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

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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 working temperature of a receiver offers downstream thermodynamic efficiency gains in accordance Carnot efficient limits. However, higher receiver temperatures also translate into higher thermal losses from the hotter receiver external surfaces. Among numerous possible receiver configurations, this paper limits consideration to widely-adopted approach of tubular receivers that indirectly heat a working fluid within irradiated tubes. At high temperatures, use of cavity geometries facilitates reduction of thermal emission losses, and is discussed in several studies that have examined cavity optimization approaches: to average the flux on the internal walls of the receiver [7], minimize overall radiative losses [3] or improve optical efficiency using bottom convex cylindrical geometry [9]. 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 direct steam generation mono-tube cavity receiver based on its overall thermal efficiency, using coupled radiative and hydrodynamic analyses. Convective losses to the environment are not considered. The geometry of the receiver is defined by a four parameter axisymmetric profile, designed to be placed at the focal point of a 500 m² paraboloidal dish concentrator at the Australian National University [5].

2. Receiver model

2.1. Calculation of optical efficiency

Ray-tracing is used to evaluate optical losses including: blockage, parasitic absorption by the concentrator, spillage and reflective losses. The "Tracer" package [**6**], a Python-based ray-tracing library from University of Tel Aviv, is used to perform Monte Carlo ray-tracing simulations. The existing package was extended to allow modelling of realistic Gaussian bivariate shape-error optics [**4**], Buie sunshape distribution [**1**] and diffuse grey surface approximations for the active zone of the receiver.

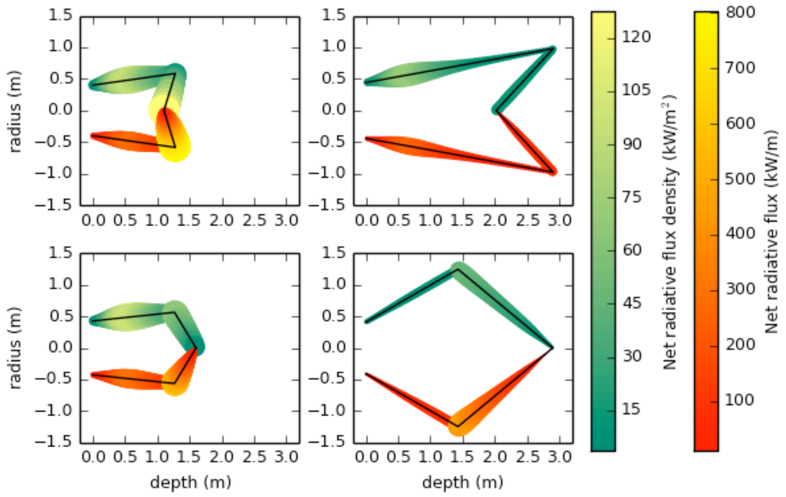

Figure 1. Examples of axisymmetric net radiative flux density (upper part of the profile) and net radiative flux (lower part of the profile) from ray-tracing simulations.

2.2. Hydrodynamic model, and calculation of thermal emission losses

A steady-state one-dimensional model of a mono-tube cavity receiver models the heat transfer to the water/steam working fluid. A finite-difference approach is adopted and steady-state energy balances are solved for each segment of tube length to determine the tube wall temperatures that balance internal convection to the fluid, incident radiation on the segment, and thermal emission losses. Internal convection calculation iteratively solves enthalpy gain and pressure drop for the fluid in the segment, based on bulk fluid properties from steam tables [**8**], and relevant correlations [**2**]. Thermal emission losses are evaluated using the radiosity method. Associated view-factors are calculated using an adapted ray-tracing routine. The one-dimensional modeling approach results in a set of profiles as a function of flow path-length for each receiver geometry, including fluid temperature, wall temperature, and flux maps, as shown in Figure 2.

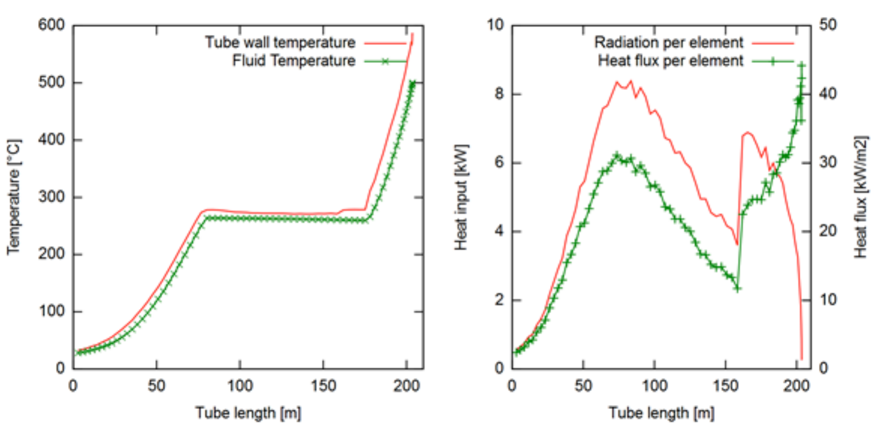

Figure 2: Temperature profile and heat flux distribution along tube length for a simplified receiver.

3. Optimisation

Using four geometrical parameters plus tube diameter as variables in a stochastic optimization, we show that the variation of the shape of the receiver influences radiative losses as well as the efficiency of the heat transfer in the receiver, leading to receiver geometries that balance heat-loss reduction with adequate heat transfer to the working fluid. Results are discussed to highlight insights into good receiver design practices.

References

[1] D Buie, AG Monger, and CJ Dey. Sunshape distributions for terrestrial solar simulations. *Solar Energy* **74**(2), 113 – 122, 2003.

[2] VP Carey. *Liquid–Vapor Phase-change Phenomena*. Hemisphere, New York, 1992.

[3] J Pye C-A Asselineau, E Abbasi. Open cavity receiver geometry influence on radiative losses. In Solar2014, annual conference of the Australian Solar Energy Society, Melbourne, May 2014.

[4] W Huang and Z Han. Theoretical analysis of error transfer from the surface slope to the reflected ray and their application in the solar concentrated collector. *Solar Energy* **86**(9), 2592 – 2599, 2012.

[5] K Lovegrove, G Burgess, and J Pye. A new 500m^2 paraboloidal dish solar concentrator. *Solar Energy* **85**(4), 620 – 626, 2011. SolarPACES 2009.

[6] Y Meller. Tracer package: an open source, object oriented, ray-tracing library in python language. https://github.com/yosefm/tracer.

[7] Y Shuai, X-L Xia, and H-P Tan. Radiation performance of dish solar concentrator/cavity receiver systems. *Solar Energy* **82**(1):13 – 21, 2008.

[8] W Wagner and A Pruss. The IAPWS formulation 1995 for the thermodynamic properties of ordinary water substance for general and scientific use. *J Phys Chem Ref Data* **31**(2) 387–535, 2002.

[9] F Wang, R Lin, B Liu, H Tan, and Y Shuai. Optical efficiency analysis of cylindrical cavity receiver with bottom surface convex. *Solar Energy* **90**:195 – 204, 2013.