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COUPLED OPTICAL-THERMAL-FLUID MODELING OF A DIRECTLY HEATED TUBULAR SOLAR RECEIVER FOR SUPERCRITICAL CO_2 BRAYTON CYCLE

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ABSTRACT

Recent studies have evaluated closed-loop supercritical carbon dioxide (s-CO_2) Brayton cycles to be a higher energy-density system in comparison to conventional superheated steam Rankine systems. At turbine inlet conditions of 923K and 25 MPa, high thermal efficiency (~50%) can be achieved. Achieving these high efficiencies will make concentrating solar power (CSP) technologies a competitive alternative to current power generation methods. To incorporate a s-CO_2 Brayton power cycle in a solar power tower system, the development of a solar receiver capable of providing an outlet temperature of 923 K (at 25 MPa) is necessary. The s-CO2 will need to increase in temperature by ~200 K as it passes through the solar receiver to satisfy the temperature requirements of a s-CO_2 Brayton cycle with recuperation and recompression. In this study, an optical-thermal-fluid model was developed to design and evaluate a tubular receiver that will receive a heat input ~2 MW_{th} from a heliostat field. The ray-tracing tool SolTrace was used to obtain the heat-flux distribution on the surfaces of the receiver. Computational fluid dynamics (CFD) modeling using the Discrete Ordinates (DO) radiation model was used to predict the temperature distribution and the resulting receiver efficiency. The effect of flow parameters, receiver geometry and radiation absorption by s-CO_2 were studied. The receiver surface temperatures were found to be within the safe operational limit while exhibiting a receiver efficiency of ~85%.

INTRODUCTION

Extensive investigation of the potential of supercritical cycles for power generation dates way back to 1960's [1, 2]. CO_2 as a potential working fluid for a Brayton power cycle was found viable with nuclear energy as the heat source [3, 4]. Garg et al. have performed detailed irreversibility analysis of transcritical, subcritical and supercritical CO_2 Brayton cycles for concentrated solar power [5]. The dynamics of s-CO_2 based power conversion systems using CSP are presented by Singh et al. [6].

At typical turbine inlet conditions for a s-CO_2 Brayton cycle (150 bar, 1000 K), the density of s-CO_2 is more than 11 times the density of air in an air-Brayton cycle (~ 40 bar, 2000 K), while the corresponding enthalpy of s-CO_2 is about 53 % of the value for air [7] Due to its favorable heat transfer properties, the use of s-CO_2 as a working fluid provides the benefit of having a compact receiver, resulting in low heat losses and a low capital cost. In comparison to other heat transfer fluids, s-CO_2 requires smaller mass flow rates for carrying away the same amount of heat from the receiver surface.

For materialization of an efficient s-CO_2 based CSP plant, there is a need to develop receivers which can withstand high pressures and high temperatures. An overview of existing receiver designs and past experiences is presented by Ho and Iverson [8]. A recent design for a high temperature gas tubular receiver was demonstrated by DLR at Plataforma Solar De Almeria to have a thermal efficiency of 43% [8]. A review of demonstrations of volumetric receiver configurations is provided by Antonio L. Avila Marin [9]. Although volumetric receivers have been successful in dispensing working fluid at temperatures above 1000 K and at efficiencies greater than 75%, the problem of sealing and manufacturing of high pressure window poses a major engineering challenge. Problems of unstable flow and local overheating in volumetric absorbers have been studied by Becker et al. [10] and Kribus et al. [11] respectively. The falling particle receiver technology is still not mature poses many practical problems which remain unsolved as of date. In light of the practical problems discussed above, a tubular receiver seems to be the best alternative for direct heating of s-CO_2 in a pressurized environment

In this work, a tubular receiver for direct heating of s-CO_2 has been proposed and the same has been analysed using numerical code ANSYS FLUENT 14. In the subsequent sections, the material considerations for the current receiver will be discussed followed by the modeling details and results.

MATERIAL CONSIDERATIONS

From the possible scenarios described by Dostal et al, an outlet pressure of 25 MPa and outlet temperature of 923 K are required from the receiver in order to achieve a 50% thermal efficiency [12]. Ortega et al. has published an analogous work containing the results of a structural analysis performed using analytical and numerical methods to select the optimal material and dimensions of the tubes of tubular receiver [13]. From the analogous work performed by Ortega et al. the material selected for this work is Haynes 230. Haynes 230 displays superior allowable stress levels throughout the required temperature range. For the tube dimensions, a 2 m. long tube with an outside diameter of 12.7 mm (1/2”) and wall thickness of 2.7686 mm (0.109”) was selected. In this case the length of the tube was fixed by the maximum optical aperture from National Solar Thermal Test Facility (NSTTF) heliostat field.

MODELING

In this study, a coupled optical-thermal-fluid model was developed using SolTrace and ANSYS Fluent to design and evaluate the performance of the tubes of the receiver using computational fluid dynamics (CFD). The results obtained in SolTrace were coupled with ANSYS Fluent using a MATLAB code developed that will generate a file which can be used as a boundary condition in ANSYS Fluent.

Geometry

The receiver geometry (figures 1-4) consists of 5 straight parallel tubes, each of length 2 m. The effect of having a staggered arrangement is studied using the geometry shown in figures 2-4. Every alternate tube is shifted in the front so as to form some angle with the tubes at the rear. 15, 30 and 45 degree offsets are studied in this paper [19].

All tubes have an outer diameter of 12.7 mm and a thickness of 2.7686 mm. The gap between the outer walls of the tube was ignored for modeling purposes.

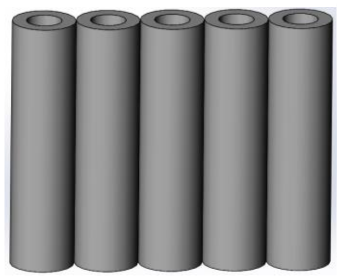

Figure 1: Tubes with 0 degree offset. Provisional patent submitted [19].

Figure 2: Tubes with 15 degree offset. Provisional patent submitted [19].

Figure 3: Tubes with 30 degree offset. Provisional patent submitted [19].

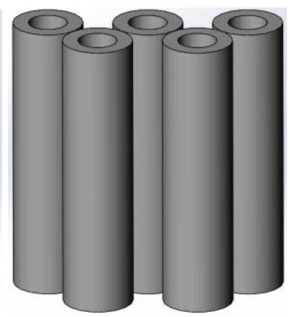

Figure 4: Tubes with 45 degree offset. Provisional patent submitted [19].

Optical Model

The heliostat field from the National Solar Thermal Test Facility at Sandia National Laboratories, Albuquerque has been modeled in SolTrace, along with the receiver geometries mentioned in the previous section. SolTrace is an optical modeling software developed by NREL, which uses the Monte-Carlo Ray tracing methodology for prediction of intensity distribution of intersections on a surface [16]. The results of the ray tracing (figure 5a) generate a profile describing the distribution of heat flux on the receiver surface (figure 5b) from the actual field. The reflectivity of the tubes was specified as 0.04 assuming that a Pyromark coating was applied [17]. The flux profiles obtained as a result of this optical modeling had to be manipulated using a MATLAB code. The MATLAB code operates on the planar flux profile obtained from SolTrace and maps it to the actual 3-dimensional geometry. The Direct Normal Insolation from the sun was assumed constant at 1000 W/m^2.

Ray trace results have been coupled to Fluent before onto flat surfaces, but this is the first time this is done for direct tubular receivers. It is expected to yield highly accurate prediction of results and bridge the gap between modeling and reality, as opposed to a constant flux distribution which has been conventionally used by researchers.

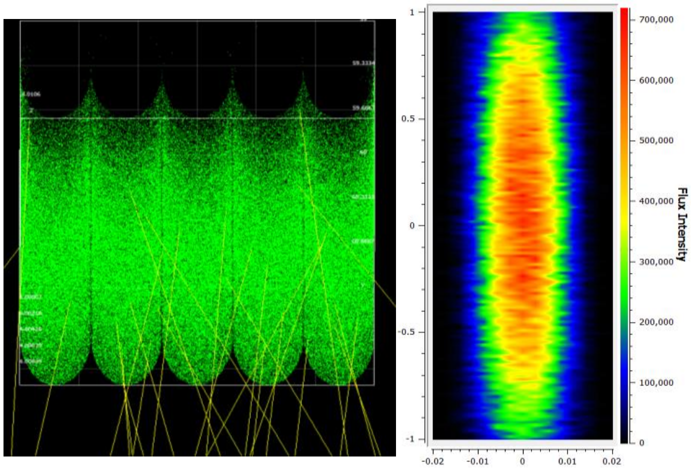

Figure 5: a) SolTrace ray intersections and b) heat flux distribution on a tube surface.

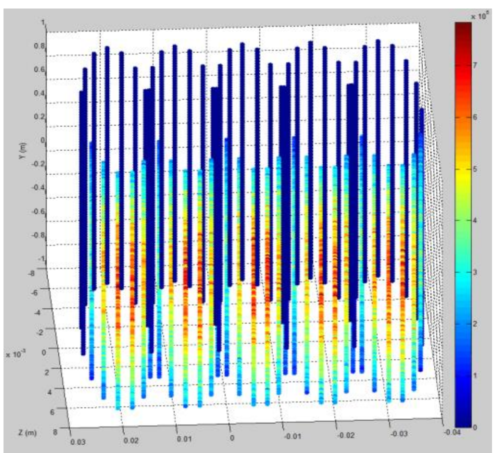

Figure 6: Heat flux bins mapped from 2D to 3D space.

CFD Modeling

A uniform, hybrid mesh with hexahedral and tetrahedral elements was generated using ANSYS 14 Workbench. Equations describing mass, momentum and energy transport, the 2 equation SST k-ω turbulence model, and the discrete ordinates method (DOM) for radiation were solved using ANSYS FLUENT 14, which uses the finite volume method to discretize the transport equations. The steady state, pressure based solver using SIMPLE algorithm and second-order upwind for spatial discretization was used for the simulation. The grid was refined until doubling the number of grid points yielded less than 0.2% difference in the solution parameters. Figure 7 shows the final grid used consisting of ~3.3×10^6 cells. Mass flux, energy flux and scaled residuals were continuously monitored as the solution developed, and convergence was assumed only when the quantities of interest exhibited negligible variation and the scaled residuals for all equations dropped to at least below 10^{-3} and remained constant thereafter.

To obtain accurate thermo-physical properties for s-CO_2, FLUENT was linked to REFPROP, viz. a database provided by NIST [13]. The equation of state for CO_2 provided by Span and Wagner is used by this database [14].

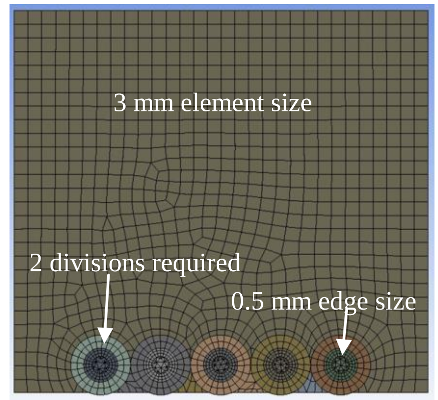

Figure 7: Mesh generated and used for the analyses.
Number of elements: 3,265,094
Number of nodes: 9,847,084
Average Element Quality: 0.75

SST k-ω model is more accurate and reliable for a wider class of flows because the wall boundary conditions for the k equation in the k-ω models are treated in the same way as the k equation is treated when enhanced wall treatments are used with the k- ε models. This means that all boundary conditions for wall-function (coarse) meshes will correspond to the wall function approach, which is the mesh type used as shown in figure 7.

A gray-body model was implemented to capture the radiation interaction between the tubes and the environment. The outer walls of the tube were assumed to have a constant emissivity of 0.86 assuming a Pyromark coating was applied [17]. The inner surface of the tubes were assumed to have a constant emissivity of 0.86, nonetheless, Caliot et al. show that for a turbulent flow, radiation has negligible influence on the heat transfer [18].

The actual flux distribution profile obtained from the processing of the SolTrace output in MATLAB was applied as a heat generation profile boundary condition on the heated walls of the tube. This enables the coupling of the external air domain with the internal domains of tube thickness and fluid domain containing s-CO_2.

Three different cases were analyzed for the four geometries and are described in table 1. A uniform flowrate was specified to each tube and its value was calculated such that the bulk average outlet temperature for different irradiances was obtained at the desired value. All simulations were carried out at an operating pressure of 25 MPa and receiver inlet temperature of 763 K.

Case	Mass Flow Per Tube (kg/s)	Peak Flux (kW/m^2)	Required Inlet/Outlet Temperature (K)
1	0.0294	~400	763/923
2	0.0526	~700	763/923
3	0.0769	~1000	763/923

Table 1: Input conditions for the three different cases.

The boundary conditions can be observed in figure 8. The convective and radiative losses to the atmosphere were modelled using natural convection in the outer domain and the discrete ordinates radiation model in ANSYS Fluent, The ambient temperature was assumed as 300 K. Both, air and s-CO_2 molecules was assumed to be non-participating in the wavelength range of interest.

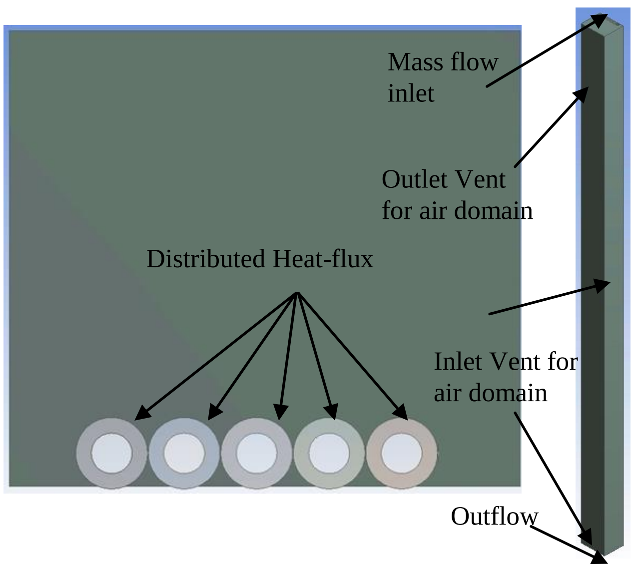

Figure 8: Boundary conditions for the cases analyzed.

RESULTS AND DISCUSSION

The heat-flux distributions on figure 9 correspond to the NSTTF model from SolTrace which currently has a single point aim strategy in the center of the receiver. By applying more aim points, the heat-flux distribution can be enhanced, therefore, providing a more monotonic temperature distribution on the surface.

Three different cases were analyzed for the four geometries which have different offsets. As previously mentioned, the idea was to increase the receiver efficiency by light trapping using the tubular surfaces. Figures 10a and 10b show the receiver efficiency and the corresponding radiative and convective losses for each case. Several things can be concluded from these results:

1. From figure 9, even though the outlet temperature was kept constant by increasing the mass flow rate proportionally to the heat flux applied, the wall-temperature difference increases due to the increase in heat transfer rate. It is important to consider a thermal-structural analysis to ensure the mechanical stability of the receiver.
2. Radiative losses account for approximately 10-19% while convective losses account for approximately 1-10% of the total heat transfer as observed on figures 10a and 10b respectively.
3. Efficiencies above 85 % were observed in concentrations ~1000 kW/m^2. Although these concentrations are achievable, most likely they will yield temperatures above the temperature limits at the current high pressures. Therefore, an optimal peak flux must be determined. It is important to consider the material limitations at high temperature to avoid creep rupture.
4. By selecting a stronger material or increasing the thickness of the tubes, the life of the receiver can be extended. Nonetheless, increasing the thickness of the tubes will increase the thermal gradient on the tube wall, hence, increasing the thermal stresses, while reducing the absorbed heat.

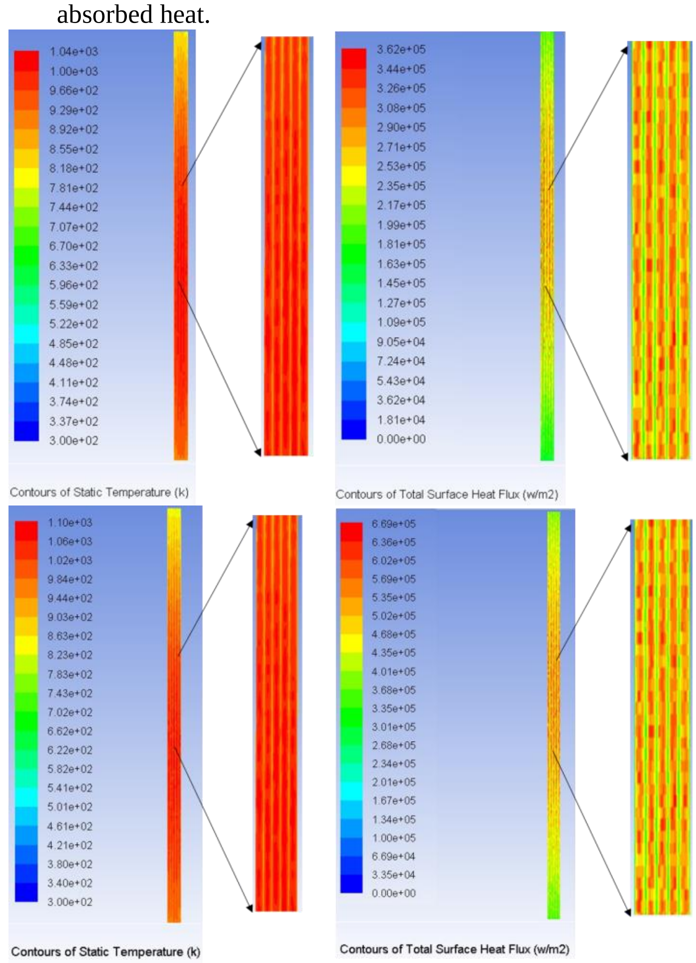

Figure 9: Temperature and heat flux contours of the cases in table 1 corresponding to a 0 degree offset and a) ~400 kW/m^2 and b) ~700 kW/m^2

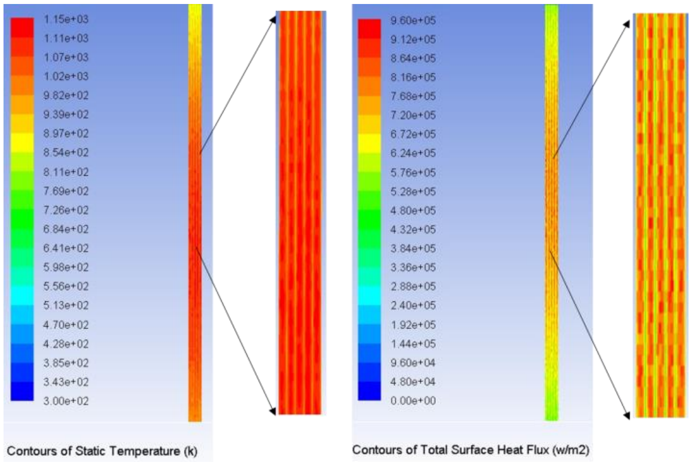

Figure 9c: Temperature and heat flux contours of the cases in table 1 corresponding to a 0 degree offset and ~1000 kW/m^2

For 0 degree offset with DNI of 1000 W/m2, a case with constant heat flux instead of the non-uniform distribution from SolTrace was simulated. The total power input was specified to be same, but the value of peak flux intensity was only about 40 % in the uniform distribution case in comparison to the non-uniform distribution case from SolTrace.

The predicted receiver efficiency was higher in the case of the uniform flux distribution case by only 0.5 %. An important observation was that the predicted peak temperature on the uniformly heated walls was 1087 K, while in the case of actual heat flux distribution from SolTrace, it was 1153 K. In different conditions, the need to map actual heat flux instead of using a constant heat flux approximation might be even more significant if an accurate prediction of the temperature distribution is desired.

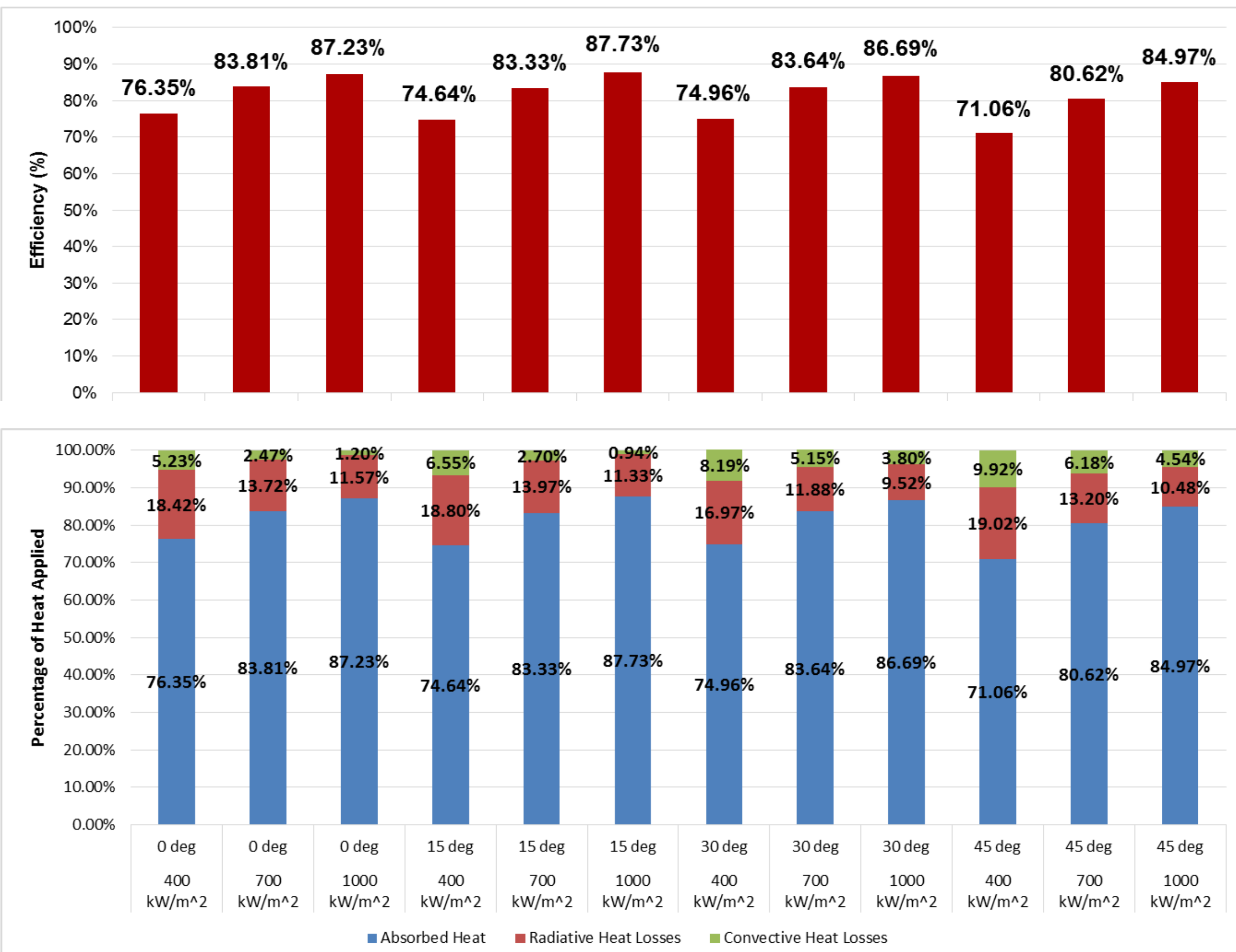

Figure 10: a) Thermal Efficiencies of the twelve cases and b) Heat losses of the twelve cases

A coupled optical-fluid-thermal model was developed using SolTrace and FLUENT to evaluate the receiver efficiency of the tubes of a tubular receiver. This is the first time a SolTrace-FLUENT coupling method is used to evaluate the receiver efficiency of a solar thermal receiver.

Three major conclusions could be made from this work.

1. An s-CO2 tubular receiver intended for use in a solar power tower has been modeled using computational fluid dynamics coupled with a ray tracing software.
2. The effect of mass flow rate and geometric parameters on the receiver efficiency and peak temperatures has been investigated.
3. The use of actual heat flux distribution profile, rather than the constant heat flux distribution approximation was successful. This optical coupling is expected to be used in the future to predict the performance of the receiver with higher accuracy owing to the more representative heat flux profiles on the tube surfaces.

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