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Design of a high temperature (1350 °C) solar receiver based on a liquid metal heat transfer fluid: Sensitivity analysis

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ABSTRACT

One approach to reducing the cost of concentrated solar power is to improve the heat engine efficiency by increasing its maximum operating temperature. To achieve higher operating temperatures, we have studied using a liquid metal heat transfer fluid in conjunction with a receiver made from a ceramic/refractory material. As a first step in the design of such a receiver, we conducted sensitivity analyses of several receivers, allowing us to determine what factors most significantly affect receiver performance. Material properties, natural convection from the receiver cavity, and the location of hot spots within the cavity were found to have the largest effect on receiver efficiency. It was also determined that stresses due to thermal expansion can exceed the fracture strength of the receiver material if care is not taken to minimize these stresses. Interestingly, the stress as opposed to performance considerations, set the most important constraints on the receiver geometry.

1. Introduction

Considering the imminent effects of climate change (Pachauri et al., 2014), developing a carbon-neutral approach to electricity is becoming an ever increasing priority. Although many renewable technologies, such as wind and photovoltaics (PV), have experienced major reductions in their levelized cost of energy (LCOE) (Branz et al., 2015; Donohoo-Vallett, 2016), it has now become clear that finding an inexpensive way to dispatchably store energy is critical (Denholm et al., 2016, 2013; Denholm and Mehos, 2014; Sioshansi et al., 2014). Concentrated solar power (CSP) with thermal energy storage (TES) is currently the most cost effective option, but it is still too expensive, as it currently costs about twice that of new installations of natural gas combined cycle plants (EIA, 2013; NREL, 2016). While there exist several avenues to reducing CSP costs (Pitz-Paal et al., 2005), one of the best opportunities for cost reduction is improving the efficiency of the plant, particularly by increasing the hot side temperature of the power block from 565 °C to temperatures high enough to allow for a Brayton-Rankine combined cycle to be used (i.e. $> \sim 1000$ °C); doing so can increase the power block efficiency by upwards of 50% (Rolf et al., 1999).

1.1. Material selection for high-temperature CSP

Current state of the art CSP utilizes molten nitrate salts as the HTF and stainless steel or, in some cases, nickel alloys as the containment material (Fernandez et al., 2012; Goods and Bradshaw, 2004). To achieve temperatures necessary for a combined cycle however, refractory materials not found in current CSP plants must be used. Finding a suitable HTF to use in a CSP plant is one of the primary limitations that prevents CSP from attaining extreme temperatures and is problematic for a number of reasons (Becker et al., 2006; Bertocchi, 2002; Bradshaw and Meeker, 1990; Bradshaw and Siegel, 2008; Bugge et al., 2006; Cable et al., 2003; Fernandez et al., 2012; Garcia-Casals and Ajona, 1999; Goods and Bradshaw, 2004; Karni et al., 1997, 1998; Kribus et al., 1999; Kruizenga and Gill, 2014; Margolis et al., 2012; Pitz-Paal et al., 1997; Ries et al., 1997; Ries and Spirkl, 1996; Siegel et al., 2010; Weitzel, 2011; Wright et al., 2004). To overcome the issues presented by other heat transfer media, a liquid metal heat transfer fluid (LMHTF) is considered herein for use in a power tower receiver. LMHTF's have many properties that make them desirable for use at extreme temperatures (Pacio and Wetzel, 2013; Yang and Garimella,

Abbreviations: PV, photovoltaic; LCOE, levelized cost of electricity; CSP, concentrated solar power; TES, thermal energy storage; TIT, turbine inlet temperature; LMHTF, liquid metal heat transfer fluid; MCRT, Monte Carlo ray tracing; HFSS, high flux solar simulator; CFD, computational fluid dynamics

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Nomenclature

A	area (m^2)
C_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
E	Young's modulus (Pa)
F	view factor
g	gravitational acceleration ($m\,s^{-1}$)
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
$\dot{m}$	mass flowrate ($kg\,s^{-1}$)
p	pressure (Pa)
q''	heat flux ($W\,m^{-2}$)
R	thermal resistance ($K\,W^{-1}$)
T	temperature (K)
u	fluid velocity (m/s)
α	thermal expansion coefficient
ε	radiative emissivity
ε	strain
η	efficiency
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	Stefan-Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
σ	stress (Pa)
Φ	viscous forces term of Navier-Stokes equations
ϕ	flux ($W\,m^{-2}$)

2010), particularly their high thermal conductivity and the large temperature range over which they remain liquid. Several LMHTF candidates for CSP exist; however, few are liquid in the temperature range of interest and unreactive/non-toxic enough in liquid form to use safely, and even fewer are economically feasible in a large-scale plant. Nevertheless, we have identified two LMHTF's as candidates for use in high-temperature CSP applications (Wilk, 2016), namely aluminum-silicon (Al-Si) alloys and tin (Sn). We limit our sensitivity analysis here to the latter. Graphite is used as the containment material, as it is a refractory that does not form compounds with Sn and thus, it can be used to make an entire system without any corrosion whatsoever (Amy et al., 2017; Zhang et al., 2018); mullite was considered for similar reasons, but was not used in later receiver designs. Furthermore, a recent demonstration of an all ceramic pump operating at 1200 °C, pumping liquid tin, has opened up the potential for a new version of CSP that leverages such a refractory based infrastructure.

1.2. Receiver design for high-temperature CSP

While most existing commercial plants employ external receivers, at the extreme temperatures of interest (i.e., > 1000 °C), an external receiver would lose too much heat through reradiation to yield a net gain in overall system efficiency. Thus a cavity design is necessary to construct a high-efficiency receiver, to limit the view factor of the receiver to the surroundings. The present investigation is a first step to reducing losses from a receiver assembly. Here, we perform a sensitivity analysis to identify the most important design parameters and attempt to answer the question of whether an efficient (~90%) receiver can be realized at temperatures > 1000 °C. Here, the receiver efficiency, η, is defined as

$$\eta = \frac{\int_{T_{inlet}}^{T_{outlet}} \dot{m} C_p(T) dT}{\int \phi(r,\theta,z) dA} \quad (1)$$

where T_{inlet} is the inlet temperature of the HTF, T_{outlet} is the average outlet temperature of the HTF, $\dot{m}$ is the mass flow rate of the HTF, $C_p(T)$ is the specific heat of the HTF as a function of temperature, $\phi(r,\theta,z)$ is the spatially dependent radiant flux entering the cavity through an aperture, given in $kW\,m^{-2}$, and A is the area of the aperture.

Cavity receiver efficiency is fundamentally limited by its reradiation. Steinfeld provides an expression for the theoretical maximum efficiency of a cavity receiver, by assuming the only loss is reradiation through the aperture, via (Steinfeld, 2002)

$$\eta_{max} = 1 - \frac{\sigma T^4}{\phi} \quad (2)$$

where σ is the Stefan-Boltzmann constant, T is the nominal blackbody temperature of the receiver, and ϕ is the average flux of light coming through the receiver aperture.

Not only do thermal losses increase at higher temperatures, but thermal stresses in the receiver also become more significant. Furthermore, even though it possesses superior thermal shock resistance, graphite has a low fracture strength (~50 MPa), and a critical stress intensity factor, K_c, of only ~1 MPa-$\sqrt{m}$ (Rose, 1985). Thus, it is not clear without first calculating the temperature distribution that the thermal stresses will not exceed the limits of the candidate material. Therefore, it is necessary to model the system to calculate expected temperature profiles so that subsequent stress analyses and efficiencies can be evaluated for feasibility.

Here, we attempt to analyze a small-scale receiver as an important first step towards determining what factors must be considered at larger scales. Although one can qualitatively predict *a priori* what types of materials and system properties are likely to yield the best performance, it is not clear if the properties that can be realized with commercially available materials are sufficient to allow for actual testing without immediate failure, or whether such materials are even sufficient to reach the nominal target of 90% efficiency after optimization. Among the most significant questions associated with the design of such a receiver are the following:

- The difference between the inlet and outlet temperatures of the receiver is on the order of 1000 °C, and the thermal conductivity of graphite changes by nearly an order of magnitude over this temperature range. Is graphite sufficiently thermally conductive, such that it does not form hot spots leading to substantial reradiation from the cavity or thermal stresses in excess of graphite's fracture strength?
- To construct an efficient receiver, thermal losses must be quantified. Radiation and convection from the cavity aperture as well as off the surfaces of the insulation are primary loss mechanisms, but it is not clear *a priori* which loss mechanisms will dominate, or which options are available to mitigate such losses.
- The radiative heat flux on different parts of a cavity receiver can potentially vary by orders of magnitude and is highly dependent on receiver geometry. Reradiation depends on the temperature at a given location in the receiver, which is in turn affected by several factors, such as the incident flux at that particular location. Thus, another question is to what extent can the temperature/radiation distribution in the cavity be manipulated to improve efficiency by suppressing reradiation?

In the following sections, we describe a full, steady-state model constructed to evaluate the aforementioned effects and to assess the sensitivity of a receiver to each of these various parameters. The parameters altered include the thermal conductivity and emissivity of both graphite and insulation, dimensions and receiver geometry, LMHTF flowrate, and the value of convective coefficient on both the outer insulation surface and the surfaces inside the receiver cavity.

2. Methodology

To create an efficient receiver geometry, a base-case receiver was