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Off-design simulation and performance of molten salt cavity receivers in solar tower plants under realistic operational modes and control strategies

S. Saeed Mostafavi Tehrani *, Robert A. Taylor

School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, NSW 2052, Australia

HIGHLIGHTS

- Model developed for cavity receivers for design and off-design performance analysis.
- Receiver performance degraded with increased receiver inlet temperature.
- Receiver control strategies were found to alter the inlet temperature and DNI limits.
- A combined control approach was proposed to maximize receiver operation range.
- Off-design receiver efficiency correlations are provided for these strategies.

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ABSTRACT

Solar irradiation is intermittent, but concentrated solar thermal (CST) plants are typically designed and analyzed solely based on their steady design point. Unlike coal power plants, however, CST plants frequently experience thermal loads well above and below their rated design point, leading to off-design operation for much of the operational year. Importantly, if a latent heat thermal energy storage (LHTES) system is employed, the receiver inlet temperature can vary under these conditions. To date, there is a clear lack of knowledge for how to handle off-design conditions in terms of developing appropriate control strategies to maximize the receiver thermal output and its operational region. In this study, a thermal model was developed and validated that is suitable for design/off-design performance analyses of molten salt cavity receivers in both steady state and transient conditions. The study investigated two control strategies – a fixed receiver flow rate (FF) and fixed receiver outlet temperature (FT) – for their off-design performance in each of two off-design operational modes (storage and non-storage). Solar field utilization (SFU) is variable in non-storage mode, but in the storage mode, it is whether variable or fixed at design point (SFU = 1). The feasible operating region in this study refers to the zone restricted by maximum allowable operational parameters defined based on design point analysis, mainly maximum receiver outlet temperature, maximum flow rate, and maximum receiver surface temperature.

Through this analysis, it was found that receiver inlet temperatures above the design point (560 K) degrade the receiver performance in both control strategies and under all operational modes. The results also revealed that the maximum allowable receiver inlet temperature that maintains the receiver operation inside the feasible region could not go beyond ~700 K or 600 K with the FF and FT strategies (in the storage mode with variable or fixed SFU), respectively. These values also indicate the charging cut-off temperature for the fluid flowing out in LHTES systems. In the non-storage mode, the receiver inlet temperature is remained constant at design point by varying the SFU over the time. While the design point direct normal irradiation (DNI) was 900 W m^{-2}, the maximum allowable DNI is 700 W m^{-2} and 500 W m^{-2} with the FF and FT strategies, respectively. These results motivate a hybrid control strategy that switches between the FF and FT strategies to maximize the performance and the number of operational hours of a CST plant during the day. As a final aspect of this study, off-design receiver efficiency correlations are developed that can be used in any simulation environment to accurately predict receiver performance.

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* Corresponding author.
E-mail addresses: s.mostafavitehrani@unsw.edu.au (S.S. Mostafavi Tehrani), robert.taylor@unsw.edu.au (R.A. Taylor).

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Nomenclature

A	area [m^2]
C	concentration ratio [–]
C_p	specific heat [$J\ kg^{-1}\ K^{-1}$]
d	diameter of receiver tube [m]
Ex	exergy [W]
Fr	view factor [–]
h	enthalpy [$J\ kg^{-1}\ K^{-1}$] or convective heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
H	height of receiver aperture [m]
k	thermal conductivity [$W\ m^{-1}\ K^{-1}$]
$\dot{m}$	mass flowrate [$kg\ s^{-1}$]
N	number of receiver tubes
Nu	Nusselt number
Pr	Prandtl number
q	thermal energy per area [$W\ m^{-2}$]
Q	thermal energy [W]
Q_{abs}	receiver absorbed energy [W]
Q_{design}	required thermal energy for design point operation of the Rankine cycle [W]
Re	Reynolds number
$\dot{S}_{gen}$	entropy generation [$W\ K^{-1}$]
T	temperature [K]
V	velocity [$m\ s^{-1}$]
W	power output [W] or width of receiver aperture [m]

Greek symbols

η_{field}	heliostat field efficiency
$\eta_{rec,energetic}$	receiver energetic efficiency
$\eta_{rec,exergetic}$	receiver exergetic efficiency
λ	conductivity [$W\ m^{-1}\ K^{-1}$]
δ	thickness [m]
ε	emissivity
ρ	density [$kg\ m^{-3}$] or reflectivity

Subscripts

abs	absorbed
abs	ambient
cond	conduction
field	heliostat field
fc	forced convection
i or in	inlet, inner, or inside
ins	insulation
ms	molten solar salt
nc	natural convection
o	outer or outlet
out	outlet
PB	power block
rad	radiation
rec, ap	receiver aperture
rec, in	receiver inlet or incident on receiver
rec, out	receiver outlet
rec, sur	receiver surface
rec, tube	receiver tube
ref	reflection
w	receiver wall

Abbreviations

CST-tower	tower-based concentrated solar thermal
DNI	direct normal irradiation [$W\ m^{-2}$]
FF	fixed flow rate
FT	fixed receiver outlet temperature
HTF	heat transfer fluid
LHTES	latent heat thermal energy storage
SFU	solar field utilization (the ratio of active heliostats divided by the total number of heliostats)
TES	thermal energy storage

1. Introduction

In response to worldwide energy and environmental concerns, replacing conventional fossil fuel-based energy conversion technologies with renewables has become a global priority [1,2]. Concentrated solar thermal (CST) plants are a promising technological solution as they can be integrated with thermal energy storage (TES) to meet peak demand, even in times of low solar irradiance. Parabolic troughs technology dominates today's CST market, but the future ascendancy of tower systems seems evident [3–6]. The fundamental reason for this shift is related to the higher receiver and cycle efficiency in tower systems due to their higher concentration ratio (~1000× as compared to ~100× in parabolic trough plants) [7]. Accordingly, as reported in [8–10], tower systems represent the next generation of CST plants as they can achieve higher efficiency and lower cost.

The four main subcomponents of molten salt tower-based CST (CST-tower) plants are the heliostat field, receiver, a thermal energy storage system (TES), and a power block. Of the four main subcomponents, the thermal efficiency of the whole plant is most sensitive to the performance of the receiver as a supplier of heat for the Rankine cycle. Therefore, the receiver efficiency and reliability across the *whole operational range* of heat transfer fluid (HTF) temperatures and flow rates must be determined a priori – e.g. before building a CST plant costing upwards of ~1 Billion USD [4,11]. To date, many CST-tower designs have been evaluated with simulations and/or experiments. These include tubular, cavity, multi-cavity, volumetric receivers and direct absorbing receivers which can employ steam, molten salt, molten metal, gas, and particles [12–14]. Among them, the molten salt cavity receiver has been proposed as the most cost effective and efficient for the near term [7,15,16]. One advantage of molten salt cavity receivers – over gas receivers – is their relatively energy dense flow which goes directly to and from storage, enabling higher dispatchability and round trip storage efficiency.

When it comes to minimizing the thermal heat loss of cavity receivers, several studies have found that all three mechanisms of heat transfer (conduction, convection, and radiation) play a role [17–22]. Li et al. [20] has shown that apart from three conventional ways of heat transfer, the highest loss in cavity receivers corresponds to reflection losses, which can amount to 50% of the total loss. It has been shown that conduction heat loss accounts for the smallest share of heat loss (usually $< 1\%$) in cavity receivers. Hinojosa et al. [23] presented numerical results of natural convection and surface thermal radiation for open cavity receivers based on the Boussinesq approximation. Gonzalez and Palafox [24] found that radiation heat transfer is greater than convection heat transfer when there is a large temperature difference between the hot wall and the bulk fluid (e.g. $\Delta T > 200$ K). Clausing [25] showed that the influence of wind for normal operating conditions (<8 m/s) has minimal influence on convective heat losses for a cavity receiver. Along with these studies on the heat transfer mechanisms