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Initial analysis on the novel Spiky Central Receiver Air Pre-heater (SCRAP) pressurized air receiver

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Abstract

A combined cycle (CC) concentrating solar power (CSP) plant provides significant potential to achieve an efficiency increase and an electricity cost reduction compared to current single-cycle plants. A CC CSP system requires a receiver technology capable of effectively transferring heat from concentrated solar irradiation to a pressurized air stream in a gas turbine. The small number of pressurized air receivers demonstrated to date have practical limitations, when operating at high temperatures and pressures. As yet, a robust, scalable and efficient system has to be developed and commercialized.
A novel receiver system, the Spiky Central Receiver Air Pre-heater (SCRAP) concept has been proposed to comply with these requirements. The SCRAP system is conceived as a solution for an efficient and robust pressurized air receiver that could be implemented in CC CSP concepts or standalone solar Brayton cycles without a bottoming Rankine cycle.
The presented work forms part of an initial analysis intended to provide an answer to whether the proposed SCRAP concept can effectively absorb the concentrated solar radiation and transfer the captured heat into a pressurized air stream in a robust and cost-effective manner, while maintaining an acceptable pressure-drop. A ray-tracing study was executed to identify the sensitivity of the SCRAP receiver to optical plant parameters, such as the heliostat size. A one-dimensional heat transfer analysis was initiated to develop initial understanding of the thermal system behavior and generate a tool for rapid geometry optimization.

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Keywords: SCRAP; CSP; pressurized air receiver; tubular receiver;

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1. Introduction

To date a relatively small number of pressurized air receivers have been proposed. The receiver technologies that reached demonstration status [1-5] are typically cavity receiver types. Compared to an external receiver type, such a design is used to reduce thermal losses at the cost of increased optical losses (e.g. due to spillage). Often quartz glass windows are employed to separate two pressure or temperature zones, requiring higher system sophistication but also adding an element that has shown to be prone to defects [6].

After high temperatures above 1000 °C were achieved [1,2] with volumetric cavity receivers, recent efforts have been focused on tubular cavity receiver technologies. Due to material limitations these systems are intended to heat pressurized air to lower temperature ranges of up to about 800 °C, but are suggested to be more robust, cheaper and less complex technologies [3-5]. To achieve higher temperatures either co-firing, a sequential volumetric cavity receiver or both are proposed.

A recent review [7] of the systems demonstrated to date has indicated a need for a technology that:

- Provides effective heat transfer from the concentrated solar radiation to a pressurized air stream
- Does not require secondary concentrators
- Can operate with a 360°/surrounding heliostat field
- Is a robust and practical technology
- Demands a low pressure drop

Nomenclature

I-IV	Sections I, II, III & IV of a spike
SCRAP	Spiky Central Receiver Air Pre-heater
$\dot{q}''$	heat transfer rate [W/m^2]

Subscripts

ax	axially
cond	conduction
conv	convection
r	radius/radially
rad	radiation
rect	rectangular (duct)

2. The SCRAP receiver concept

The SCRAP receiver [8] is a novel pressurized air receiver technology of the external tubular receiver type. The tubular absorber assemblies (referred to as spikes) are concentrically arranged in a way that they describe a body of increasing density towards the receiver center and allow for a receiver type that can operate with a surrounding heliostat field (see Fig. 1).

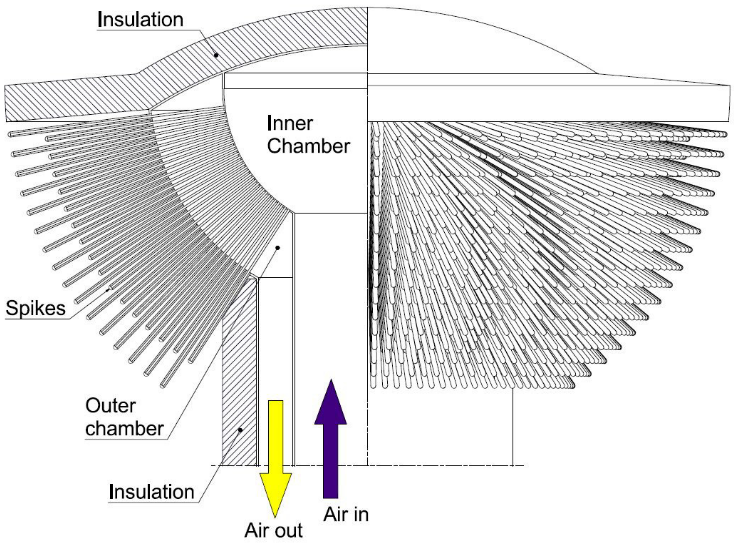

Fig. 1. Possible layout of a SCRAP receiver (left half in section) [8]

The ‘cold’ air (e.g. from a compressor stage) enters the receiver through an inner chamber. From there the air stream is directed through a multitude of circular tubes into the absorber assemblies. Each spike (see Fig 2.) consists of two concentric tubes, where the inner tube supplies the cold air stream from the inner chamber to the spike tip (outermost point) from where the air flow is directed back by 180° towards the receiver center, passing through the outer tube. The outer tube's outer surface is exposed to the concentrated irradiation, and in the process heated up, transferring thermal energy into the inner air stream. To enhance the heat transfer the outer tube is internally finned. The fins describe multiple narrow passages of rectangular cross section. To enhance heat transfer and balance flux inhomogenity the fins may be of helical shape instead of straight fins.

The spikes function as the heat exchangers, absorbing the concentrated irradiation and transferring the thermal energy onto the pressurized air stream. The heated air is passed on to the outer chamber from where it exits the receiver.

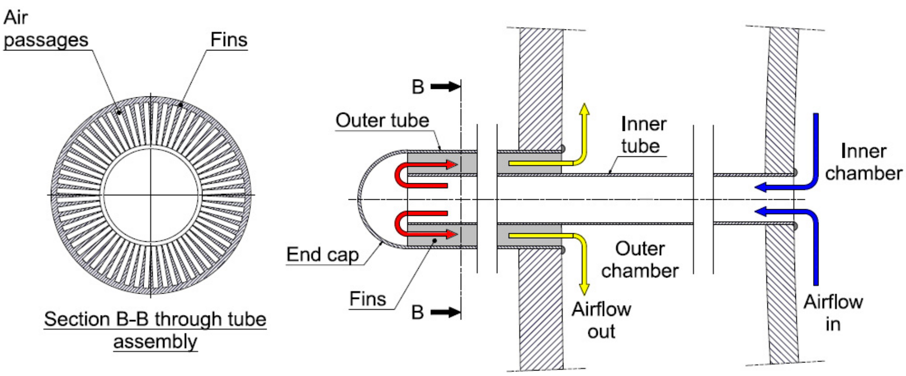

Fig. 2. Geometry of the internally finned tube [8]

In operation, the cooler air stream exiting the inner tube impinges on the spike tip and is heated up from there on its way through the rectangular passages in the outer internally finned tube. Similarly, the temperature of the outer tube wall is intended to rise from the spike tip towards the highest temperature at the spike root. With radiative heat losses gaining significance at higher temperatures this spike surface temperature distribution becomes advantageous. As a result a macro-volumetric effect is envisaged, where high material temperatures occur deep within the receiver. A high cooling effect is achieved at the most exposed area, the spike tip, where relatively cool air exits the inner tube. With lower solar irradiation expected toward the spike root, the risk of absorber pipe overheating is lowered.

An in principle similar, but geometrically less pronounced receiver has been developed by Garbrecht *et al*. [9], where pyramid-shaped absorber assemblies heat a molten salt heat transfer fluid. Due to the change in geometry, they have shown significant drop in losses due to reflected irradiation and thermal radiation at the backdrop of increased convective heat loss. At the higher temperatures experienced in air receivers the significance of radiative heat losses increases.

3. Development approach

To develop the SCRAP receiver from concept to a working prototype a number of sequential steps are planned. A pseudo one-dimensional heat transfer code was programmed. This program provides initial insight into the heat transfer throughout a spike, thus serving as a useful tool for understanding and improving the design. A test system with an internally finned tube section will be set up to verify the theoretical model.

Testing will be carried out under moderate temperatures of up to about 300 °C due to availability of laboratory equipment. A series of tests will be undertaken to verify the theory for different flow and heating conditions. Further performance enhancement is expected using internally finned tubes where the fin profile is spiraled axially along the tube length. The swirl flow generated requires CFD analysis of both, the flow and the heat transfer conditions. The performance gain of spiraled fins over straight fins is to be determined. The spike tip is subject to the highest radiation flux density of any part of the spike. The tip is furthermore the most exposed part of the SCRAP receiver, experiencing the least radiation trapping effects. Therefore, efficient cooling of the spike tip requires investigation to reduce heat losses and reduce the risk of component overheating. Cooling methods such as jet impingement cooling will be investigated for cooling the spike tip effectively and avoiding air flow stagnation.

An irradiation analysis is required to quantify the flux onto the receiver surface and establish models for the flux density along the spike lengths and circumference for heat transfer calculations. This model provides understanding of influx onto different spike lengths and positions dependent upon receiver system layout and solar field geometry.

Using a design point solar radiation, it is possible to optimize the spike geometry according to requirements such as metal temperature, efficiency and pressure drop. With a geometry defined, a section of a SCRAP receiver (or spike cluster) can be modeled in a commercial CFD code. That CFD model, including heat losses to ambient, can be used to make receiver performance predictions.

The receiver performance can then be confirmed with testing a spike cluster under real conditions at a receiver test facility and re-modeling the test conditions using the CFD model. For additional future topics to improve the understanding of the SCRAP concept, see section 6.

1. Begin with a default design
2. Preliminary ray-tracing investigation
3. Development of one-dimensional code to simulate flow and heat transfer
4. Verification of (3.) in laboratory test
5. Development of a spike model in commercial CFD software
    a. Verify in (3.) and (4.)
    b. Develop details e.g. for tip cooling, spiraled ducts
6. Ray-tracing of receiver for design case

7. Optimization of spike geometries, using (3.)
8. Simulation of a spike cluster in commercial CFD software
9. Interpretation of results (η_{th}, Δp, $T_{\mathrm{metal,max}}$, T_{air})
10. Development of receiver test model
11. Material considerations
12. In depth ray-tracing study
13. Aiming strategies

4. Preliminary ray-tracing study

A preliminary ray-tracing study was undertaken, employing the Tonatiuh [10] Monte-Carlo ray-tracing software. The purpose of the study was to develop understanding for the sensitivities of the flux to be expected along the absorber geometry (spikes). The parameters were heliostat size or heliostat field density for a simplified field layout. The heat transfer analysis of the spikes requires understanding of the distribution of the impinging flux along a spike. A simplified representative flux model is therefore required. A post-processor was written in Scilab and a basic mesh for a spike is shown in Fig. 3.

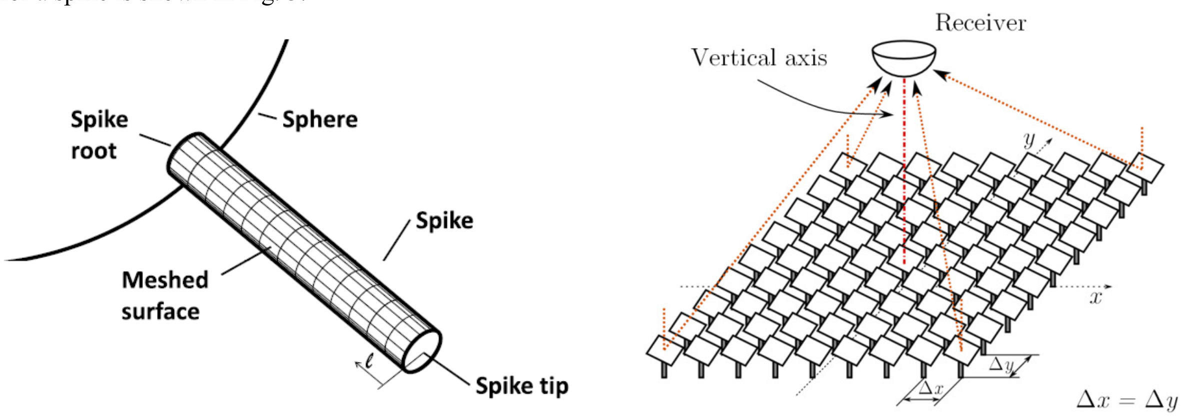

Fig. 3. Terminology describing a spike (left) and visualization of heliostat field with investigated spike pointing along the vertical axis toward the heliostat field (right)

A ray-tracing scenario was created that contained a quadratic heliostat field with uniform heliostat spacing in all directions, as shown in Fig. 3 (right). A script allows specification of the field dimensions, the heliostat size, the gap size between heliostats and the optical properties. The heliostats have a single flat facet and are positioned with Tonatiuh's Azimuth-Zenith tracking. All heliostats aim at the centre point of the receiver.

A SCRAP receiver was situated in the centre of the field at 82 m elevation without a tower being modeled to avoid blocking of rays. The tower height was established, using a curve fit on towers with surrounding heliostat fields for similar thermal receiver capacity as estimated for a SCRAP receiver of 4 m diameter of the outer chamber surface (a simple energy balance with an assumed receiver efficiency provided a thermal receiver capacity to be used as a starting point). The spikes were then distributed on the surface of that sphere. The spike locations were computed using geodesic coordinates with a frequency of 30. The spikes are 1.3 m long with a diameter of 0.07 m. As all spikes protrude radially from the SCRAP center only a single spike is pointing vertically downwards. The impinging rays on that spike are recorded and saved. This way a uniform representative flux on a spike is achieved. The sun is positioned in zenith with the *DNI* set at 1000 W/m^2. Mirror reflectivity as well as absorptivity of the spikes (and sphere) were set to 0.9.

The heliostat field size was adjusted according to the rays reaching the sample spike. Due to the geometry of the receiver a large number of rays is absorbed or reflected from neighboring spikes, missing the spike of interest. As a result, a total of 50 x 10^6 rays to 500 x 10^6 rays were used, depending on the accuracy desired.

Fig. 4 shows the flux along the length of a spike as percentage of the flux measured at the spike tip for heliostats of the dimensions 1 m x 1 m, 2 m x 2 m and 3 m x 3 m. For each case the heliostat field density is kept at 50 % (mirror surface to attributed area per heliostat). Within 1.5 %, the three cases show the same total energy absorbed along the spike surface.

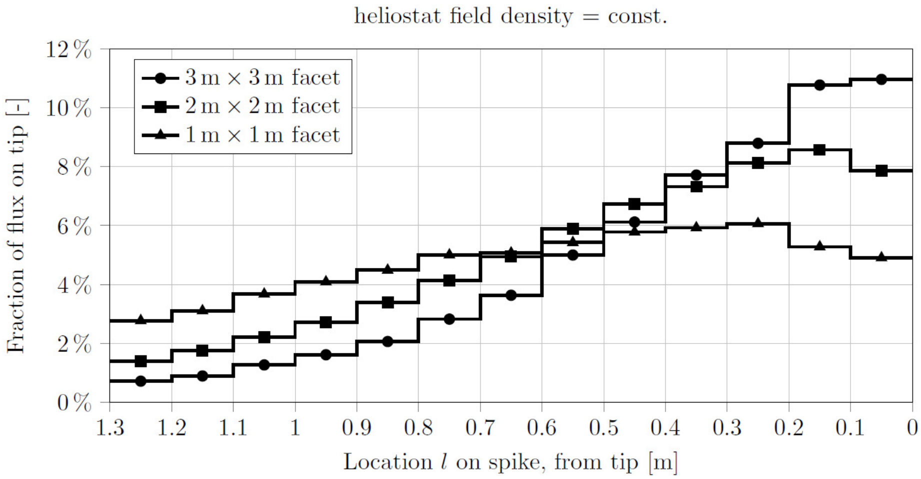

Fig. 4. Flux along a spike for identical heliostat field density of 50 %

An important observation made from Fig. 4 is that the sensitivity of the flux impinging along the spike surface from 0 m at the tip down to 1.3 m at the root is noticeably influenced by the heliostat size. Smaller heliostats achieve a higher penetration into the depth of the receiver, while larger heliostats lead to flux distribution increasing towards the tip. This effect is expected to increase with further increase in heliostat size. The simulated heliostats were flat single-facet mirrors. Canted mirrors or multi-faceted heliostats are expected to contribute further to depth penetration of flux.

It is thus concluded that the heliostat field has a significant effect on the flux distribution. With the observed information it is possible to investigate the heat transfer characteristics of a spike in detail. This is expected to lead to a good understanding of desired flux along a spike. A heliostat type, heliostat field layout and aiming strategy can then be developed accordingly.

Based on the findings shown in Fig. 4, initial heat transfer analysis can be executed with a uniform flux along the spike or a parabolic curve as a simplification of the flux created by the 1 m^2 heliostats.

5. Simplified heat transfer analysis of a single spike

The SCRAP absorber elements, referred to as spikes (Fig. 1 and Fig. 2), are concentric cylindrical tube assemblies, providing a counter-flow passage for a pressurized air stream. This air stream flows from the cold chamber through the spike and return to the hot chamber, while in the process being heated up. Heat transfer enhancement in the form of internal fins on the outer tube creates rectangular passages for the air stream to pass through, as illustrated in Fig. 2.

A one-dimensional model was developed for the flow analysis and heat transfer onto the air stream to initially analyze the problem and develop an understanding of the heat transfer into a spike. The purpose of the program is to

- aid understanding of heat transfer mechanisms taking place,

- aid understanding of sensitivities of heat transfer to parameters,
- have a tool that allows for rapid change of parameters and viewing of their effect and
- have a tool that allows for easily programmable optimization of geometries.

A code has been developed to satisfy the above purposes. This code is intended as a tool for further development but not to provide final answers on SCRAP receiver system behavior such as the reference value of receiver thermal efficiency. Initially the program assumes a uniform concentrated solar flux across the circumference of the outer tube, while being variable axially. The program is developed in a way that it can be extended to permit circumferentially varying flux.

The topography of the code is depicted in Fig. 5. The four regions of interest are marked as (I) the inner tube leading toward the spike, (II) the inner tube within the spike, (III) the spike tip region and (IV) the outer internally finned tube.

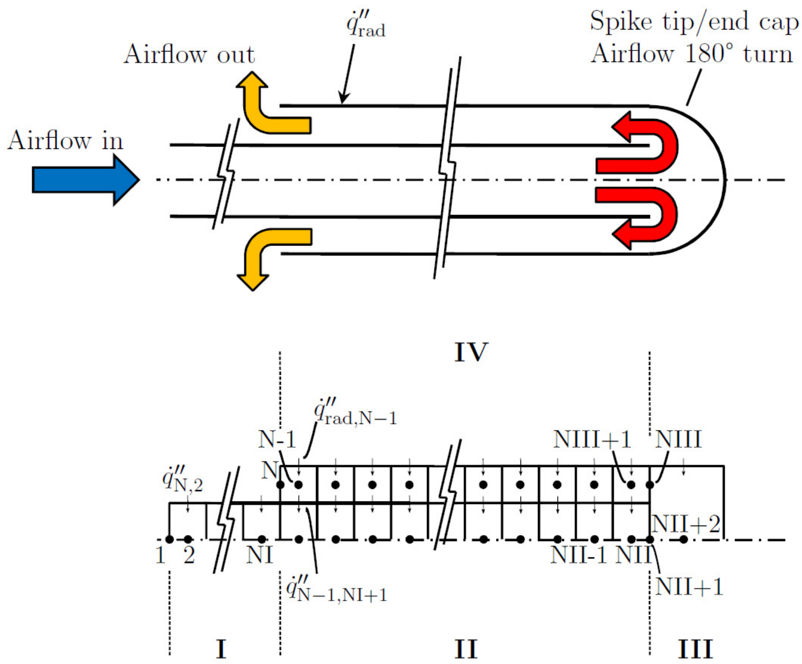

Fig. 5. Topography of the investigated spike

The flow as well as the heat transfer simulations are meshed one-dimensionally for the flow in the circular duct as well as the rectangular ducts. Due to the initially assumed uniform flux around the spike circumference, only a single rectangular duct needs to be solved. The counter-flow links the inner flow (inner tube) and the flow in the rectangular ducts thermally by heat transfer through the wall of the inner tube. This is solved by iteration.

Governing equations for the flow and heat transfer computation are the conservation equations (momentum, mass and energy). For the laminar flow regime in the rectangular ducts, equations from [11] are used. Air properties are temperature dependent and based on [12]. Metal properties are programmable, depending on the choice of material.

Fins and wall temperatures are computed based on energy balances. The fins in the outer tube are discretized radially, using a single heat transfer coefficient initially. This allows to use an average fin wall temperature to compute convective heat transfer towards the one-dimensional flow. For the fin computation it is assumed that a temperature depression at the root does not exist.

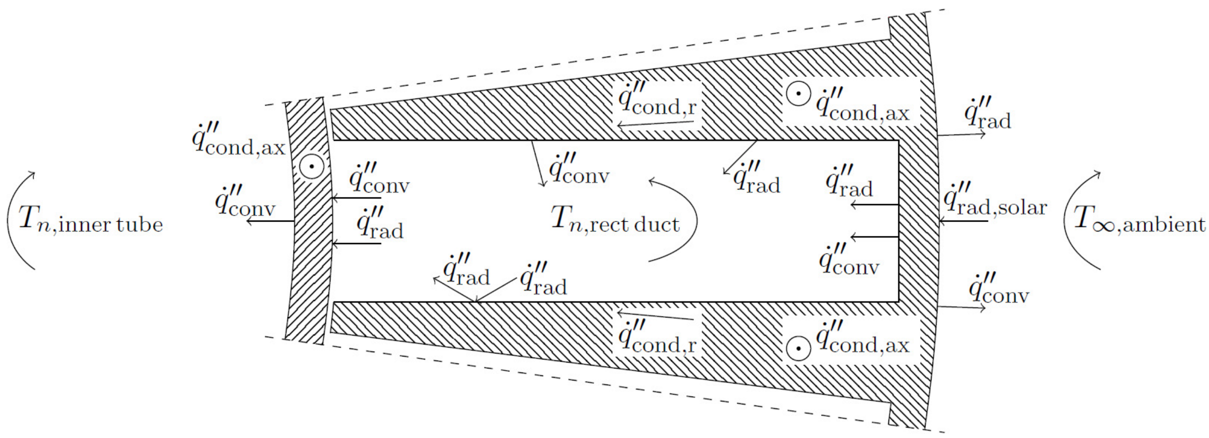

Fig. 6. Visualization of heat transfer mechanisms occurring within a rectangular duct

Fig. 6 illustrates that, besides conductive heat transfer in axial direction, the inner tube wall is heated by convective heat transfer from the air flow in the rectangular ducts as well as radiative heat transfer from the fins and outer tube. A noteworthy observation after screening the first simulation runs is that radiative heat transfer from the fin walls and the outer duct wall onto the exposed wall of the circular inner tube can contribute to the heating of the inner tube wall at a similar magnitude as compared to the convective heat transfer from the air stream. This identifies a possible way to influence the amount of pre-heating the air flow in the inner tube experiences, should it be identified as advantageous or undesired.

Fig. 7 shows some results for a simple run of a preliminary version of the code, neglecting heat losses (convective and radiative) to ambient (the program is intended to understand internal heat transfer mechanisms). The inlet temperature is the compressor outlet temperature of 300 °C. The spike is heated by an axially and circumferentially uniform flux of 50 kW/m^2 along its length of 1.3 m, with the tip being exposed to a peak of 1.0 MW/m^2. The heating of the air flow at a pressure of 10 bar and an inlet velocity of 5 m/s is illustrated. Due to the selected default geometry, the inner duct has a diameter of 13 mm and the annular outer duct 23 rectangular channels of 3 mm by 18 mm dimension. As a result, with the illustrated scenario, the flow is turbulent in the inner tube and laminar in the rectangular ducts. According to desired heat transfer behavior, dimensions can be adjusted at a later stage to provide the desired flow and heat transfer characteristic for design point operation of the receiver.

The spike tip is simulated as a black box that exerts a pressure drop based on empirical equations initially from literature [e.g. 13]. This model will be improved with data extracted from CFD simulations for jet impingement cooling of the spike tip. In Fig. 7 it can be seen that the tip surface is at this stage a single node at furthest point of the outer tube.

Investigations with the aim of representative results are subject to refinement of the program, addition of a model representing the spike tip behavior and verification of the code by laboratory testing. The assumptions made will be confirmed or adjusted after comparing simulation data to laboratory testing of a spike and defined boundary conditions.

6. Outlook

6.1. Short term

In the near term the one-dimensional heat transfer program will be further refined and verified in a laboratory test setup. This should provide sufficient confidence to be able to utilize the program for design improvement and comparison with a CFD model.

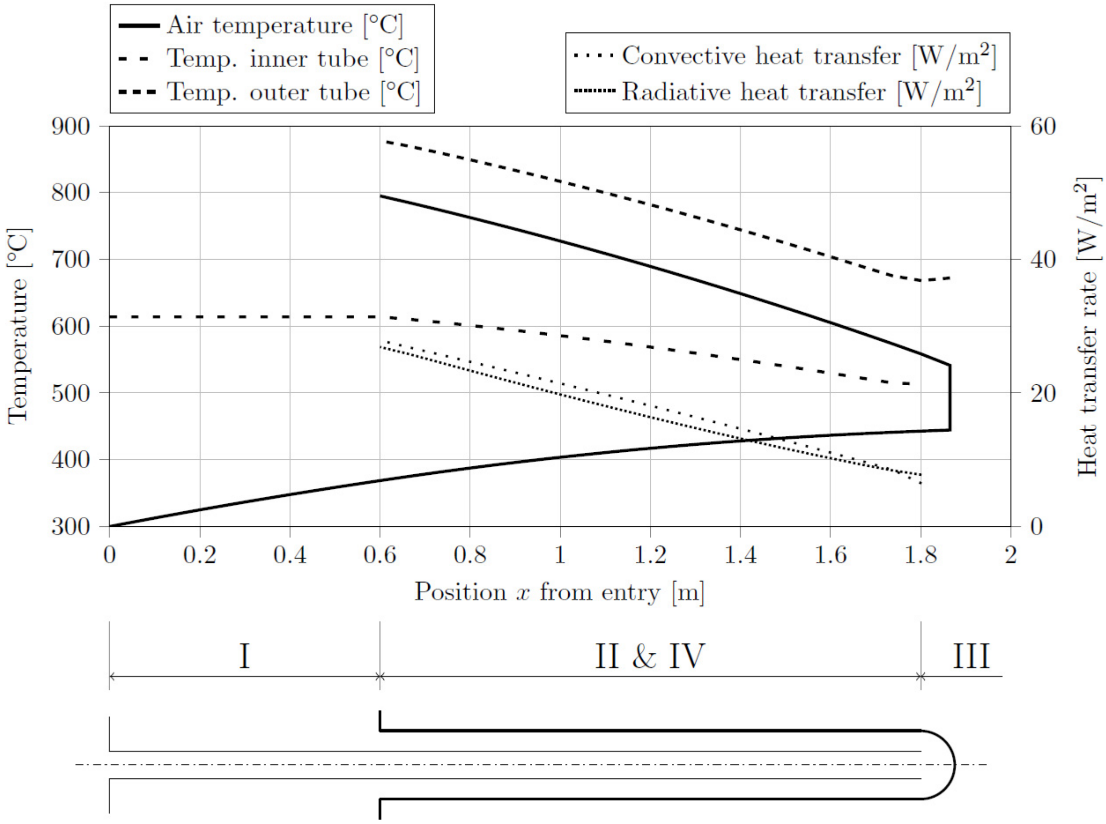

Fig 7. Exemplary results of an initial simulation

To complete the program, a spike tip will need to modeled, using a commercial CFD package. As seen in the ray-tracing section, the flux at the spike tip is considerably higher than along the spike length. The heat should be effectively removed using jet impingement cooling techniques, which are to be modeled in the CFD software. The results will be implemented into the one-dimensional code to add further detail. With that it should be possible to improve the spike for certain desired conditions.

Two relevant end-results are the receiver efficiency and the pressure drop demanded. These will be resulting from a CFD model simulation of a SCRAP section with a multitude of spikes. Such a section can be tested at a receiver test facility to verify the simulated results.

6.2. Long term

With a longer horizon in mind further considerations are of importance. The material stress under thermal cycling will require thorough consideration. Small improvements in a tubular receiver design can have large effects on the system lifetime [14].

The ray-tracing analysis done to date was essential for understanding of dependencies and levels of freedom. A more extensive study is required to understand flux variations over a receiver and over individual spikes over the course of a day and over different seasons.

The shape of the SCRAP receiver is visibly different to conventional receiver designs. The radially protruding spikes define a shape that allows rays to directly penetrate deeply into the receiver, or be reflected multiple times or be absorbed at the first impingement. As a result, conventional heliostat aiming strategies may not be applicable to the SCRAP receiver. Better understanding of the heat transfer and the sensitivity of the spikes and the heat transfer to circumferential and axial flux variation will provide an answer to the necessity of sophisticated aiming strategies and possible requirements for such.

7. Results and conclusion

The ray-tracing analysis showed that the flux distribution can within limitations be influenced by adjusting the heliostat shape and receiver geometry. An initial flux model is assumed and the flux distribution is recommended to be revised at a later stage, when better understanding of the heat transfer behavior of the spike suggests a specific desired flux distribution. The heat transfer analysis provides improved understanding of the heat transfer behavior and sensitivities. The one-dimensional model will form the foundation for a further CFD simulation, using commercial CFD software, where a CFD absorber model will be extended with a thermal radiation model and a ray-tracing model to simulate interaction between spikes of a SCRAP receiver.

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