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Numerical simulation on convective thermal loss of a cavity receiver in a solar tower power plant

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ABSTRACT

A numerical simulation model is employed to evaluate the convective thermal loss of a one-point focusing central cavity receiver with a trapezoidal cross-section cubic structure in a solar tower power plant. Due to being laid at the top of the solar tower with a height of several decameters, the cavity receiver is suffering from low temperature and cold wind from its special ambient environment. Consequently, the effect of the natural convection on its thermal performance could not be neglected while the one of the turbulent flow field inside the cavity receiver entering from its aperture is comparably significant. Therefore, a three-dimensional turbulent flow model is established to calculate mixed convection heat loss which is usually used to evaluate the thermal performance. Under the certain wall temperature condition inside the receiver, the receiver laid inclination, the wind incidence angle and wind speed around the receiver are particularly considered in the proposed convection heat loss model. The simulation results show that the trend of mixed convection heat loss changing with the laid inclination is similar to that of natural convection when wind speed is relatively low. The maximum mixed convection heat loss happened in the case of wind direction $\alpha = 90^\circ$, and minimum at $\alpha = 0^\circ$. Under some certain windy condition, mixed convection heat loss may be lower than the natural convection value. In order to explain the variation of mixed convection heat loss, the profiles of flow velocity vector field and the temperature contours around the receiver are illustrated accordingly for each case. Furthermore, the flow pattern and turbulent vortex for the flow field are also presented. Finally, a heat transfer coefficient correlation considering receiver laid inclinations, wind speed and wind incidence angle was proposed to estimate the convection heat loss.

1. Introduction

Concentrating solar power (CSP) is becoming a promising technology for future alternates of traditional fossil fuel generating. Among four major types of CSP technology, which are linear Fresnel reflectors, center towers, parabolic troughs and parabolic dishes, the center tower system is assumed as the lowest cost way for CSP technology in the large-scale power generation. Consequently, this kind of CSP technology is getting more and more attention for high conversion efficiency, high operation temperature. As known, in a solar tower system many mirrors, named as heliostat, reflect sunlight onto a central receiver, which is usually laid at the top of the solar tower with a height of several decameters, in which working fluid is heated to produce steam for generating electricity. Under the normal operation conditions, the receiver is suffering from low temperature and cold wind around its special ambient environment. Therefore, the thermal efficiency of the central receiver is an important parameter for the performance of a solar tower system. Moreover, the type of the central receiver plays an important role in evaluating the efficiency of the CSP system. There are some types for the central receiver such as external tubular receiver, cavity receiver and volumetric receiver. For the sake of a lower heat loss, the cavity receiver with one-target focusing is widely employed in the solar power tower system, such as SP10, SP20 in Spain and the Dahan power plant in China. The cavity receiver is an inner absorbing structure with an aperture at one side, by which the concentrated incident radiation from the heliostats field enters the inner of the receiver and is absorbed by the heated panels attached at its inner walls. So far, lots of studies focus on the thermal efficiency of a cavity receiver. Logically, the thermal efficiency of the receiver is related to various heat losses, including convection and radiation heat loss between the cavity and its ambient air through the aperture, and conduction

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Nomenclature

A	heat transfer area of receiver (m^2)
c_1	coefficient in $k-\varepsilon$ model
c_2	coefficient in $k-\varepsilon$ model
g_i	gravitational acceleration component in i, j, k direction ($m\ s^{-2}$)
Gr	Grashof number
h	heat transfer coefficient ($W/m^2\ K$)
k	pulsation kinetic energy ($m^2\ s^{-2}$)
l	characteristic length (m)
n	index number
Nu	Nusselt number
Pr	Prandtl number
$Qconv$	convection heat loss of the receiver (W)
Re	Reynolds number
T	air temperature (K)
T_w	the surface temperature of receiver (K)
T_c	the reference temperature (K)
T_∞	ambient temperature (K)
μ	dynamic viscosity coefficient of air (Pa s)
x_i, x_j, x_k	distance component in i, j, k direction (m)
u_i,u_j, u_k	velocity component in i, j, k direction ($m\ s^{-1}$)
μ_t	vortex dynamic viscosity coefficient (Pa s)
v	kinematic viscosity coefficient of air ($m^2\ s^{-1}$)

Greek symbols

θ	receiver inclination (°)
α	wind direction (°)
σ_k	coefficient in $k-\varepsilon$ model
σ_T	coefficient in $k-\varepsilon$ model
σ_ε	coefficient in $k-\varepsilon$ model
ε	turbulence diffusivity ($m^2\ s^{-3}$)
ρ	density of air ($kg\ m^{-3}$)
ρ_c	reference density of air ($kg\ m^{-3}$)
α_v	volume expansion coefficient (K^{-1})
λ	thermal conductivity of air (W/m K)
ΔT	difference temperature (K)

heat loss through the insulation layer attached the outside of the cavity. It is obvious that the conduction heat loss and radiation heat loss are independent on the receiver laid inclination and could be predicted reasonably by many available proposed models (Stine and McDonald, 1989; Leibfried and Ortjohann, 1995). However, convection heat loss could not be easily calculated due to the complexity of buoyant flows depending on surrounding wind velocity, ambient temperature, the inner wall temperature and the receiver structure.

In general, lots of studies attribute the thermal loss of the receiver to nature convection with its ambient air. Various natural convection correlations for the cavity receiver have been proposed by previous numerical or experimental studies (Koenig and Marvin, 1981; Siebers and Kraabel, 1984; Stine and McDonald, 1989; Sendhil Kumar and Reddy, 2007, 2008; Reddy and Sendhil Kumar, 2009; Wu et al., 2010). These correlations consider the receiver laid inclination, the aperture size and other parameters. And, as noted, the universality of those correlations is limited due to their dependence on special geometrical structures of receivers. Among early famous studies, Clausing (1981, 1983) and Clausing et al. (1987) proposed and revised continuously an analysis model of estimating natural convection heat loss of a small scale receiver, a 0.4-m-high cubic cavity. He noted that air heated by the receiver inner wall was an important factor leading to natural convection heat loss in comparison with mass and energy transferring through the aperture. By contrast, a large number of researchers considered that the mixed convection is a major heat loss way of the receiver. Many of them are about small-size cavities for dish systems. Ma (1993) conducted experiments on convection heat loss of a cylindrical cavity receiver with an internal diameter of 0.66-m under windy conditions, and the results showed that the changing treads of convection heat loss at wind speeds greater than 3 m/s were similar to that of no-wind cases. It was also found that convection heat loss from the receiver is substantially increased by the presence of side-on wind for all receiver inclinations. Paitoonsurikarn and Lovegrove (2002, 2003, 2006) firstly carried out a three-dimensional simulation of cavity receiver to investigate the effect of receiver structure and inclinations on the natural convection heat loss. The receiver consists of a frustum cavity with an aperture diameter of 0.20-m. After that, they studied the mixed convection heat loss under head-on and side-on wind conditions. The results showed that the local wind speed at the receiver aperture was the maximum when the freestream wind was parallel to the aperture plane. It was also found that some wind speeds reduced heat loss over the nature convection level. Some experiments and simulations were carried out to study the convective loss of a downward facing dish receiver with a length of 0.5-m, an internal diameter of 0.3-m (Prakash et al., 2009). The results indicated that the wind induced convective loss is larger than that of no-wind at all receiver inclinations except 0° receiver inclination angle. And the head-on wind led to greater convection heat loss than that of side-on wind. A cylindrical solar cavity receiver with a diameter of 0.28-m, a depth of 0.32-m was investigated in a high temperature dish system. The simulation on combined the free-forced convection heat transfer of the cavity was undertook, and it was found that under some certain windy conditions, the mixed convection heat loss reduced below the natural convection value (Xiao et al., 2012).

There are also a small number studies focusing on the large-size cavity receiver for solar tower system by means of numerical simulation or experiment methods. A cavity receiver with the heat-absorbing surface of 5.6-m in length and 3.5-m in width was investigated by Mcmordie (1984) in different wind speeds. Tan et al. (2009) studied wind effect on the performance of a solid particle solar receiver with and without the protection of an aerowindow. The receiver had a dimension of 2-m × 1.58-m × 3-m with an aperture of 1.5-m × 1.5-m. The results indicated that the aerowindow formed by an air jet with velocity of 8 m per second could enhance the cavity efficiency in many cases, especially when the wind speed was not very high. Fang et al. (2011) proposed a combined calculation method to evaluate the thermal performance of a cavity receiver with the aperture of 4-m × 4-m. It was found that the wind incidence angle or speed could obviously affect the air velocity inside the receiver and the air velocity reached the maximum value when the wind came from the side of the receiver. Robert et al. (2014) studied the impact of head-on wind and side-on wind on a large cavity receiver with different inclinations. They found that in some cases, a reduction of the heat loss was observed when wind was flowing parallel to the aperture plane. And, in case of an inclined cavity wind had a larger impact on the convective loss than that of a horizontal cavity. A solar gas reformer with the size of 2.4-m × 1.2-m was presented in Liovic's simulation (Liovic et al., 2014). It was concluded that the receiver geometry, inner wall temperature and wind interact resulted in