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Geometrical shape optimization of a cavity receiver using coupled radiative and hydrodynamic modeling

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Abstract

By using a two-stage optimisation process we maximise the heat rate output of a four-parameter axisymmetric direct steam generation cavity receiver. The model includes radiative and hydrodynamic considerations. We show that a significant range of geometrical shapes show similar efficiencies while having different wall flux and temperature profiles.

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Keywords: Receiver, Ray-tracing, Hydrodynamics, Heat-transfer, Optimisation.

1. Introduction

In concentrated solar power systems, receivers convert concentrated solar radiation into heat and consequently have a major impact on overall system efficiency and economic viability. Increasing the temperature of operation of existing receivers offers non negligible thermodynamic efficiency gains, as stated by the Carnot theorem; however, higher receiver temperatures translate into higher energy losses at the receiver location. Among the options envisioned to convert concentrated solar radiation into heat, indirect heating of a heat carrier circulating in irradiated tubes has been favored up to now in commercial applications. At high temperatures, cavity receivers can offer an advantage to contain emissive losses and thus improve the overall efficiency of the system. Recently, several studies

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Nomenclature

r	Radius, m	*Subscripts:*	
l	Length, m	s	Optimisation routine step s
$\dot{Q}$	Radiative power, W	a	Aperture
J	Radiosity, W	f	Frustum
n	Tube element index	c	Cone
g	Total number of geometries for an optimisation	r	Receiver
N	Raytrace scale array	sun	Sun
	Absorptivity	fl	Fluid
ε	Emissivity	w	Wall
σ	Standard deviation	abs	Absorbed
F_{ij}	View factor of element i looking at element j	emit	Emitted via thermal emissions
IC_{tot}	Overall amplitude of the confidence interval	abs net	Net absorbed: absorbed - emitted
p	Population of receiver geometries		
γ	Convective heat transfer coefficient, W/m^{2}K		
x	Steam quality		
T	Temperature, K		
P	Pressure, Pa		
h	Enthalpy, kJ/kg		
ρ	Fluid density, kg/m^3		
A	Area, m^2		
D	Internal diameter of the tube, m		

focused on cavity geometry optimization for different purposes: to average the flux on the internal walls of the receiver [1], to minimize overall radiative losses [2], to improve optical efficiency using bottom convex cylindrical geometry [3] or to study optimal geometrical aspect ratio for cylindrical cavity receivers at the focus of multi-dish concentrators [4]. All these studies agree on the strong influence of cavity shape on flux distribution on the internal walls of the cavity while only taking into account the radiative component of receiver losses. This study proposes an attempt to optimize the shape of a cavity receiver based on its overall thermal efficiency using coupled radiative and hydrodynamic modeling. Convective losses to the environment are not yet considered. The receiver considered is a once through direct steam generation receiver placed at the focus of the SG4 parabolic dish at the Australian National University (ANU) [5]. The geometry of the receiver is defined by a four-parameter axisymmetric profile.

2. Model system

The present study considers a system composed of a parabolic dish concentrator with a cavity receiver placed at its focus. The dimensions of the simulated parabolic dish fit those of the SG4 dish at the ANU [5]. Parasitic absorption of solar radiation due to non ideal reflectivity of the mirrors, and concentrator slope error due to non-ideal orientation of the reflective surface are considered. The SG4 Dish, being in reality an assembly of spherically curved square mirrors and thus has a spatial flux distribution of the reflected radiation that differs from an ideal parabolic concentrator. The Dish model used in this study is a modified parabolic dish implementation able to reproduce experimental measurements of the concentrated flux distribution [5].

The receiver, placed at the focus of the concentrator, is an axisymmetric cavity defined by four geometric parameters: aperture radius r_{a}, cone radius r_{c}, frustum length l_{f} and cone length l_{c}. As shown in Fig. 1, the combination of these four-parameters is able to create a variety of geometries. Cavity walls are considered to be grey and diffuse. Receiver absorptivity α_{r} is set to 0.95 and receiver emissivity ε_{r} is set to 0.85, as if painted with Pyromark® 2500 paint [6]. The receiver is open as opposed to windowed receiver. The internal walls of the receiver are covered by a single coiled tube in which a water/steam mixture circulates. In this study, water enters the receiver at the aperture and leaves it at the tip of the conical section, following the receiver profile. Lastly, the receiver is placed into a cylindrical housing envelope whose radius and length are respectively 100 mm more than the