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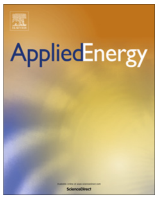

Numerical investigation on the thermal performance of molten salt cavity receivers with different structures

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HIGHLIGHTS

- Numerical method was developed to calculate the thermal performance of the molten salt cavity receiver.
- Complicated photo-thermal conversion process in the molten salt receiver was studied in detail.
- Optimum cavity geometry was obtained with a lesser depth for improving thermal efficiency.

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ABSTRACT

The geometry of a solar cavity receiver affects the absorption of incident solar energy and the temperature distribution on the absorber tube panels, and hence affects the operation stability and efficiency of the solar receiver. A modified combined computational method was proposed to investigate the thermal performance of the three dimensional (3-D) molten salt cavity models in steady state. This computational method was also used to calculate the thermal performance of the receiver in the Molten-Salt Subsystem/Component Test Experiment (MSS/CTE) in the United States, and the results agree well with published data. Molten salt cavity receivers with different heights were studied. The results show that a too-low or too-high height leads to low thermal efficiency of a receiver. Therefore, appropriate heights shall be chosen to enable receivers achieve relatively high efficiencies and reach low temperatures. The molten salt cavity receivers with different cross-sections in the chosen heights were then studied, to obtain a high-efficiency cavity receiver structure without increasing the inner surface area or the depth of the cavity, under the condition that the molten salt cavity receivers were in the same perimeter of the cross-section, aperture size, cavity height, tube panel and fluid flow layouts but different cavity depths. When only the lengths of the back walls next to the side walls had been increased, the thermal efficiency decreased first and then increased with the depth decreasing, which reached the lowest value when the depth was 2.71 m. When the depth of the modified receiver is small enough, its thermal efficiency can be higher than that of the MSEE receiver. When only the lengths of the two walls adjacent to the aperture had been increased, the thermal efficiency increased with the depth decreasing, and was always higher than that of the receiver in the Molten-salt Electric Experiment (MSEE) in the United States. The thermal-efficiency difference between the two arrangements of the side walls decreased with a decrease in the cavity depth. The cross-section of the MSEE receiver is similar to that of the receiver in the molten salt electric experiment by Sandia National Laboratories. Under the condition of side-on wind at a velocity of 8.3 m/s, the thermal efficiency of the modified cavity with the minimum depth is 2% higher than that of the MSEE cavity with the maximum depth. The convective heat loss is 3.1% lower, while the radiative and reflective heat losses changed slightly. Therefore, the modified cavity in the present study is capable of achieving a higher efficiency with a less depth.

1. Introduction

The energy and environmental crisis has been promoting the exploitation of clean and renewable energy. Concentrating solar power (CSP) systems use combinations of heliostats or lenses to

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Nomenclature

V	wind velocity, $\mathrm{m{\cdot}s^{-1}}$
D	cavity depth; diameter, m
N	number
Q	heat rate, W
x, y	cartesian coordinates
R	random number
RD	radiative heat transfer factor
M	number (of units)
S	area, $\mathrm{m^2}$
T	temperature, K
h	heat transfer coefficient, $\mathrm{W{\cdot}m^{-2}\,K^{-1}}$
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
f	friction factor
u	velocity component, $\mathrm{m{\cdot}s^{-1}}$
Cp	specific heat, $\mathrm{J{\cdot}kg^{-1}\,K^{-1}}$
l	tube length
g	acceleration due to gravity, $\mathrm{m\,s^{-2}}$
G_k	generation of k, $\mathrm{kg{\cdot}m{\cdot}s^{-3}}$
H	cavity height, m
L	length, m

Greek symbols

λ	thermal conductivity, $\mathrm{W{\cdot}m^{-1}\,K^{-1}}$
ε	emissivity
α	absorptivity
θ	zenith angle, degree
φ	circle angle, degree
σ	Stefan-Boltzmann constant, $\mathrm{W{\cdot}m^{-2}\,K^{-4}}$
ρ	density, $\mathrm{kg{\cdot}m^{-3}}$
μ	dynamic viscosity, $\mathrm{kg{\cdot}m^{-1}\,s^{-1}}$
μt	turbulent eddy viscosity, $\mathrm{kg{\cdot}m^{-1}\,s^{-1}}$
κ	turbulence kinetic energy, $\mathrm{m^2{\cdot}s^{-2}}$
ε	turbulence dissipation rate, $\mathrm{m^2{\cdot}s^{-2}}$

Subscripts

t	tube
c	cavity
i	inner
o	external
pa	pass
tu	tube per pass
Ap	aperture
Ref	reflective
$loss$	heat loss
Rad	radiative
$Conv$	convective
$Cond$	conductive
w	out wall
f	heat transfer fluid
a	average
s	cavity surface

concentrate direct normal irradiance (DNI), the concentrated solar energy can be used directly to generate electricity or produce fuels, and can be stored in the form of sensible or latent heat to be used in various downstream technologies. The most common CSP technologies include parabolic-trough collectors, linear Fresnel reflector systems, power towers or central receiver systems, and dish/engine systems [1]. Central receiver systems (CRSs) use large heliostat fields and solar receivers mounted on top of a tower. The high concentration ratio of CRSs makes it theoretically possible to reach a high temperature and achieve a high power level. Heat Transfer Fluids (HTF) in the receiver of a solar power tower system, are usually water/steam, molten salts, or air [2]. CRSs use molten salt as the heat transfer fluid, in the receiver and for heat storage, enabling solar collection to be decoupled from electricity generation. Those systems employ on-line storage systems and buffer the electric power generation system from cloud transients experienced by receivers, thus providing an inexpensive source for thermal storage and a constant temperature heat source for the steam generation [3]. The pioneer systems, with molten salt as the heat transfer fluid, were adopted in the THEMIS tower (2.5 MW) in France [4], the MSEE (1 MW) [5], the subsequent experiment MSS/CTE (4.5 MW) [6] and the Solar Two (10 MW) in the U.S. Based on the lessons learned from Solar Two, some commercial-scale plants using molten salt as the heat transfer fluid in the receiver and for heat storage, have been built, such as the Gemasolar power plant (19.9 MW) [7] and the Crescent Dunes tower-type solar power plant (110 MW) [8].

The solar thermal central receiver (SCR) which converts solar energy into thermal energy, is one of the most important components of the tower-type solar power system. According to the geometrical configuration, there are basically two designs, external and cavity-type receivers [1]. Cavity-type receivers are of higher efficiency compared with external receivers, as it is much more difficult for absorbed energy to escape from the cavity [9]. Meanwhile, heat loss from apertures is inevitable, and convective and radiative losses influence the efficiency of the receiver. The thermal performance of the cavity receiver was numerically studied by many researchers. Fang et al. [10,11] proposed a new method to simulate the thermal performance of a water/steam cavity receiver. The thermal performance of a six-side prism cavity under different wind conditions was simulated. The energy needed by the aperture during the receiver start-up was calculated by adopting a modified calculation method, which was built based on the previous model. It was found that when the receiver was under the side-on wind condition, the air velocity inside the cavity and the heat loss of the receiver reached the maximums. The convective heat loss is the dominant heat loss pattern even at the end of start-up. An experimental platform was also designed and built by the same author for testing the thermal performance of a water/steam cavity receiver [12]. It was found that the thermal efficiency increases with increasing mass flow rate within a certain range, and that the increase is more remarkable at low mass flow rates. Some scholars have studied the thermal performance of the molten salt receiver. Yang et al. [13] used the computational fluid dynamics to study the heat transfer characteristics of a single molten salt tube receiver. They indicated that the heat transfer coefficient was higher than the prediction by the Sieder-Tate equation and that the value of the local Nu number was almost unchanged at different cosine angles. Li et al. [14] established an easy-to-use global steady-state model to calculate heat loss from each part of the molten salt cavity receiver. Zhang [15] presented a dynamic mathematical model of the molten salt cavity receiver that couples the conduction, convective and radiative heat transfer processes in the receiver. A model of molten salt cavity receivers for design and off-design performance analyses was developed by Tehrani et al. [16]. A combined control approach was proposed to maximize receiver operation range.

The concentrated solar radiation is absorbed by interior surfaces after multiple reflections within the cavity. Some authors

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