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A comprehensive model for uniform heat flux inside cavity receiver with air-carbon mixture

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Abstract

Cavity receiver is one of the main components of efficient concentrating solar collector systems. It has the ability to operate at relatively higher temperature and efficiency. The safety and thermal efficiency of solar cavity receiver can affect the efficiency of the whole power system. However, the non-uniform distribution of heat flux and temperature inside the cavity tends to cause the operation instability and bring damage to the tube as well. In the present work, a comprehensive numerical model was developed by coupling Monte Carlo Ray Tracing (MCRT) and Finite Volume Method (FVM) to simulate the thermal performance of a 2D square solar cavity filled with air-carbon particle mixture. Firstly, the complicated photon transmission in the air-carbon particle mixture absorber is simplified as the transmission process in the statistically homogenous and isotropic turbid media. The solar heat flux distribution from the aperture to the wall is simulated by MCRT, and the photo-thermal convection process in the cavity receiver is modeled by FVM. Then the two parts are coupled in the cavity receiver by transferring the absorbed energy computed by MCRT to FVM, and this energy is applied as a source term of the energy equation in the FVM part. Based on this model, the temperature and heat flux characteristics of the cavity receiver were studied at various carbon densities. The result indicated that the air-carbon particle mixture can actively take part in the radiation and it appears that it has a remarkable effect on the temperature homogenization. It decreases the temperature of wall 3 dramatically and increases the temperature of wall 2 and wall 4. The relationships between the temperature unevenness and the number particle density were also analyzed. The temperature unevenness on the wall 3 drops most with the increase of number density of carbon particle, from 25.0K to 2.4K. The unevenness of temperature on the top and bottom walls also decreases slightly by 3K. In addition, the present model is proved to be accurate and reliable for studying the complex energy convection process in the cavity filled with air-carbon particle mixture. The result of the cavity receiver study can also provide a method to effectively improve the uniformity of the heat flux distribution on the wall.

Keywords: solar cavity receiver; non-uniform; air-carbon particle mixture; homogenization;Monte Carlo ray tracing ;Finite volume method

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1. Introdution

Solar receiver, which converts solar energy into thermal energy, is a key component in a tower power system. Its thermal performance has direct relationship with the thermal efficiency of the whole power generation system. One possible configuration usually used is cavity receiver because of its large surface area and low heat loss compared with the external receiver. There is an aperture in front of the cavity, through which the sunlight concentrated by heliostats projects onto the inner surfaces of the receiver. The solar cavity receiver regularly operates in severe working conditions. The incident solar flux on the aperture plane of the cavity shows high density and non-uniformity due to concentration of heliostats. This, therefore, has a great effect on heat flux and wall temperature distributions inside the receiver. The non-uniform heat flux on the surface of absorber tubes arranged inside the receiver will lead to large wall temperature difference along tube axial direction. Uneven thermal expansion and thermal stress will occur on tubes due to temperature gradient, affecting the reliable operation of the receiver and reducing its service life.

So far, a few studies have focused on improving surface heat flux and temperature uniformity inside cavity receivers. Montes[1] analyzed a new design of central solar receiver, which optimizes the heat transfer on the absorber surface. Chang[2] developed a model combining radiation, convection and conduction heat transfer modes to simulate the thermal performance of a molten salt cavity receiver for the different types of flow layouts. The result showed that the center side flow layout, which represents the molten salt flowing from the center of the receiver panels toward the sides, has the highest homogeneous molten salt and external tube temperatures with no obvious high or low temperature zones in absorber panels. Tu[3-5] proposed an optimized distribution of absorptivity in the solar wavelength band for the absorber surfaces to improve the uniformity of surface heat flux distribution. Salomé[6],Besarati[7],Yu[8] and Sánchez-González[9] analyzed the effect of aiming strategy on the homogenization of incident solar flux. The distribution of solar flux indicated much more uniform after the multi-focal point strategy was employed. As the air-carbon mixture demonstrates the great ability to participate in the solar radiation and infrared radiation, to a certain extent, filling this kind of mixture into solar cavity ought to decrease the non-uniformity of heat flux. The main focus of this work is to raise a homogenization method and develop a new model, which to simulating the solar radiation and energy convection process in a square solar cavity filled with air-carbon particle mixture. A calculation model coupled the Monte Carlo Ray Tracing method (MCRT) and Finite Volume Method (FVM) was established to solve the radiation and the convection inside the cavity. The temperature field and heat flux field of the cavity under different density conditions of air-carbon particle mixture were calculated. The relationship between the density of air-carbon particle mixture and the uniformity of heat flux inside the cavity was analyzed as well.

2. Calculation method

A combined calculation method was established to evaluate the thermal performance of the solar cavity. The method coupled two aspects of heat transfer processes: To combine the MCRT and FVM models, firstly, match the different quadrilateral girds on the computational domain of MCRT and FVM. The then solar fluxes in receiver are computed by MCRT and converted to a data file that can be read by the ANSYS FLUENT 15.0. Finally, the fluxes absorbed by the wall read in the FVM model are treated as the boundary conditions, and the heat fluxes absorbed by the carbon particle are treated as a volume source. The whole flowchart of the mathematical models is given in Fig.1,and the details of the model are as follows.

2.1. Monte Carlo ray trancing model

Firstly, the radiation heat transfer inside the receiver is calculated by a self-programming package via the MCRT method and the flowchart as Fig.1. The basic thought of MCRT method on radiation, explained in details in the textbook by Modest [10-12], is that the radiation heat transfer process can be divided into four sub-processes: emission, reflection, scattering and absorption. Every sub-process has an occurrence probability and is established with a separate mathematical model. The object is divided into many units (surface units and volume units). Let every unit emit a certain quantity of light rays, then every ray is tracked and judged considering