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Research Paper

Coupled modeling of a directly heated tubular solar receiver for supercritical carbon dioxide Brayton cycle: Optical and thermal-fluid evaluation

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ABSTRACT

Single phase performance and appealing thermo-physical properties make supercritical carbon dioxide (s-CO_2) a good heat transfer fluid candidate for concentrating solar power (CSP) technologies. The development of a solar receiver capable of delivering s-CO_2 at outlet temperatures ~973 K is required in order to merge CSP and s-CO_2 Brayton cycle technologies. A coupled optical and thermal-fluid modeling effort for a tubular receiver is undertaken to evaluate the direct tubular s-CO_2 receiver's thermal performance when exposed to a concentrated solar power input of ~0.3–0.5 MW. Ray tracing, using SolTrace, is performed to determine the heat flux profiles on the receiver and computational fluid dynamics (CFD) determines the thermal performance of the receiver under the specified heating conditions. An in-house MATLAB code is developed to couple SolTrace and ANSYS Fluent. CFD modeling is performed using ANSYS Fluent to predict the thermal performance of the receiver by evaluating radiation and convection heat loss mechanisms. Understanding the effects of variation in heliostat aiming strategy and flow configurations on the thermal performance of the receiver was achieved through parametric analyses. A receiver thermal efficiency ~85% was predicted and the surface temperatures were observed to be within the allowable limit for the materials under consideration.

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1. Introduction

Possible use of supercritical cycles for power generation has been a topic of research since the 1960s [1,2]. Supercritical carbon dioxide (s-CO_2) has the potential to become the working fluid for a Brayton power cycles since it has been found viable to adapt to nuclear energy applications [3,4]. Garg et al. have performed detailed irreversibility analysis of transcritical, subcritical and supercritical CO_2 Brayton cycles for concentrated solar power [5]. Also, the dynamics of s-CO_2 based power conversion systems using CSP technologies have been investigated by Singh et al. [6].

Thanks to the favorable heat transfer properties that s-CO_2 possesses, its use as a working fluid provides the benefit of having a solar receiver with a smaller footprint, which can result in low heat losses and a low capital cost. These features make s-CO_2 systems more energy-dense and they require lower mass flow rates compared to other heat transfer fluids. For example, at turbine inlet conditions for a s-CO_2 Brayton cycle (15 MPa, 1000 K), the density of s-CO_2 is ~11 times the density of air in an air-Brayton cycle (~0.4 MPa, 2000 K), while the corresponding enthalpy of s-CO_2 is about 53% of the value for air [7].

In order to develop an efficient s-CO_2 based CSP plant; there is a need to develop receivers which can endure a high operating pressure and high fluid temperature. An overview of existing receiver designs and past experiences is presented by Ho and Iverson, in which a theoretical maximum receiver efficiency of 80–85% is illustrated [8]. A recent design for a high temperature gas tubular receiver was demonstrated by DLR at Plataforma Solar De Almeria to have a receiver efficiency of 43% [8]. A review of demonstrations of volumetric receiver configurations is provided by Ávila-Marin [9]. Although volumetric receivers have been successful in dispensing working fluid at temperatures above 1000 K and at efficiencies >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. and Kribus et al., respectively [10,11]. 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.

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Nomenclature

η_{opt}	optical efficiency of the receiver
$\dot{Q}_{surf}$	power absorbed by the receiver surface (W)
$\dot{Q}_{in}$	incident power on the receiver surface (W)
n	number of aim points
k	turbulent kinetic energy (J)
ω	specific turbulence dissipation (1/s)
Y+	non-dimensional cell height
ε	turbulence dissipation (J/kg s)
η_{th}	thermal efficiency of the receiver
$\dot{Q}_{abs}$	power absorbed by the fluid (W)
$\dot{Q}_{rad}$	power lost to atmosphere by radiation (W)
σ	Stefan-Boltzmann's constant (W/m^2 K^4)
A	total area of tube surface (m^2)
T_{surf}	tube surface temperature (K)
T_∞	average ambient temperature (K)
$\dot{Q}_{conv}$	power lost to atmosphere by convection (W)
h	convection heat transfer coefficient (W/m^2 K)

In this work, a direct tubular receiver using s-CO$_2$ as the heat transfer fluid has been proposed. The receiver has been analyzed by simulating with distinct flow configurations and aiming strategies using ANSYS Fluent 16 to evaluate the receiver's thermal performance. The subsequent sections will describe the modeling details and results.

2. Material considerations

Dostal describe possible s-CO$_2$ conditions which can yield 50% thermodynamic cycle efficiency [12]. From those conditions, an operating pressure of 20 MPa and an outlet temperature of 973 K are required for the receiver to achieve the prescribed cycle efficiency.

In a complementary work, the results of a structural and creep-fatigue analysis performed using analytical and numerical methods to select the optimal material and dimensions of the tubes of tubular receiver are presented. The material selected for this work is Inconel 625, since it displays outstanding allowable stress levels throughout the required temperature range. Fig. 1 shows the footprint of the illuminated receiver; tubes with outside diameter of 12.5 mm and wall thickness of 2.1 mm were selected.

3. Modeling

A coupled optical-thermal-fluid model was developed using SolTrace and ANSYS Fluent to evaluate the optical and thermal performance of the direct tubular receiver using optical ray-tracing and computational fluid dynamics (CFD). The results of the ray-trace analysis were coupled to ANSYS Fluent using the methodology described by Ortega et al., as a boundary condition [13].

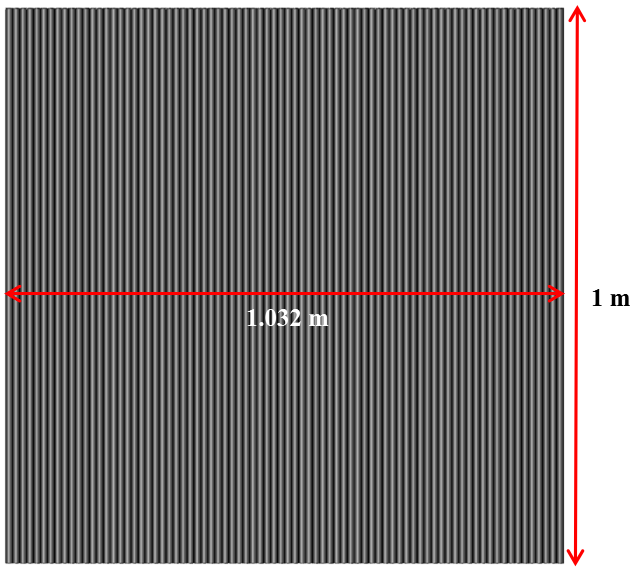

Fig. 1. The geometry used for this analysis consisted of 80–12.5 mm tubes with 0.2 mm gaps for thermal expansion allowance.

3.1. Geometry

The simplified receiver geometry, shown in Fig. 1, consists of 80 straight parallel tubes, each of length 1 m, outside diameter of 12.5 mm and wall thickness of 2.1 mm. Using 80 tubes is intended to maintain an aperture of ~1 m^2. Ortega et al., investigated the effect of having staggered tube arrangements and showed no favorable increase in the receiver efficiency, since it required a more complex flow distribution through the receiver [14]. The 80 tubes are divided into groups of 20. As shown in Fig. 2, these 20 tubes will form a single panel which consists of tubes connected to headers, at the top and bottom, to evenly distribute the s-CO$_2$ flow. Fig. 2 also shows the complete receiver geometry which is made out of 4 panels and will be used to generate several flow patterns which could lead to high receiver efficiencies.

3.2. Optical ray-tracing modeling

Fig. 3 shows the heliostat field from the NSTTF modeled in SolTrace, along with the receiver geometries mentioned in the previous subsection. SolTrace is an optical modeling software developed by National Renewable Energy Laboratory (NREL), which uses the Monte-Carlo Ray tracing methodology for prediction of intensity distribution of intersections on a surface [15,16].

Due to the size of the receiver considered, the amount of irradiance spillage is not considered for the calculation of effective solar absorptance which is calculated as:

$$\eta_{opt} = \frac{\dot{Q}_{surf}}{\dot{Q}_{in}} \qquad (1)$$

where η_{opt} the optical efficiency is the effective absorptance of the receiver $\dot{Q}_{surf}$ is the power absorbed by the receiver surface and $\dot{Q}_{in}$ is the incident power on the receiver surface.

Fig. 4 shows the four aiming strategies selected to investigate the uniformity of the heat flux distributions on the tube surfaces. The aim-points were generated by assuming a virtual intercept divided into $(n+1)^2$ sections with n being the number of aim-points required. Three virtual apertures of 1 m^2, 4 m^2 and 9 m^2 were considered and the aim-point locations were considered as shown in Fig. 4.

The reflectivity of the receiver surface was specified as 0.1 for oxidized Inconel [17]. Upon further investigation, the best distribution using 4 aim-points was displayed using a 2.5 m × 2.5 m virtual intercept. Fig. 5 shows the results of the ray tracing with the selected heat flux distributions on optical intercept of the receiver, to be used for subsequent sections of this work. The

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