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Heat transfer performance evaluation of a large-size cavity receiver in the solar power tower plant based on angle factors

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ABSTRACT

The thermal performance of a cavity receiver in the solar tower power plant crucially relies on the spatial relationship of its polyhedral geometric inner surfaces. So far, it has always been a focus to propose a model coupling the convection and radiation heat transfer for a large-size receiver. Based on the net energy exchange and thermal equilibrium principle, a radiation heat transfer model in terms of the angle factor equations of inner surfaces in the receiver was developed in this work. The finite difference method with an automatic mesh generation technique was employed to disperse the angle factor equations of inner surfaces in the receiver. Consequently, the thermal performance of the cavity receiver was evaluated while convection heat transfer between the receiver inner surfaces and ambient air was to consider with the available convection correlation. The results showed that the thermal efficiency of the cavity receiver increased with the increase of incident heat flux. When the width-depth ratio decreased, the cavity efficiency increased first and then decreased. With regard to different receiver structure parameters, the total heat loss of the receiver varied differently with the increase of the heat absorption area to the aperture area ratio. Meanwhile, the design of the cavity receiver structure in the MW solar power tower plant in Yanqing, Beijing was optimized according to the model proposed.

1. Introduction

During the past several decades, the solar tower power technology was widely approved to be feasible due to its comprehensive superiority on higher efficiency, relatively lower capital cost and longer campaign life. As one of significant components of this Concentrating Solar Power technology (CSP), the cavity receiver can directly determine the safety, stability and economy of the whole tower power system. However, since the large-scale dimension of the receiver and the high concentrated solar flux on it, there is a complex heat transfer process involved in radiation, convection and conduction in the receiver. These heat transfer process can strongly affect the thermal performance of cavity receivers. Referring to the available investigations, the primary study of cavity receivers has been focused on the convection and radiation heat transfer process. Much work has been done on convection heat transfer in solar cavity receivers, some promising results by which already has been obtained. The analysis model was provided by Clausing (1981) to assess the convection heat transfer, and then Clausing (1982) optimized and verified the feasibility of model by the demonstration test. Based on the study above, Clausing et al. (1987)studied the influence on the convection heat transfer with different receiver cavity size obtained by the demonstration test. LeQuere et al. (1981), Koenig and Marvin (1981) proposed an experimental correlation formula on the natural convection heat transfer of solar cavity receiver. Stine and McDonald (1989), Harris and Lenz (1985) and Kaushika (1993) studied the influence on the convection heat transfer with different inclined angle and structure of receiver. Paitoonsurikarn et al. (2004) performed three-dimensional numerical simulation for the cavity receiver to study the influence on the convection heat transfer with different inclined angle and structure of receiver. Sendhil Kumar and Reddy (2007) built two-dimensional numerical simulation to obtain the natural convection heat transfer.

With regards to the radiation heat transfer in a cavity receiver, a prevailing method employed is the Monte Carlo method (MCM), which is also called ray tracing method and based on a mathematical probability model (Tan et al., 2006). The essential process to calculate radiation heat transfer with the MCM can be described as follows. The radiation heat transfer could be divided into many sub-processes, including emission, transmission, reflection and

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Nomenclature

A_i	outer surface area of heating surface i/m^2
A_{ni}	contact area of working fluid and tube wall of heating surface i/m^2
a	bottom width of cavity receiver/m
$F_{i\text{-}j}$	angle factor of heating surface i to j
H_i	total radiation force entered into heating surface i/W m^{-2}
h	vertical depth of cavity receiver/m
h_{lf}	convection heat transfer coefficient of working fluid in tubes/kW m^{-2} K^{-1}
h_{mf}	mixed convection heat transfer coefficient of outer face of heating surface and ambient air/kW m^{-2} K^{-1}
h_{NB}	the bubbly boiling heat transfer coefficients in tubes/kW m^{-2} K^{-1}
h_t	the height of the solar tower/m
J_i	effective radiation force of heating surface i/W m^{-2}
m	width-depth ratio of cavity receiver
Nu_{mf}	mixed convection heat transfer Nusselt number
r	radial distance of two radiation surfaces
T_i	temperature of heating surface i/K
T_{sat}	temperature of working fluid in tube/K
T_{air}	temperature of ambient air/K
u_f	wind velocity/m s^{-1}
ε	emissivity of heating surface i
θ	included angle of heating surface i and its normal direction
κ	absorptive area to incident area ratio of cavity receiver
σ	surface tension coefficient/N m^{-1}
γ	latent heat of vaporization/kJ kg^{-1}
μ	viscosity/Pa s
Δt_{sat}	degree of superheat/K
Δp_{sat}	saturation pressure difference of the tubes wall/Pa

absorption. By fabricating the probability model of each sub-process, the radiation heat transfer in a cavity can be solved. Based on MCM, Steinfeld and Schubnell (1993) studied the influence of baffles on the property of a parabolic cavity receiver under optimal parameters. Sootha and Negi (1994) investigated the optical design of a tubular receiver and the property of solar radiation concentration using MCM. They also presented the local heat flux distribution and the maximal temperature zone of the tubular receiver surface. Spirkl et al. (1998) utilized MCM to explored the effect of a kind of asymmetric reflection from a heliostat field in a high latitude area in a spherical receiver, proposing that the slant conical reflection was more appropriate for the spherical receiver. Pancotti (2007) proposed an optimal back-ray tracking model based on MCM to simulate the reflection of the absorbing plane at solar receivers. He obtained the distribution of radiation heat flux in the receiver through the model. Shuai et al. (2008) investigated the radiation thermal performance of a cavity receiver in a dish solar power plant using MCM, taking a full consideration of the influence of baffles and receiver heated surface angles. Meanwhile, they proposed a model of a reverse pyriform cavity receiver on the basis of constant heat flux. Aiming at the solar reflection concentrator in a large-scale dish solar power plant, Shuai et al. (2006) studied the effect on receiver performances depended on sunlight non-parallelism and heliostat tracking precision with numerical simulation. Then they simulated the distribution of collected solar in receiver further using MCM. Fang et al. (2011) utilized MCM to simulate the absorption and reflection of rays in a cavity receiver, obtaining the distribution of reflected solar heat flux in the cavity. Meanwhile, the convection heat transfer of working fluid and ambient air was calculated using convection heat transfer model. Fuqing et al. (2011) simulated the spread of sunlight in a cavity receiver by means of MCM. They also investigated the influence of incident angle and porous media property on the distribution of heat flux in a metal foam receiver. Wang et al. (2000, 2005) studied the high-temperature solar parabolic tracking concentrator and the distribution of heat flux in a vacuum tube in a receiver with modeling and experiments.

Nevertheless, the Monte Carlo method has no demonstrable physical significance because of its basis of a mathematical probability model. Besides, in order to gain high-precision results emission and absorption of tens of thousands of rays need to be tracked when simulating a large size receiver using MCM, which could cost huge calculation amount in time and memory inevitably. Moreover, the description for the radiation heat transfer in the receiver is not complete by MCM because it only considers the activity of incident rays, not including the radiation force of cavity surfaces themselves. Actually, a statistical error will be imported due to the probability statistic model used by MCM.

The actual radiation heat transfer in a hexahedral cavity receiver is a coupled process involving multiple surfaces due to its spatial structure. Therefore, referring to the interaction of multi-surfaces radiation in a large size cavity receiver, the objective is to propose a radiation heat transfer model based on the net heat method and thermal equilibrium principle in this study. By combining the finite difference method and an automatic mesh-generating technique, a set of angle factor equations of the polyhedral structure in a receiver are to be solved to obtain the heat transfer characteristics of the receiver. The method on the basis of angle factors is to be expected to overcome the disadvantages of the Monte Carlo method on huge amount in time and memory when calculating the radiation in a cavity receiver. Furthermore, by considering the convection heat transfer between the receiver inner surfaces and ambient air with the available convection correlations, a comprehensive model of heat transfer in the cavity receiver is completed. Later, regarding to the cavity receiver of the MW solar power tower plant in Beijing, the thermal efficiency of the cavity receiver is to be evaluated, and the cavity receiver structure is to be optimally designed according to the model proposed.

2. Modeling

2.1. Radiation-convection heat transfer model in a cavity receiver

Generally, the geometric prototype of a cavity receiver in a tower solar thermal plant is a hexagonal-prism cubic structure. Because all of the heated tube panels are attached at the inner surfaces of the receiver, the mutual spatial geometries of its six inner surfaces determines largely its radiation thermal performance. Actually, the cavity receiver is an artificial gray body by its non-orthogonal inner surfaces to enhance the absorptivity for the solar irradiation entering from the aperture, and concentrated by the heliostat field, as shown in Fig. 1. Since the amount of radiant heat lost or received by the receiver is the algebraic sum of all radiant fluxes exchanged by its any inner surface with the surrounding sources, it can be calculated from the measured temperature of