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Field synergy principle analysis for reducing natural convection heat loss of a solar cavity receiver

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ABSTRACT

Due to the operating temperature from 900 K to 1300 K produced by the concentrating ratio over 2000 in solar parabolic dish-engine system, the natural convection heat loss driven by the buoyancy force of air contributes an important role in the energy loss of cavity receiver. 3-D numerical simulations were performed and the results are analyzed from the novel viewpoint of field synergy principle (FSP) in order to study the heat transfer and fluid flow characteristics in natural convection heat loss of cavity receiver. The effects of geometric parameters, including the inclination angle, aperture size, aperture position and cavity geometric shape on the natural convection heat loss of cavity receiver were examined. The FSP analysis on the simulation results demonstrates that FSP can well explain the reduction mechanism for natural convection heat loss of cavity receiver because the smaller inner production of velocity vector and temperature gradient always corresponds to the lower Nusselt number occurred in the cases with lager inclination angle, smaller aperture size, lower aperture position and frustum-cylinder cavity, respectively. Therefore, the reducing natural convection heat loss attributes to the weakening synergy between velocity vector and temperature gradient. In addition, the local heat transfer performance is studied by the presented distributions of heat transferred via fluid motion, where more interesting natural convection heat loss characteristics of cavity receiver and the detailed explanations were provided. The results of this work offer benefits for the development of theory and technique about reducing natural convection heat loss of cavity receiver.

1. Introduction

In the solar thermal technologies, solar parabolic dish-engine system has demonstrated the highest efficiency, producing a concentrating ratio over 2000 and operating temperature from 900 K to 1300 K [1,2]. A cavity receiver is often located at the focal plane of parabolic dish concentrator to retrieve high temperature. Heat pipe receiver has become a more recent type of cavity receiver due to its appealing advantages including the improvement of reliability by the specificity of temperature uniformity and the lightening and downsizing of receiver by the effective use of phase change thermal storage materials (sodium, potassium or other liquid metals) [3]. The heat losses from the cavity receiver due to the radiation, convection to the air and conduction through the insulation can drastically reduce the system performance, in which the radiation heat loss followed by natural convection heat loss plays a dominant role [4]. For heat pipe receiver, under the isothermal work condition, it has been concluded that the effect of thermal radiation on the natural convection heat loss characteristics can be neglected [5] and conduction and radiation heat losses can be readily determined [6]. On the other hand, the determination of convection heat loss is rather difficult due to the complexity of the temperature and velocity fields in and around the cavity [7,8]. Therefore, the convection heat transfer and fluid flow characteristics in heat pipe receiver need to be understood in detail so that the theory and technique about reducing natural convection heat loss of cavity receiver can be developed.

Many numerical investigations have been conducted previously to investigate the natural convection heat loss of cavity receiver. Stine and McDonald [9] revised the Nusselt number correlation suggested by Siebers and Kraabel [10] and proposed a model incorporating aperture size, cavity surface temperature and inclination angle of cylinder cavity receiver. Based on a physics understanding for the natural convection heat loss of cubical cavity receiver, Leibfried and Ortjohann [11] put forward a more general correlation involving the definition of characteristic length,

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Nomenclature

d	characteristic length, m
e	enthalpy, J/kg
g	acceleration of gravity, m/s^2
c_p	specific heat, J/kg K
h	heat transfer coefficient, W/m^2 K
p	pressure, bar
T	temperature, K
$\vec{U}$	velocity vector
$\vec{n}$	outward normal unit vector
Nu	Nusselt number
Ra	Rayleigh number
HT	heat transferred via fluid motion, W/m^2
OR	opening ratio
DR	displacement ratio
D	diameter, m
H	distance between the center of aperture and the base of cavity, m
$\mathrm{IPVT_m}$	average inner production of velocity vector and temperature gradient, K/s
u, v, w	velocity component in x, y, z-directions
x, y, z	Cartesian coordinate

Greek symbols

α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, m/K
μ	dynamic viscosity, pa s
ρ	density, kg/m^3
ν	kinematic viscosity, m^2/s
λ	thermal conductivity, W/m K
φ	inclination angle, °
ξ	universal variables u, v, w and T

Subscript

w	wall
f	fluid
c	cavity surface
a	air
ap	aperture
atm	atmosphere

buoyancy height and the convective zone area. In order to develop a model that can reliably predict the natural convection heat loss of cylinder cavity receiver at all inclination angles, Paitoonsurikarn and Lovegrove [12] introduced a concept called the ensemble cavity length as the characteristic length. Sendhil Kumar and Reddy [13] used 2-D and 3-D numerical models to assess the natural convection heat loss in a modified cavity receiver. By the comparison of natural convection heat losses in the cavity, semi cavity and modified cavity receivers, Sendhil Kumar and Reddy [14] found that the modified cavity receiver was the most efficient. The numerical results carried out by Wang and Siddiqui indicated that the aperture size and different inlet/outlet configuration of the cavity receiver had a considerable impact on the receiver wall temperature [15]. To validate the proposed correlations, experimental methods were used by Taumoefolau et al. [16], and Prakash et al. [17]. These studies concluded that each correlation had a limited range of applicability and inherently depended on particular cavity geometry and operating condition. Therefore, the heat transfer and fluid flow characteristics in natural convection heat loss should be further studied.

As mentioned above, there exists extensive literature dealing with the natural convection heat loss of cavity receiver [9–17] that they mainly focused on assessing the performance of natural convection heat loss. However, the natural convection heat loss mechanism is rarely reported, which is worthwhile being studied and can serve as a guideline to design and optimize the high efficiency cavity receivers. Guo and co-works [18] proposed a concept called field synergy principle (FSP) for the 2-D parabolic convective flow. This principle indicated that the heat transfer performance depended not only on the velocity field and the temperature field, but also on their synergy related to the inner production of velocity vector and temperature gradient. In Ref. [19] FSP was extended to the 3-D elliptic flow. Since FSP was proposed, drawing researchers' extensive concern, it has been successfully applied to analyze the heat transfer models in various fields. Guo et al. [20] performed a 3-D numerical simulation to investigate the heat transfer characteristics of the tubes fitted with helical screw-tape inserts based on FSP. It was found that the periodic changes of the flow field induced by the alternate right and left twists improved the synergy between velocity vector and temperature gradient, which eventually led to the better heat transfer performance. In Ref. [21] the thermal mixing efficiency of two-dimensional, steady-state, low Reynolds number flows in a Y-shape channel was investigated, and the results revealed that the mixing efficiency was closely related to the intersection angle between velocity vector and temperature gradient. Cheng et al. [22] used the field synergy number as objective function to optimize electronic cooling, and it was found that the conjugate heat transfer increases as the field synergy number increases.

The present work attempts to explain the reduction mechanism for natural convection heat loss of cavity receiver from the novel viewpoint of FSP. The effects of geometric parameters, including inclination angle, aperture size, aperture position and cavity geometric shape on natural convection heat loss are examined. The variations of natural convection heat loss with the geometric parameters are analyzed based on FSP. The published literature relating to FSP are mainly focused on overall heat transfer performance, while the local heat transfer performance has not received much attention. It will be analyzed in this work by the presented distributions of local heat transferred via fluid motion. Using the analysis based on FSP, the reduction mechanism for natural convection heat loss of cavity receiver is explored and more interesting natural convection heat loss characteristics are also found. This work provides a better insight into natural convection heat loss in the cavity receiver of solar parabolic dish systems.

2. Field synergy principle

For an elliptic convective heat transfer case as shown in Fig. 1, the integral form of energy governing equation can be rewritten as Eq. (1) based on the assumption of steady state [18]:

$$\iint_{\Omega abcdea} \rho c_p (\vec{U}\cdot\nabla T)\mathrm{d}x\mathrm{d}y = \int_{bcd} \vec{n}\cdot\lambda\nabla T\mathrm{d}S + \int_{efa} \vec{n}\cdot\lambda\nabla T\mathrm{d}S + \int_{ab} \vec{n}\cdot\lambda\nabla T\mathrm{d}S + \int_{de} \vec{n}\cdot\lambda\nabla T\mathrm{d}S \qquad (1)$$

where ρ is the fluid density; c_p the specific heat capacity at constant pressure; λ the thermal conductivity; $\vec{U}$ the velocity vector; ∇T the