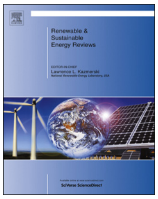
Renewable and Sustainable Energy Reviews 29 (2014) 835–846

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



# Review of high-temperature central receiver designs for concentrating solar power

Clifford K. Ho*, Brian D. Iverson

*Sandia National Laboratories, Concentrating Solar Technologies Department, PO Box 5800, Albuquerque, NM 87185-1127, USA*

ARTICLE INFO

*Article history:*
Received 2 November 2012
Received in revised form
25 August 2013
Accepted 26 August 2013

*Keywords:*
Concentrating solar
Receiver
Volumetric
External
Cavity
Solid particle

ABSTRACT

This paper reviews central receiver designs for concentrating solar power applications with high-temperature power cycles. Desired features include low-cost and durable materials that can withstand high concentration ratios (~1000 suns), heat-transfer fluids that can withstand temperatures >650 °C, high solar absorptance, and low radiative and convective heat losses leading to a thermal efficiency >90%. Different receiver designs are categorized and evaluated in this paper: (1) gas receivers, (2) liquid receivers, and (3) solid particle receivers. For each design, the following information is provided: general principle and review of previous modeling and testing activities, expected outlet temperature and thermal efficiency, benefits, perceived challenges, and research needs. Emerging receiver designs that can enable higher thermal-to-electric efficiencies (50% or higher) using advanced power cycles such as supercritical $CO_2$ closed-loop Brayton cycles include direct heating of $CO_2$ in tubular receiver designs (external or cavity) that can withstand high internal fluid pressures (~20 MPa) and temperatures (~700 °C). Indirect heating of other fluids and materials that can be stored at high temperatures such as advanced molten salts, liquid metals, or solid particles are also being pursued, but challenges include stability, heat loss, and the need for high-temperature heat exchangers.

**Contents**

## 1. Introduction

Higher efficiency power cycles are being pursued to reduce the levelized cost of energy from concentrating solar power tower technologies [1]. These cycles, which include air-Brayton, supercritical-$CO_2$ ($sCO_2$) Brayton, and ultra-supercritical steam cycles, require higher temperatures than those previously achieved using central receivers. Current central receiver technologies employ either water/steam or molten nitrate salt as the heat-transfer and/or working fluid in subcritical Rankine power cycles. The gross thermal-to-electric efficiency of these cycles in currently operating power-tower plants is typically between 30 and 40% at inlet temperatures

---

* Corresponding author. Tel.: +1 505 844 2384.
*E-mail address:* ckho@sandia.gov (C.K. Ho).

1364-0321/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2013.08.099

$<600$ °C. At higher input temperatures, the thermal-to-electric efficiency of the power cycles increases following Carnot's theorem. However, at temperatures greater than 600 °C, molten nitrate salt becomes chemically unstable, producing oxide ions that are highly corrosive [2], which results in significant mass loss [3].

### 1.1. Key technical challenges

Unique challenges associated with high-temperature receivers include the development of geometric designs (e.g., dimensions, configurations), materials, heat-transfer fluids, and processes that maximize solar irradiance and absorptance, minimize heat loss, and have high reliability at high temperatures over thousands of thermal cycles. In addition, consideration must be given to advantages and disadvantages of direct vs. indirect heating of the power cycle working fluid. For example, advantages of direct heating of the working fluid include reduced exergetic losses through intermediate heat exchange. Advantages of indirect heating include the ability to store the heat transfer media (e.g., molten salt, solid particles) for energy production during non-solar hours. In addition, heat addition to the receiver media (through exposure to the heat source) can also be done directly (e.g., exposed liquid films or solid particles) or indirectly (e.g., tubular receivers).

Regarding reduction of heat losses to achieve high thermal efficiencies, Eq. (1) presents the receiver thermal efficiency, $\eta_{th}$, as a function of the incoming solar radiative power, $Q_{in}$ (W), and the radiative and convective heat losses, $Q_{loss}$ (W):

$$\eta_{th}=\frac{\alpha Q_{in}-Q_{loss}}{Q_{in}}=\alpha-\frac{\varepsilon\sigma F_{view}T_R^4+f_{conv}h(T_R-T_{amb})}{\eta_{field}E_{DNI}C} \qquad (1)$$

where $\alpha$ is the receiver solar absorptance, $\varepsilon$ is the receiver thermal emittance, $\sigma$ is the Stefan–Boltzmann constant ($5.67\times10^{-8}$ W/m$^2$ K$^4$), $F_{view}$ is the radiative view factor from the receiver surface to the surroundings, $T_R$ is the receiver surface temperature (K), $f_{conv}$ is a convective heat loss multiplier, $h$ is the convective heat transfer coefficient, $T_{amb}$ is the ambient temperature (K), $\eta_{field}$ is the heliostat field efficiency (including cosine losses, reflectance losses, and spillage), $E_{DNI}$ is the direct normal irradiance (W/m$^2$), and $C$ is the concentration ratio. Assuming an absorptance, $\alpha$, of 0.95 [4,5], a thermal emittance, $\varepsilon$, of 0.85 [4], an ambient temperature, $T_{amb}$, of 20 °C, and an annual heliostat field efficiency, $\eta_{field,}$ of 0.6 [6], plots of the thermal efficiency, $\eta_{th}$, as a function of receiver temperature, $T_R$, with varying values of concentration ratio, $C$, radiative view factor, $F_{view}$, and convective heat loss factor, $f_{conv}$, can be generated (Fig. 1). Values from Solar Two are used as baseline inputs. The average flux on the Solar Two receiver was 430 kW/m$^2$ [5], so the baseline concentration ratio, $C$, is calculated (using the denominator in Eq. (1)) to be ~900 assuming a field efficiency of 0.6 [6] and an average direct normal irradiance of 0.8 kW/m$^2$ (approximated from data in [5]). In addition, the estimated baseline value for the convective heat transfer coefficient, $h$, is 10 W/m$^2$-K [5,7], the baseline convective heat loss factor, $f_{conv}$, is one, and the baseline radiative view factor is one.

The plots in Fig. 1 show that a high concentration ratio ($C>900$) on the receiver and a reduced radiative view factor ($F_{view}<1$) are critical to maintain high thermal efficiencies at temperatures above 650 °C. Reducing the convective heat loss is less significant, although it can yield a several percentage point increase in thermal efficiency at high temperatures (note that the convective heat loss in cavity receivers can be a factor of two or more greater than that in external receivers because of the larger absorber area [6]). Increasing the solar absorptance, $\alpha$, and/or decreasing the thermal emittance, $\varepsilon$, in Eq. (1) will also increase the thermal efficiency.

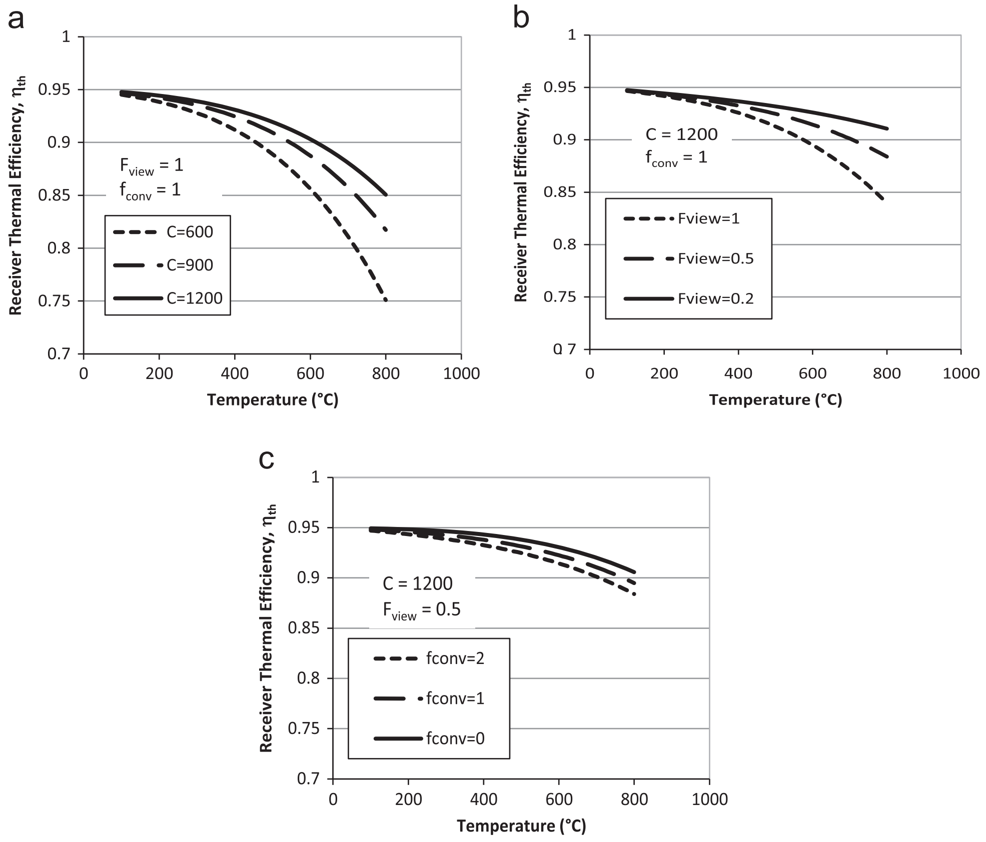


**Fig. 1.** Plots of receiver thermal efficiency as a function of receiver surface temperature with varying concentration ratio (a), radiative view factor (b), and convective heat loss (c).