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Numerical and experimental investigation of heat transfer in a solar receiver with a variable aperture

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ABSTRACT

Variable aperture can assist in maintaining semi-constant temperatures within a receiver's cavity under transient solar loading. An in-house code has been developed to model a receiver and effectively control its components to achieve semi-constant temperatures under transients. The code consists of a full optical analysis performed via the Monte Carlo ray tracing method in addition to a transient two-dimensional heat transfer analysis. The system studied consists of a cavity type solar receiver with 60 mm radius fixed aperture on the cavity body, a variable aperture mechanism mounted on the receiver's flange, and a 7 kW Xenon arc solar simulator. A composite shape consisting of a hemisphere attached to a cylinder is proposed to model the Xenon arc. The in-house code has been experimentally validated through experimental tests for different input currents to the solar simulator, volumetric flow rates, and aperture's radii. The optical analysis was validated based on heat flux measurements, where it had percentage errors of 0.8, 0.5, 1.1, and 3.2% for the peak power, total power, half width, and half power. For the heat transfer model, percentage errors of 3.2, 2.9, and 5.3% at the inlet, center, and outlet sections of the receiver were determined for different flow rates using maximum input current and opening radius. The aperture mechanism was capable of maintaining an exhaust temperature of 250 °C based on actual Direct Normal Irradiance data. Results showed that the variable aperture is a promising apparatus even in applications where the maximum temperatures are desired based on an observed optimum radius of 57.5 mm.

1. Introduction

Current energy production methods adversely affect the environment and lead to global warming. In the United States, an average of 426 million metric tons of carbon dioxide was emitted per month, as of 2017. This emission was mainly from petroleum, coal, and natural gas, where these energy sources represented 78.8% of the primary energy production [1]. The shift towards renewable energy, especially solar energy, saw its biggest increase starting in 2011. However, there are limitations and challenges of present solar thermal technologies.

A large portion of the solar energy sector consists of Concentrating Solar Power (CSP) plants. These plants implement the use of reflecting mirrors or heliostats in order to focus solar radiation from the sun onto a point or line. The main types of CSP technologies are: parabolic dish, parabolic/enclosed trough, linear Fresnel reflector, and solar tower, with the parabolic trough being the most commonly used technology. However, solar towers with central receivers are gaining much greater attention due to their efficiencies at elevated temperatures enabling implementations in thermochemical processes in addition to direct electricity generation [2]. A solar tower central receiver is a cavity with an aperture that aims for maximizing the irradiation captured while minimizing the re-radiation lost within the cavity [3]. The captured radiation provides high temperature heat that can be used in several applications, including production of direct electricity [4], fuels [5,6], metals [7], and other products [8].

One of the main challenges for solar reactors is due to the transient nature of solar irradiance intercepted by the Earth's surface. This inconsistency of irradiance significantly affects the performance of solar reactors, which require semi-constant temperatures within their cavity to maximize the process's efficiency. There are several notable solar reactor designs in literature [7–10], which aim at investigating this challenge and proposing improvements for design concepts and operating conditions. Most of these designs incorporate the use of an optimum fixed aperture size that is determined through a compromise between maximizing irradiation captured while minimizing re-radiation lost through the aperture for the anticipated working conditions [3]. However, since

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Nomenclature

A	area
C	geometry constant
c_p	specific heat capacity
D	distribution factor
d	diameter
f	focal length
h	convection heat transfer coefficient
k	thermal conductivity
m	mass
$\dot{m}$	mass flow rate
N	number of rays
n	number of total surfaces
$\hat{n}_s$	ideal normal vector
$\hat{n}'_s$	real normal vector
$\dot{Q}$	heat rate
$\mathcal{R}$	random number between zero and one
r	radius
s	arbitrary number greater than zero
T	temperature
t	time
$\hat{t}$	tangent vector
U	uncertainty

Greek symbols

ρ	density
α	absorptivity
ϱ	reflectivity
ε	emissivity
σ	Stefan-Boltzmann constant
ϕ	cone angle
θ	circumferential angle

Subscripts

ap	aperture
c	cavity
cd	conduction
cnv	convection
ex	exhaust
i, j, l, m	element number
in	incident
n	set number
r	reflected
rd	radiation
s	specular error
tr	truncated

these reactors have fixed apertures, they are not able to compensate for large fluctuations in the irradiance without sacrificing other aspects of the process. The most commonly used approach to maintaining semi-constant temperatures within the solar reactor is adjusting the feedstock's flow rate to compensate for any irradiance fluctuations [11,12]. However, this approach disturbs the flow dynamics and is usually not feasible in processes where the flow pattern has to be preserved. Furthermore, it changes the production rate.

A promising approach to compensate for the fluctuation in solar irradiance is the implementation of a variable aperture mechanism instead of a fixed one. Such aperture will then be capable of maintaining semi-constant temperatures within the solar reactor in applications where controlling the feedstock's flow rate fails to do so. The purpose of the mechanism is to act just like the iris of an eye, where it expands when the irradiance is lower than that required and contracts when it is higher. Thus, compensating for any irradiance fluctuation without the need to disturb the flow pattern. Various aperture mechanisms have been developed with different designs and approaches to make this mechanism much more effective and sustainable for solar reactors [13–15].

To be able to effectively control the aperture mechanism in addition to other components within the solar receiver, such as the feedstock's flow rate, the receiver needs to be modeled thoroughly. Therefore, an in-house code has been developed to model the receiver, which consists of a full optical analysis of the system as well as a transient two-dimensional heat transfer analysis. The modeled system consists of a solar receiver, variable aperture, and a solar simulator with a Xenon arc bulb. There are several methods that can be incorporated to conduct an optical analysis, such as the Radiosity Net Exchange (RNE) and the Monte Carlo Ray Tracing (MCRT) methods [16–18]. However, the MCRT is the most commonly used method to simulate thermal radiation due to its capability of incorporating probabilistic density functions and other surface properties that the RNE method cannot incorporate [19–21]. Therefore, the MCRT technique has been utilized to perform the optical analysis of the system.

The optical analysis begins by modeling the solar simulator and its Xenon arc to obtain the heat flux distribution and direction of the source's incident radiation into the receiver's aperture. The arc has been previously modeled as a cylindrical volume, which is mainly based on manufacturer specifications [9,22]. However, it was illustrated that the arc cannot be accurately defined and modeled by a single simple emitting shape, whether it is a sphere or a cylinder. A concentric multilayer model of the arc that incorporates both of the previously stated geometries is capable of capturing the complex characteristics of the arc [23]. Therefore, this study proposes the use of a composite shape that consists of a sphere and a cylinder, as discussed later. Once the Xenon arc source has been modeled, the optical analysis progresses to simulate the incident irradiance from the source to the solar receiver in addition to any reflections and re-radiation within the receiver's cavity to obtain the distribution of power. By then, the optical analysis concludes and the model advances to the heat transfer analysis, where it has been performed using the finite volume method due to its capability of strictly abiding to all conservation laws [24]. These two analyses are usually coupled together when an in-depth study of radiative heat transfer is necessary [25].

2. System description and experimental setup

The system consists of three main components: a cavity type solar receiver, variable aperture, and 7 kW high-flux solar simulator that acts as a radiative source. At this experimental stage, the fluid flow through the receiver is Nitrogen. The details of each component are further discussed in the following sections, while the overall experimental setup in the lab is shown in Fig. 1.

2.1. Solar receiver

This is a cavity type solar receiver that is made of a 200 mm hollow cylinder with an inner radius of 60 mm and a thickness of 15 mm. It has front and back plates bolted onto it to form the receiver's cavity. The front plate is 160 mm in radius and has a thickness of 25 mm, while the back plate is 75 mm in radius and has a thickness of 15 mm. All of the receiver's components are made of stainless steel 316. The cavity is sealed with a 3.175 mm thick quartz