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Simplified heat loss model for central tower solar receiver

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Abstract

Heat loss is an important factor in predicting the performance of solar receiver of concentrated solar power (CSP) systems. This study presents a numerical simulation calculating convection and radiation heat losses from four different receiver shapes including external and cavity type receivers with different opening ratios (ratio of cavity aperture area to receiver area). The simulation was carried out using Fluent CFD (computational fluid dynamics) software considering three different receiver temperatures (600, 750, and 900 °C), three wind velocities (1, 5, and 10 m/s), and two wind directions (head-on and side-on). The simulation results were then used for deriving a simplified correlation model which gives the fraction of convection heat loss by a function of opening ratio, receiver temperature, and wind velocity. The calculated fraction can be easily converted to convection heat loss, total heat loss, or receiver efficiency once the radiation heat loss is estimated by any applicable prediction model. Calculated heat loses by the proposed simple correlation model showed good agreements with the simulation results with 11.4% and 5.9% average absolute deviations for convection heat loss and total heat loss, respectively. Validation of the model with experimental data was also carried out using test results available from three central receiver systems (Martin Marietta, Solar One and Solar Two).

Keywords: Central tower; Solar receiver; Efficiency; Radiation; Convection; Heat loss

1. Introduction

Owing to high system efficiency and compatibility with modern power generation cycles, the central tower system is taking growing attention in concentrated solar power (CSP) technology. In order to take the full advantage of high system efficiency which is mainly from increased solar receiver temperature, the efficiency of the receiver needs to be kept high enough not to offset the benefit of increased thermodynamic efficiency of power block. Therefore, reliable estimation and proper control of the receiver efficiency are important in designing and operating the CSP systems thermodynamically and economically efficient. Also, all components of CSP system undergo part load operation when solar irradiance is lower than the designed condition, and for some components like the receiver and power block, part load operation causes notable level of efficiency decreases requiring good understanding on their part load efficiencies.

The type of central tower solar receiver varies depending on the type of power block, working fluid, operating condition, material and design preference. To date, most of large-scale commercial tower receivers adapted fully external or partial cavity designs with multiple receiver panels composed of vertical tube array. However, as the application temperature increases, the necessity of cavity becomes more significant in order to reduce heat loss from the

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Nomenclature

a, b	parameters (for wind speed dependency)
A	surface area (m^2)
F	view factor
FC	fraction of convection loss (ratio of convection loss to total loss)
OR	opening ratio (ratio of aperture area to receiver area)
Q	energy (W)
q	energy flux (W/m^2)
T	temperature (K)
V	wind velocity (m/s)

Greek symbols

ε	emissivity of wall surface
ρ	reflectivity of wall surface
σ	Stefan–Boltzmann constant, 5.67×10^{-8} ($W/m^2\,K^4$)

Subscripts

a	air
ap	aperture
conv	convection
inc	incident
net	net (leaving–incident)
out	leaving
rad	radiation
re	receiver
total	total

receiver. The type or shape of the cavity also varies depending on its design condition. Hence, it is not straightforward to derive implicit heat loss models or correlations which could be generally used over different types of receivers with a good reliability. As the system size of interest becomes larger, experimental approach for receiver efficiency study becomes more difficult, and the availability of experimental data from existing demonstration or commercial systems is very limited. Also, since the efficiency analysis involves many different heat transfers that are associated with incoming solar energy, spillage, reflection, emission and convection, the experimental investigation could involve high uncertainty related to the availability and reliability of various measurements.

Few heat loss studies for central tower receivers have been reported since early 1980s. Clausing (1981) proposed an implicit model for natural convection heat loss for large cavity receivers. The model was based on a cubical cavity including both convective and stagnant zones and provides Nusselt number equation correlating Rayleigh number and the ratio of wall temperature to ambient temperature. Calculated convection heat loss by the model was compared against the experimental results from a large scale central receiver (Clausing, 1983) showing 25% deviation. In this paper, same experimental results were compared with the calculated results from the model proposed in this study. Stoddard (1986) experimentally investigated the effect of wind velocity on the cylindrical central receiver of Solar One central tower system. The experiment measured heat loss by using heated water flowing through the receiver and obtained experimental heat transfer coefficient for convection heat loss. The result was compared with calculated heat transfer coefficient from the combined convective heat loss model by Siebers and Kraabel (1984) showing over 30% average absolute deviation. In this paper, both of experimental and calculated results from Stoddard (1986) were compared with the calculated results by the model of this study. Boehm (1987) reviewed existing experimental data from different types of central tower receivers together with relevant modeling results. But the reviewed cases were all different in receiver type and size, and the investigated data values contained different type of information (e.g. efficiency or loss, natural or forced convection) with different uncertainties. So, the study was only able to be concluded with some typical findings related to the convection heat loss study (e.g. difficulty with modeling a cavity, complexity of mixed convection, uncertainties of experimental data and etc.). More recent experimental activity was reported by Pacheco (2002) from Solar Two central tower system. The report provided extensive test results on the receiver efficiency at various incident powers and wind velocities. In this paper, Pacheco's test results were compared with the calculated results using the proposed model of this study. Fang et al. (2011) investigated receiver heat losses based on the entire heat transfer processes by using a combined CFD (computational fluid dynamics) for fluid flow and Monte-Carlo method for radiation. But the study was for investigating a numerical approach for a given receiver design rather than deriving a general heat loss model.

For small-scale cavity receivers, there have been a number of heat loss studies (Paitoonsurikarn and Lovegrove, 2003; Prakash et al., 2009, 2012; Wu et al., 2010). But most of them were considering parabolic dish systems, focusing more on the natural convection with different facing angles and testing in a small-scale at low temperature conditions, which are different from the interest of this study. In the review on different convection heat loss studies for cavity receivers by Wu et al. (2010), it was noted that the study of wind effect is still in the early stage because only few investigators have attempted convection heat loss study under wind conditions and some of the results conflict each other.