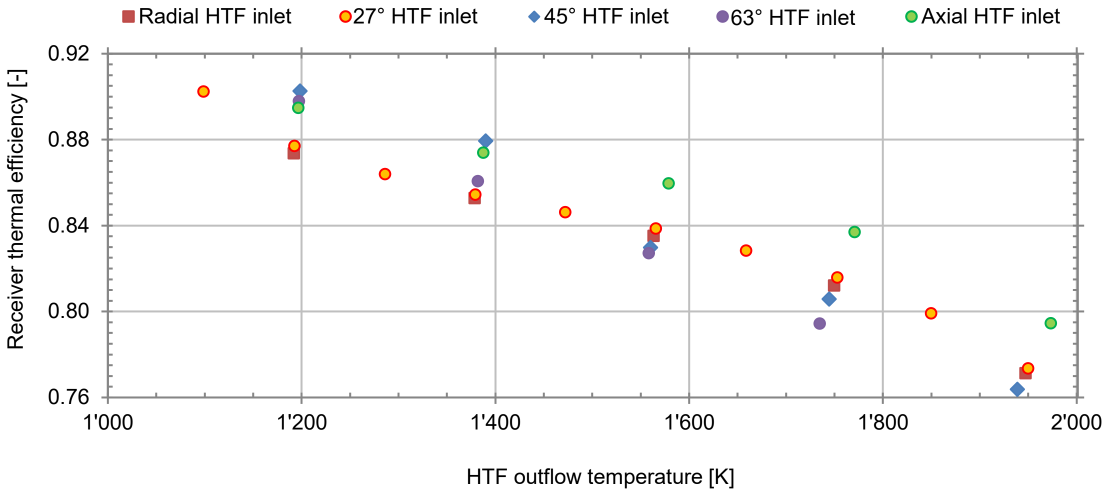

Figure 2: Variation of the receiver thermal efficiency as a function of the HTF entrance angle into the cavity.

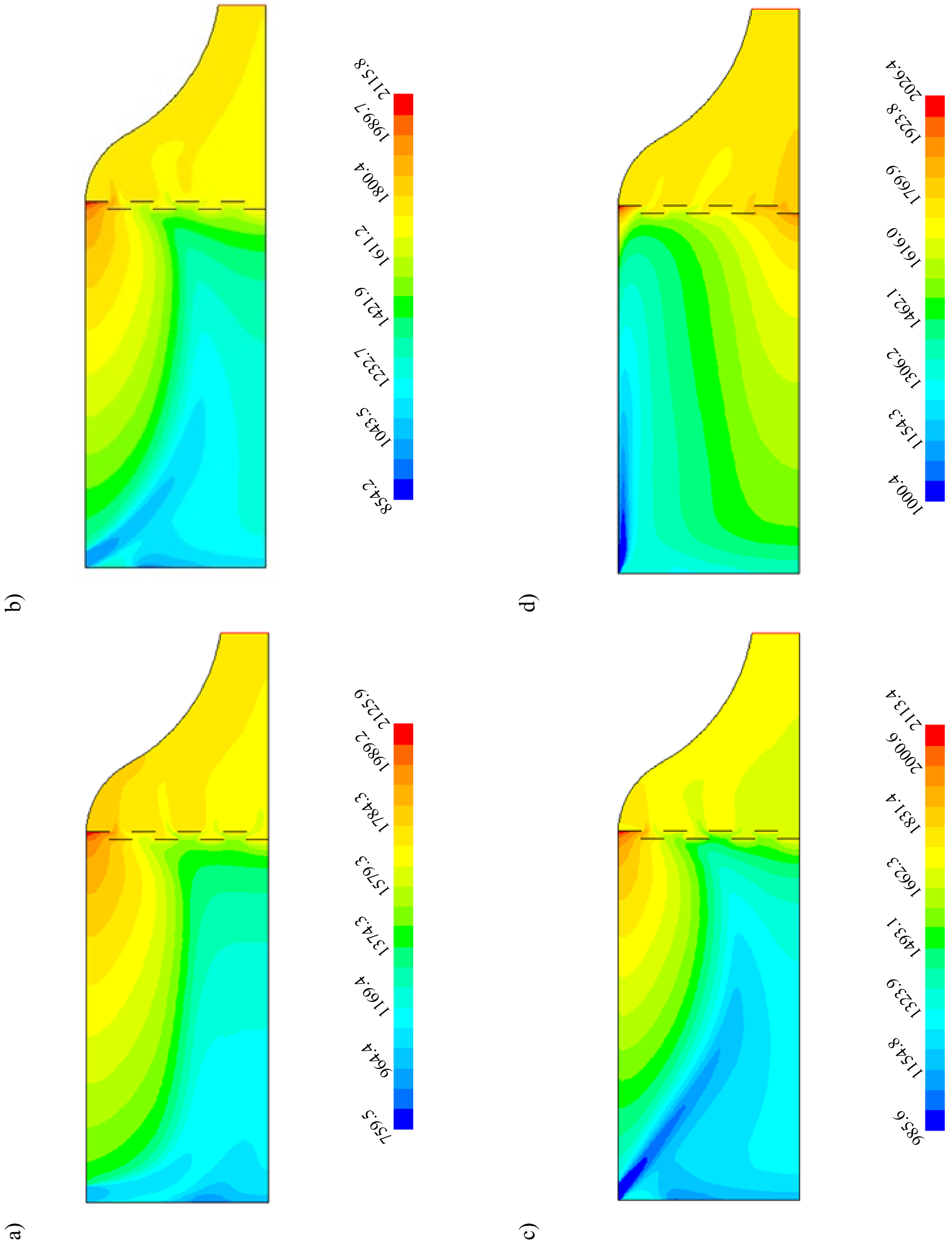

Figure 3: Temperature contours of the absorbing gas receiver operating with mass flow rate of 51 kg/s at different HTF entrance angle: a) radial, b) 27° (reference), c) 45° and d) 63°. Temperature values are [K].

2.1.2 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 1’100 K and 2’000 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 4 superimposed to those of the 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 5, 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.

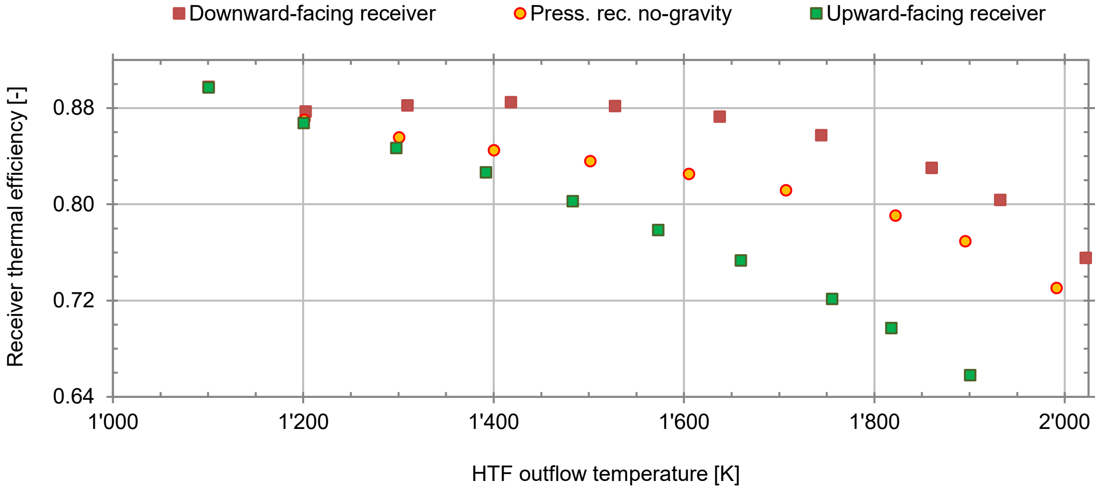

Figure 4: Variation of the pressurized receiver thermal efficiency as a function of the HTF outflow temperature for the two receiver orientations investigated: downward facing receiver (red squares) and upward facing receiver (green squares).

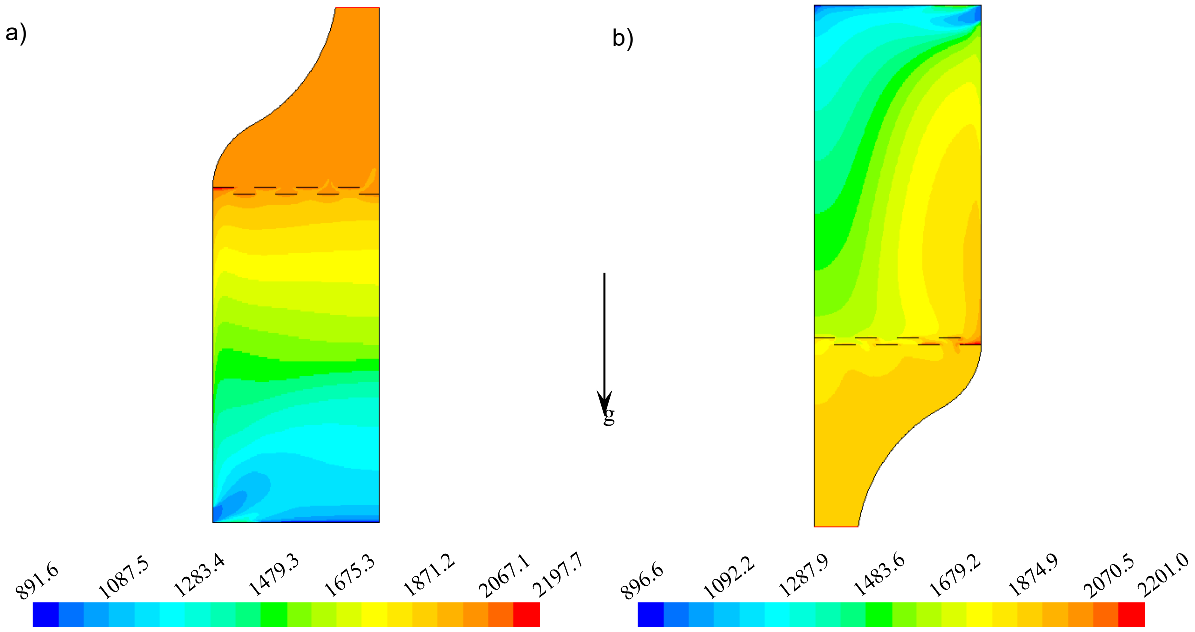

Figure 5: Temperature contours of the pressurized receiver operating with the lowest HTF mass flow rate of 0.07 kg/s: a) downward facing and b) upward facing. Temperature values are [K].

2.1.3 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 routine (UDF), was investigated.

The resulting receiver thermal efficiency is shown in the graph of figure 6. 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 7) 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.

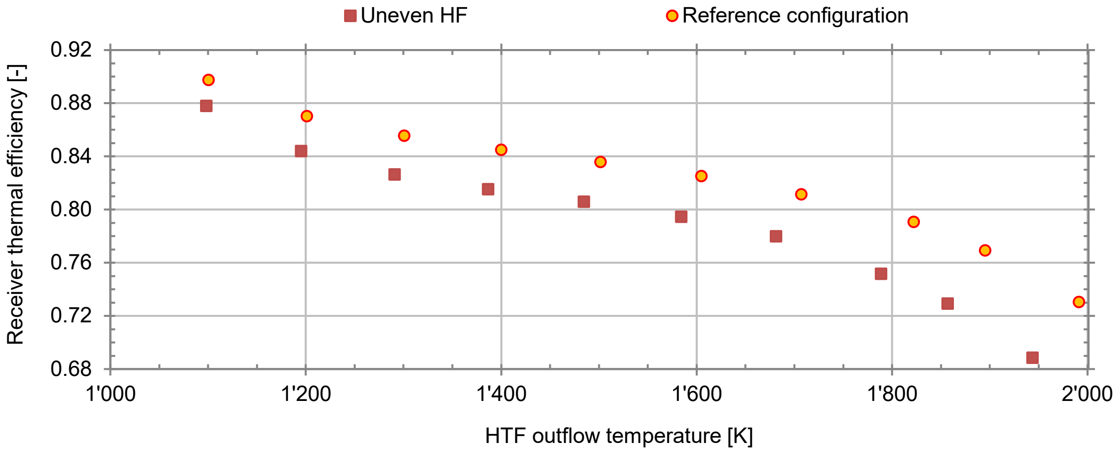

Figure 6: Variation of the pressurized receiver thermal efficiency as a function of the HTF outflow temperature assuming a realistic concentrated solar flux distribution into the cavity (red squares).

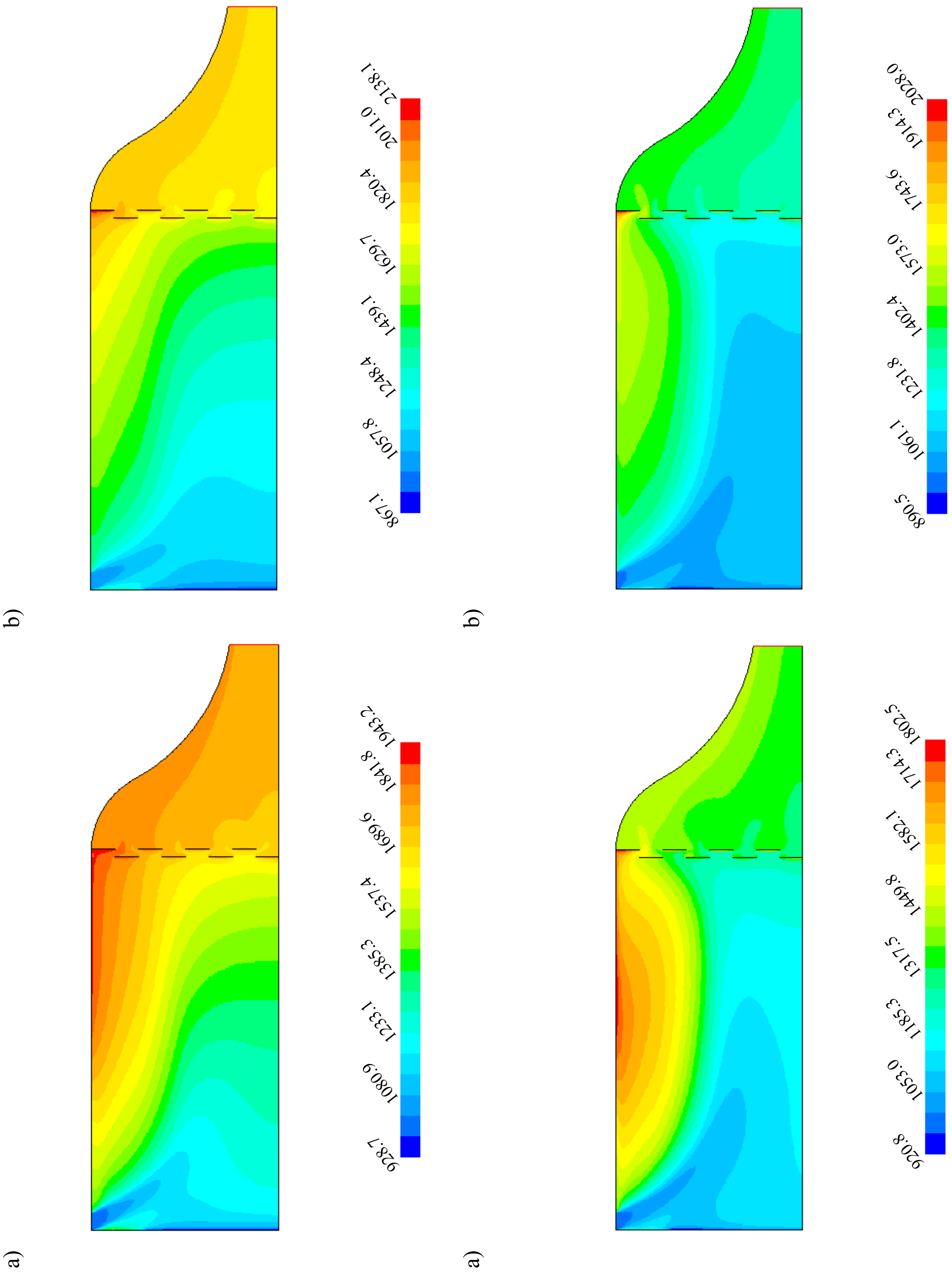

Figure 7: Temperature contours of the pressurized receiver operating with 0.09 kg/s (l.h.s.) and 0.21 kg/s (r.h.s.) assuming: a) realistic concentrated solar flux distribution and b) incoming heat flux on the absorptive surfaces only. Temperature values are [K].

2.2 Receiver prototype final design and development

The main receiver prototype components (pressure vessel, front flange, steam feed circuit, measurement setup) have been designed for pressurized operation (up to 10 bar overpressure). However, the current version described in this paragraph is meant for the first experimental campaigns at ambient pressure. For this reason, it has a flat quartz window at the inlet instead of the conventional pressure-bearing dome window. Furthermore, since the receiver orientation for the experimental tests can only be horizontal, thanks to specific CFD simulations, it was observed that gravity resulted to have an important impact on the receiver performance. For this reason, the outlet section of the receiver was moved from the axial location to the upper part ("Exit duct" in figure 9). This modification allowed to achieve higher HTF outflow temperature levels preventing the relatively cold, and denser, HTF to rapidly reach the outlet section. The receiver prototype has been tested at the DLR high-flux solar simulator facility Synlight in Jülich, Germany.

2.2.1 System overview

An overview of the receiver prototype final assembly is shown in figure 8. The receiver prototype is currently dimensioned for ambient-pressure operation (0 – 0.2 barg) and 0.015 – 0.15 kg/s HTF mass flow rate. Outlet temperatures of 800 – 1'500 °C are targeted.

Steam is generated outside the DLR Synlight building, fed through a pipe to a flow-control unit, then superheated to up to 500 °C and symmetrically fed into the receiver via two inlets.

Inside the receiver, steam is homogeneously fed into the cavity through a specific manifold. After being heated by radiative absorption in the cavity up to 1'500 °C (the core step of the process), the steam is led through an exhaust, where the maximum achieved temperature is measured by means of a series of thermocouples. Thereafter, the steam is cooled down in a custom-made chimney by mixing with a massive amount of air, before releasing it through the building ventilation system.

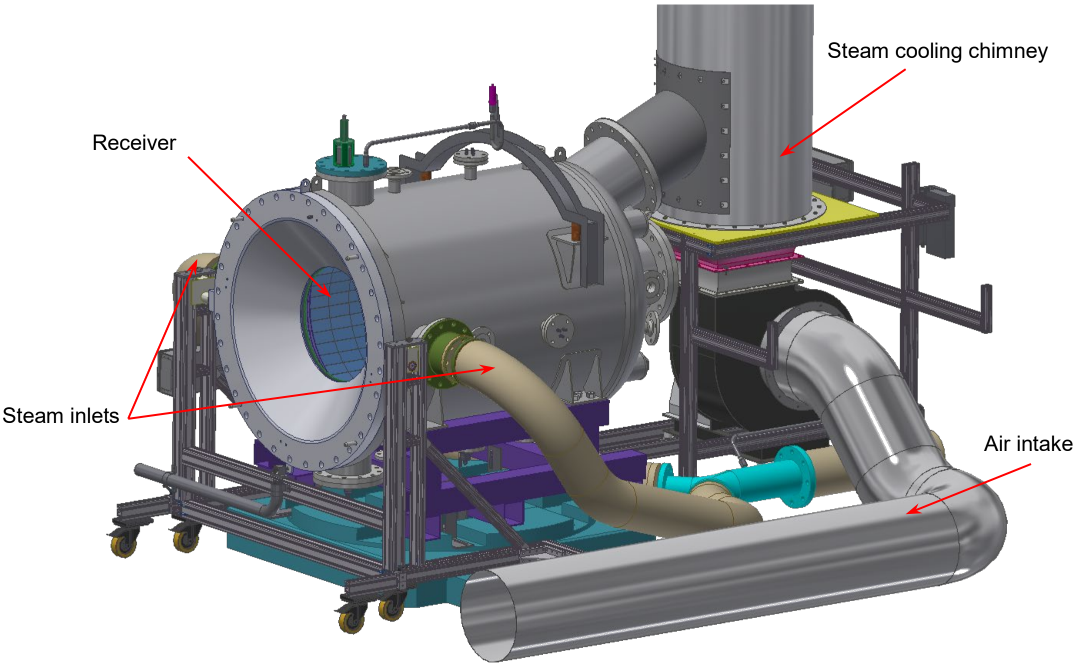

Figure 8: Receiver prototype assembly overview.

2.2.2 Receiver

The absorbing gas receiver prototype is basically a windowed and insulated cavity made of refractory material. The window aperture diameter is 560 mm (with the window itself having a diameter of 600 mm and a thickness of 12 mm). The cavity diameter is 800 mm, and the length is around 1’000 mm. The system is contained within a pressure vessel. Figure 9 shows a cross section of the final receiver prototype design with an identification of the main components.

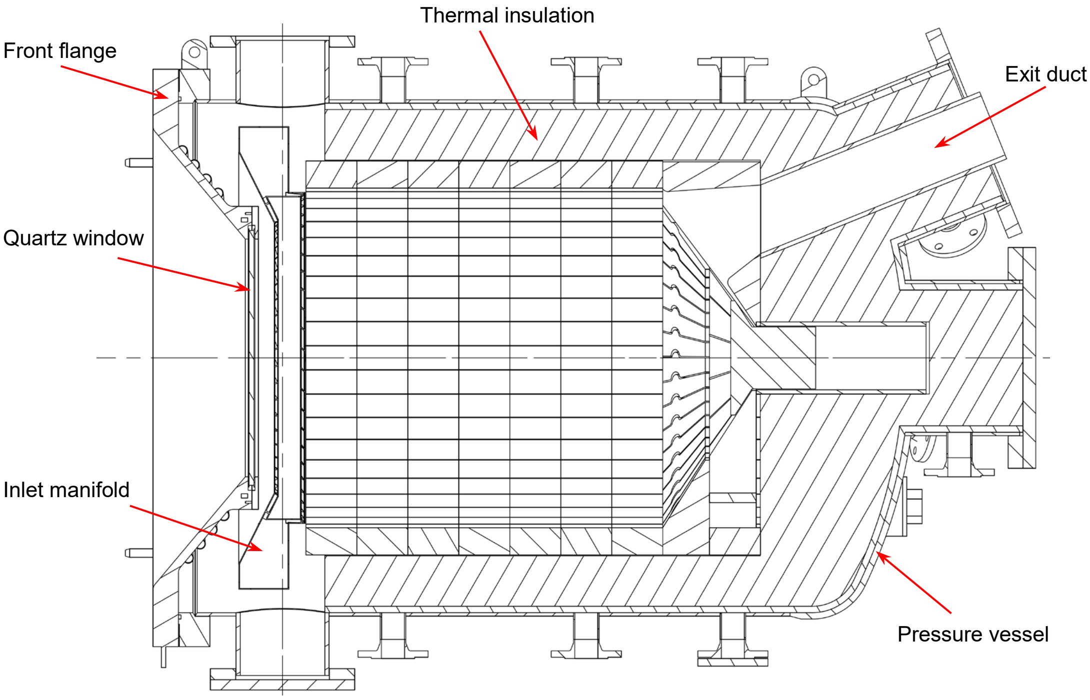

Figure 9: Cross section of the final receiver prototype and details on the main components.

2.2.3 Pressure vessel

The pressure vessel has a total volume of 1’940 L and a gross length of 1’988 mm. The materials used for its realization are stainless steel 1.4571 and 1.4404. It is designed for a pressure range of 0 – 10 barg and mantle temperature of up to 250 °C. The pressure vessel is therefore also adapted for later tests with pressurized steam.

The main flange for mounting of the front cover with quartz window has a diameter of 1’300 mm. Sixteen DN50 flanges are welded to the mantle and are used for feeding through thermocouples, pressure sensor and condensate outlet. Four DN200 flanges are also included for steam inlet and overpressure valve. Two DN350 outlet flanges are available, one centered (currently unused) and one in the upper part of the bumped vessel end (currently used for steam outlet).

The overpressure valve is custom-designed for 0.2barg. overpressure. It serves the purpose of protection of the quartz window in case the vessel outlet gets obstructed and steam cannot escape.

Along with the vessel (see figure 10), a dummy cover is manufactured for the vessel pressure testing (for which the front flange needs to be closed) and also for later pressure testing of dome-shaped quartz windows.

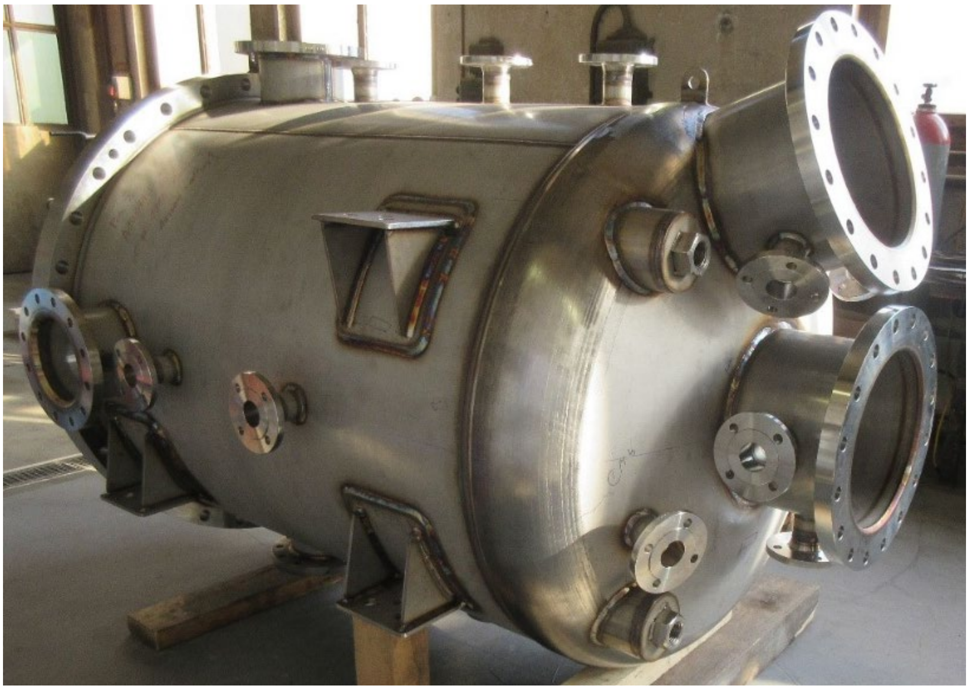

Figure 10: Pressure vessel in the final construction phases.

2.2.4 Insulation

The high-performance insulation of the system is one of the core items. It needs to withstand inner temperatures of more than 1’700 °C and, at the same time, withstand a steam atmosphere (and accidental condensation). The thermal insulation materials are mainly composed of alumina and silica.

Since the temperature at the vessel mantle shall not exceed 200 °C when the inner cavity surfaces are at 1’700 °C, the total insulation thickness in the cylindrical section of the receiver is 200 mm.

2.2.5 Front flange

The front flange (see figure 11) consists of two steel rings connected by means of a welded cone. The quartz window is mounted on the inner ring by clamping with a steel ring onto graphite sealing. A channel is milled in the inner ring for water cooling and a spiral is welded to the cone, also for water cooling. The design has been chosen to achieve best cooling homogeneity and thus to avoid thermal stress of the front flange that could lead to damage of the quartz window.

Angled feedthroughs are added to the front flange to place thermocouples to monitor temperature homogeneity at the front flange.

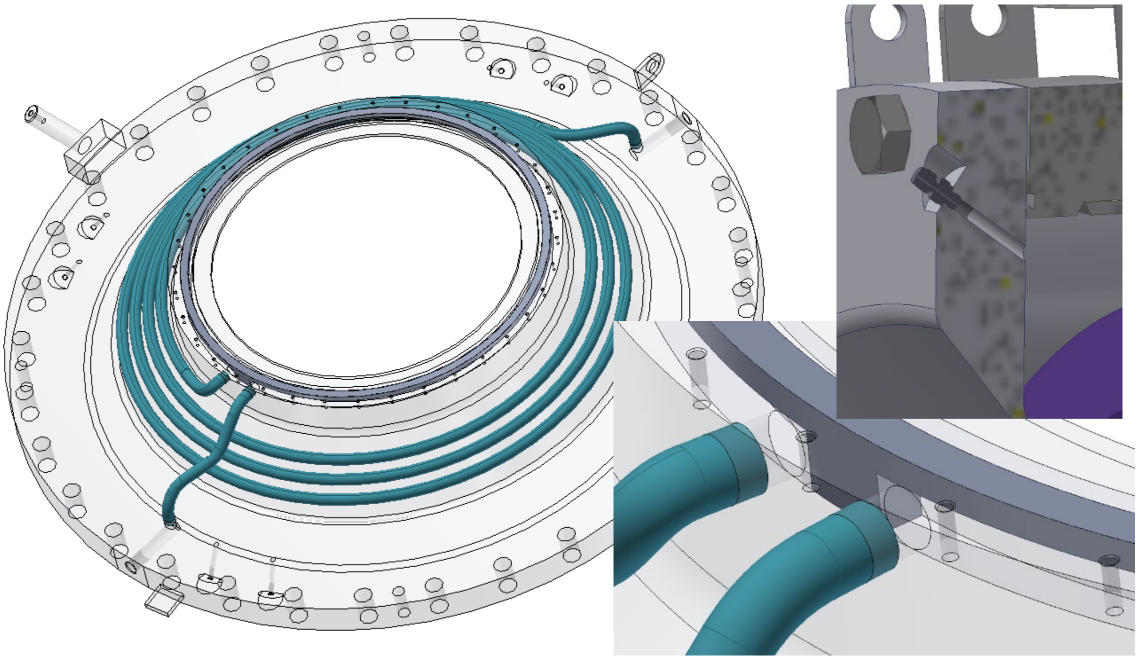

Figure 11: Overview of the front flange, with detail of the cooling channel and connection of the tubing (lower inset), and detail of the feedthroughs for thermocouple placement (upper inset).

2.2.6 Shared items

Steam generator

Steam generation (see figure 12) is done outside the DLR Synlight building with an oil-fired aggregate. Steam with a mass flow of 0.015–0.15 kg/s at a pressure of 4–11 barg and a temperature of 150–190 °C can be produced.

Figure 12: Representative example of steam generator.

Steam superheater

After the generated steam has been transported to the DLR Synlight test room, it is further heated up to 300–500 °C by a 35 kW electrical superheater (see figure 13).

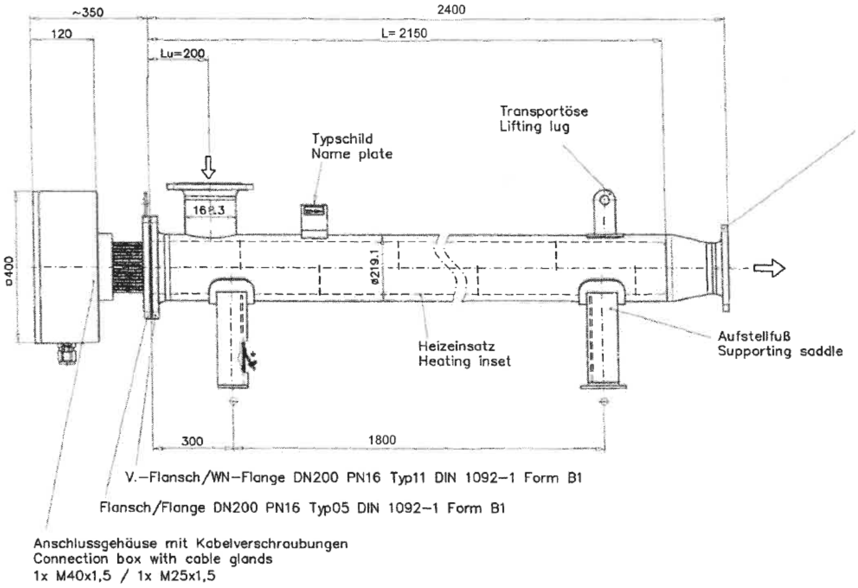

Figure 13: Electrical steam superheater.

Steam distribution

Steam distribution after the superheater is performed by means of a T-joint that splits the steam into two hoses that are fed to the manifold by means of the left and right DN200 flanges. The T-joint includes a pressure sensor and a thermocouple.

Steam cooling

At the receiver outlet section, steam is expected to reach a temperature level of up to 1’500 °C. For this reason, it needs to be cooled down to a temperature that can be handled by the DLR building ventilation facility, i.e. to no more than 200 °C. For the ambient-pressure system, this can be easily achieved by means of massive flooding of the steam with ambient-temperature air. To this end an industrial blower is used to blow up to 3 m^3/s air in a custom-designed chimney (see figure 14). The angled design is necessary to have the chimney outlet below the building ventilation.

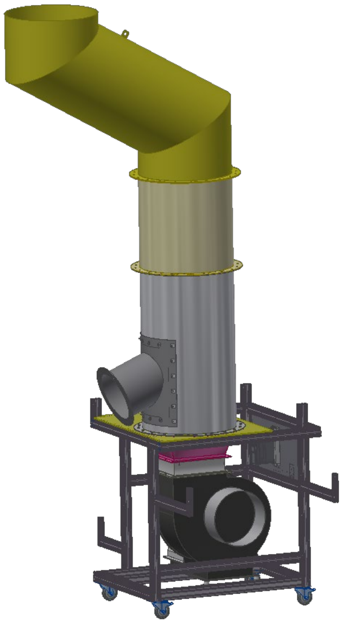

Figure 14: Steam cooling chimney.

2.2.7 Auxiliaries

Additional auxiliaries include:

- steam flow-control stage with condensate trap, mass flow control valve, overpressure valve, pressure regulator (currently optional) as well as flush-gas supply;
- front-flange pressurized cooling water supply with a water tempering unit which thermostats the water at around 200 °C (by HB-Therm);
- quartz window air cooling;
- compressed air supply for valves actuation and suction thermocouple;
- receiver frame;
- front flange frame;
- Steam cooling frame;
- misc. additional fixtures.

2.2.8 Control system

The control system includes four main layers:

(i) safety layer: upon emergency stop by the operator (responsible for monitoring machine state, process and system parameters, no automatic procedure), energy is removed for steam generator and superheater and flow control valves are closed;

(ii) PLC layer: low-level control of all aggregates;

(iii) interfacing layer in LabVIEW: bidirectional transfer of data to and from the user interface;

(iv) user interface layer, also in LabVIEW.

Additional safety measures include organizational measures such as preventing access to the test room while the system is up and running.

2.3 Receive prototype construction

2.3.1 Assembled receiver setup

Figure 15 shows the assembled receiver prototype in the test chamber at the DLR Synlight. In the following sections, the most important receiver components will be shown in more detail. At the end of this chapter, a description of the calorimeter assembly is shown.

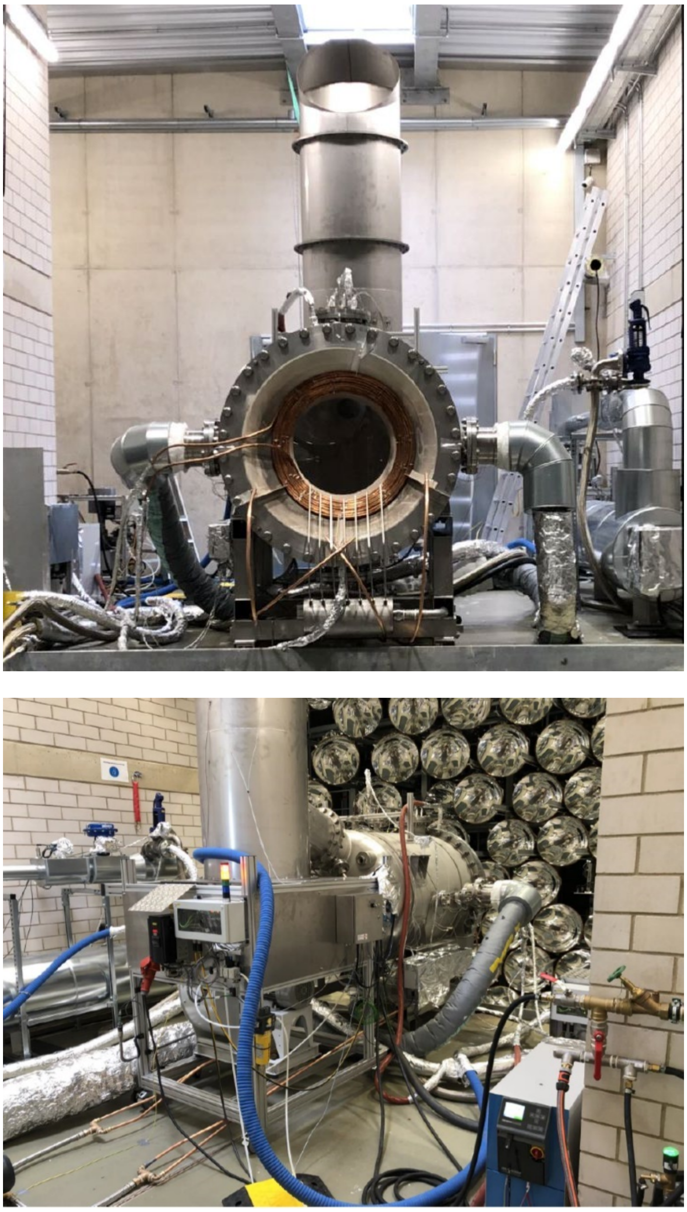

Figure 15: Assembled receiver prototype in test chamber seen from the front (top) and from the back (bottom).

Receiver insulation assembly

As shown in figure 16, during the second campaign, a front ring made of alumina was used. For better cooling of the front ring, an air-cooled front ring made from alumina was used during the third campaign. After the first tests, a larger copper coil and an additional radiation shield was installed.

The window was cooled during the first campaign by the small tubes that can be seen in figure 16 below the window.

Figure 16: Front flange section attached to the receiver with a larger copper coil and a radiation shield.

2.3.2 Steam path assembly

Steam generator

As previously introduced in paragraph 2.2.6, the steam generator is situated outside of the DLR Synlight building inside the white container (l.h.s. of figure 17). The steam flows to the test chamber via steam hoses as seen on the left side in figure 17.

Figure 17: Steam generator situated outside of DLR Synlight building (l.h.s.). Steam hoses transporting the steam from the container to the inner test chamber (r.h.s.).

Steam control line and superheater

The steam control line and the superheater are assembled on the left side of the test chamber. Figure 18 illustrates the steam control line and super heater during the assembly (l.h.s.) and after complete assembly and insulation (r.h.s.).

Figure 18: Steam control line prior to complete assembly and insulation (l.h.s.) and after complete assembly (r.h.s.).

Superheated steam feed

The superheated steam from the superheater flows to the receiver via steam hoses. A T-joint divides the superheated steam flow into two flows that are connected to the left and right side of the receiver, respectively. Figure 19 shows the steam hoses and the T-piece (l.h.s.), prior to insulation of the connecting elements. Further, an installed thermocouple can be seen at the T-joint.

Figure 19: Steam feed from the superheater to the receiver manifold.

Steam cooling

A purpose built steam cooling system was exploited to cool down the steam flow exiting the receiver by flooding the steam with a massive amount ambient air provided by an industrial blower. Figure 20 shows the assembled chimney through which the steam/air mixture exits the test chamber. The blower, which is installed below the chimney, can be seen in the image on the right.

Figure 20: Steam cooling system with chimney (l.h.s.) and industrial blower (r.h.s.).

2.3.3 Test Assembly

Figure 21 shows the receiver after experimental test runs. Left-hand side of figure 21 shows the receiver prototype after the first test run at 1’100 °C. While, r.h.s. of figure 21, shows the receiver with the larger copper coil and radiation shield after a test run at 1’400 °C.

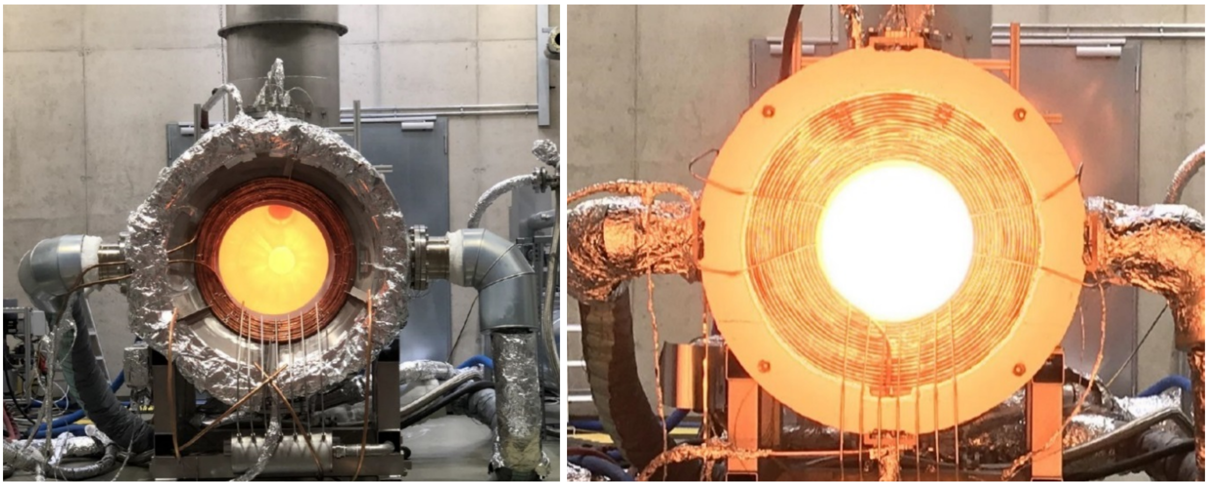

Figure 21: Receiver prototype after first test run at 1’100 °C (l.h.s.) and with larger copper coil and radiation shield after test run at 1’400 °C (r.h.s.).

2.3.4 Calorimeter Assembly

The calorimeter measurements were part of the third campaign at DLR Synlight. The objective of the calorimeter measurements was to determine the exact amount of power incident on the receiver aperture.

2.3.5 DLR Synlight facility

The receiver prototype testing was conducted at the world's largest solar simulator at DLR Synlight in Jülich, Germany. Figure 22 shows the 149 Xenon short-arc lamps that can produce solar radiation power of up to 380 kW. In the r.h.s. of figure 22, the receiver prototype, situated in the middle chamber, is in test position. Figure 23 shows the receiver prototype during a test run with the lamps switched on. A cross section of the DLR Synlight installation is reported in figure 24.

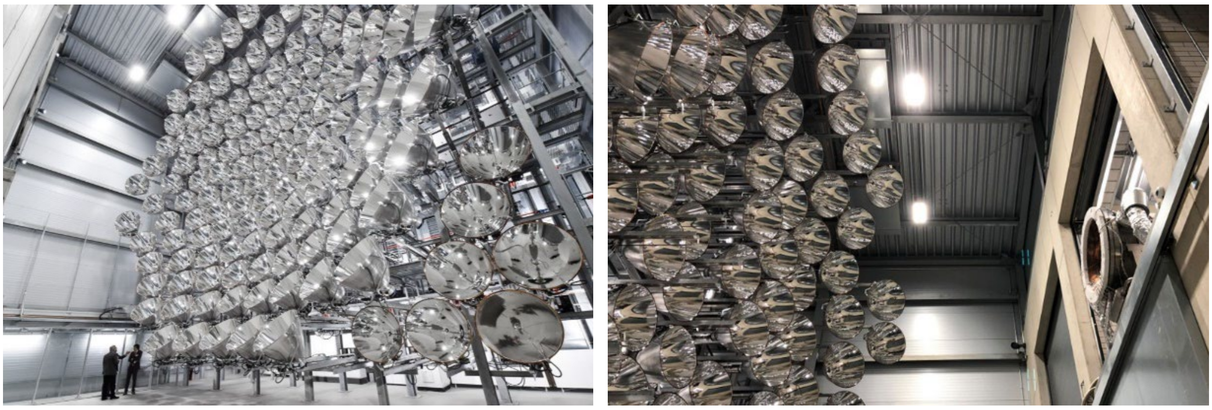

Figure 22: World's largest solar simulator at DLR Synlight. Receiver prototype in test position (right).

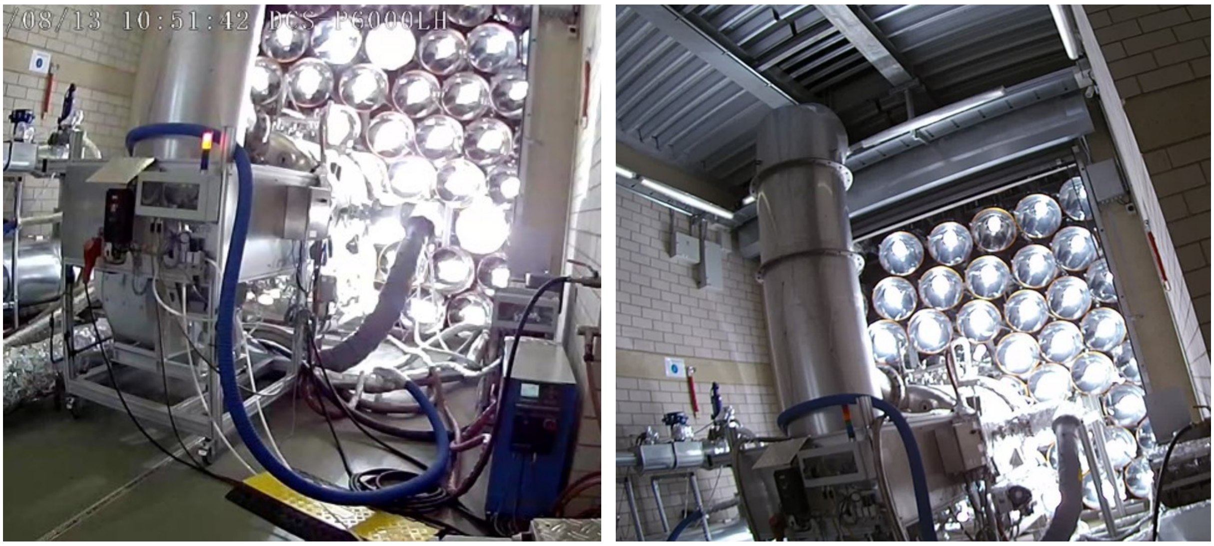

Figure 23: Irradiated receiver prototype during a test run.

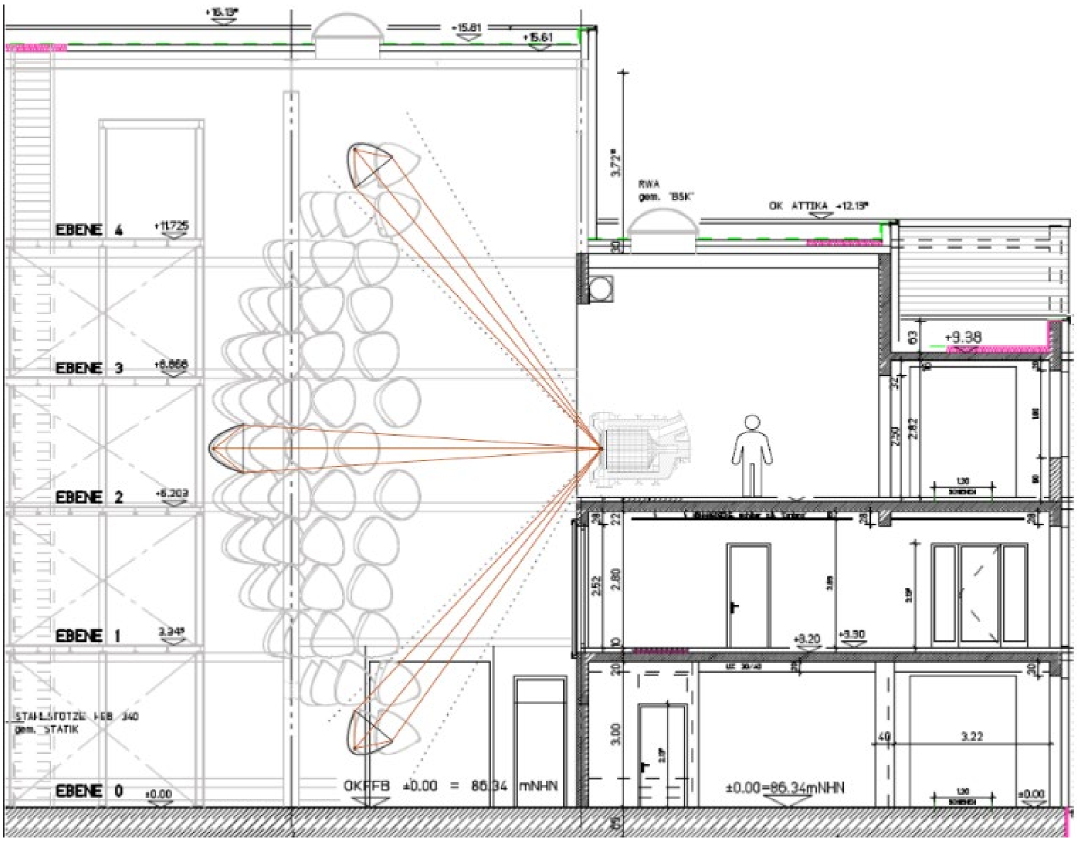

Figure 24: Cross section of the installation at DLR Synlight.

3 Concluding remarks

The elaboration of all the information gathered from both the experimental tests and simulations campaigns allowed to sensibly move further in the knowledge of this innovative absorbing gas receiver concept.

The successful experimental tests, executed at the DLR Synlight facility, which led to the achievement of an HTF outflow temperature of up to 1’550 °C, allowed to demonstrate not only the feasibility of this receiver technology but also its reliability and, especially, its remarkable efficiency.

From the CFD standpoint, the results obtained from all the simulations performed were successfully exploited to arrive to the final design of the receiver prototype. This numerical tool, developed in the framework of the BFE-funded ReceiverSIM and FUELREC projects, will be applied in the next years to assist in the design of the next absorbing gas receiver at pre-commercial scale.

3.1 Dissemination

Some of the main achievements of the project have been presented on major international conferences:

- G. Ambrosetti, P. Good, P. Furler, L. Geissbühler, D. Rutz, S. Ackermann, “Reaching Beyond 1’500°C with the Synhelion Absorbing Gas Solar Receiver: Results of Experimental Campaign”, AIChE Symposium in Honour of Prof. Aldo Steinfeld, November 16-20, Online Version, 2020.
- S.A. Zavattoni, D. Montorfano, P. Good, G. Ambrosetti, M.C. Barbato, “CFD modeling and performance evaluation of the Synhelion absorbing gas solar receiver for process heat at 1’500 °C and Beyond”, AIChE Symposium in Honour of Prof. Aldo Steinfeld, November 16-20, Online Version, 2020.
- S.A. Zavattoni, D. Montorfano, P. Good, G. Ambrosetti, M.C. Barbato, “Numerical performance evaluation of the Synhelion absorbing gas solar receiver under different operating conditions”, 26th SolarPACES Conference, September 28 - October 2, Online Version, 2020.
- G. Ambrosetti, P. Good, P. Furler, S. Ackermann, L. Geissbühler, “The Synhelion absorbing gas solar receiver: a route towards 1’500 °C process heat”, 25th SolarPACES Conference, October 1-4, Daegu, South Korea, 2019.
- S.A. Zavattoni, D. Montorfano, P. Good, G. Ambrosetti, M.C. Barbato, “The Synhelion absorbing gas solar receiver for 1’500 °C process heat: CFD modeling”, 25th SolarPACES Conference, October 1-4, Daegu, South Korea, 2019.

4 References

[1] G. Ambrosetti and P. Good, “A novel approach to high temperature solar receivers with an absorbing gas as heat transfer fluid and reduced radiative losses,” Solar Energy, vol. 183, pp. 521-531, 2019.

[2] SUPSI-DTI-MEMTi, Synhelion SA, “FUELREC - Solar receiver for the production of solar fuels from water, carbon dioxide and methane (SI/501796-01) - Annual project report,” 2018.