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A MCRT and FVM coupled simulation method for energy conversion process in parabolic trough solar collector

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A B S T R A C T

A coupled simulation method based on Monte Carlo Ray Trace (MCRT) and Finite Volume Method (FVM) is established to solve the complex coupled heat transfer problem of radiation, heat conduction and convection in parabolic trough solar collector system. A coupled grid checking method is established to guarantee the consistency between the two methods and the validations to the coupled simulation model were performed. Firstly, the heat flux distribution on the collector tube surface was investigated to validate the MCRT method. The heat flux distribution curve could be divided into 4 parts: shadow effect area, heat flux increasing area, heat flux reducing area and direct radiation area. The heat flux distribution on the outer surface of absorber tube was heterogeneous in circle direction but uniform in axial direction. Then, the heat transfer and fluid flow performance in the LS-2 Solar Collector tube was investigated to validate the coupled simulation model. The outlet temperatures of the absorber tube predicted by the coupled simulation model were compared with the experimental data. The absolute errors are in the range of 1.5–3.7 °C, and the average relative error is less than 2%, which demonstrates the reliability of the coupled method established in this paper. At last, the concentrating characteristics of the parabolic trough collectors (PTCs) were analyzed by the coupled method, the effects of different geometric concentration ratios (GCs) and different rim angles were examined. The results show the two variables affect the heat flux distribution. With GC increasing, the heat flux distributions become gentler, the angle span of reducing area become larger and the shadow effect of absorber tube become weaker. And with the rim angle rising, the maximum value of heat flux become lower, and the curve moves towards the direction $\varphi = 90^\circ$. But the temperature rising only augments with GC increasing and the effect of rim angle on heat transfer process could be neglected, when it is larger than 15°. If the rim angle is small, such as $\theta_{rim} = 15^\circ$, lots of rays are reflected by glass cover, and the temperature rising is much lower.

1. Introduction

The photo-thermal conversion process of parabolic trough solar thermal power generation system can be divided into the following sections: solar radiation is collected by the parabolic trough collectors (PTCs), then is reflected and focused to the outer surface of the absorber tube where the radiant energy is converted into thermal energy. Thermal energy will be conducted to the inner surface of the absorber tube and be transferred by the heat transfer fluid inside the absorber tube with forced convection heat transfer [1]. This is a coupled heat transfer problem with complex geometry condition.

From 1970s, some researchers have tried to use numerical method to investigate the heat flux distribution characteristics of the parabolic solar concentrators. Evens [2] and Harris et al. [3] both developed integral relationships for evaluating the intensity distribution on the flat absorbers used with cylindrical parabolic solar concentrators. Considering the influence of the finite size of the sun, the "cone optics" approach was used [2]. Then, Jeter [4,5] established a first integral of the concentrated radiant flux density for trough concentrators. Those works had given out concentrating characteristics of different parabolic solar concentrators. But all those integral approaches needed special integration routine, meanwhile, the optical parameters and geometrical properties of collectors also couldn't be changed conveniently. Monte Carlo Ray Trace (MCRT) method is a very flexible method, which can be used to solve this coupled problem. The principles of the MCRT method applied to the radiative heat transfer can be found from textbooks [6]. This method was used for simulating the

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reflection process of solar radiation [7], dish solar concentrator [8] and solar chemical reactor [9], etc.

There are also many published studies about the heat transfer process between the absorber tube wall and working fluid. A detailed thermal model was established to calculate the heat loss of trough collector [10], in which the solar radiation was regarded as a constant and the influence of nonlinearity on heat loss was also ignored. Nowadays, this model is also used to analyse the thermal efficiency of trough system [11]. In order to analyse the two-phase flow region in direct steam generation (DSG), some 2D simulation methods were also established to study the temperature distribution along the cross-section of absorber tube. In those methods, the nonlinearity of heat flux was considered, but simplified distribution assumptions were used to simplify the heat flux distribution around the tube wall. For example, Martinez et al. used a sectional heat fluxes as boundary conditions of Finite-Difference Method (FDM) to solve energy equations [12]. Eck et al. used the Finite-Element Method (FEM) program ANSYS with a typical flux distribution boundary to calculate the temperature profile for the LS-3 type collector [13], then they chose a Gaussian distribution assumption as the flux distribution boundary for Finite-Element Method (FEM) analysis and a rectangular distribution assumption as the flux distribution boundary for a simplified analytical solution [14].

Up to now, few papers have focused on the flow and heat transfer characteristics of working fluid inside the absorber tube under the realistic non-uniform heat flux distribution boundary conditions. In this paper, the realistic non-uniform heat flux distribution is used as the boundary condition to simulate the heat transfer process inside the absorber tube, and the characteristics analysis under the influence of the non-uniform heat flux distribution was made. For simulation, a coupled numerical method of MCRT and FVM was established to obtain the 3D flow fields and temperature distribution for the coupled heat transfer problem in absorber tube with the complexity of non-uniform heat flux boundary condition. In order to validate the coupled simulation method, the concentrating characteristics and heat transfer in absorber tube of the LS-2 Solar Collector were simulated and compared with test data [15]. Then the model was used to simulate the influence of the nonlinear heat flux distribution on overall heat transfer performance. The effects of different geometric concentration ratios and rim angles are also discussed in this paper.

2. Simulation method

2.1. The physical model and coordinate systems

Fig. 1 is a schematic of traditional PTC, which is made by bending a sheet of reflective material into a parabolic shape surface. A receiver tube is placed along the focal line of the parabolic reflective collector. The receiver tube usually includes an inner absorber tube and a glass cover. The glass cover is used for reducing heat loss; as well as the annular space between the inner tube and the glass cover is vacuumed, which helps to decrease the convection heat loss [1].

Two coordinate systems are used in this paper. The Cartesian coordinate system is used for tracing photon movements in MCRT code and solving correlated equations in FLUENT, as shown in Fig. 1. In the cross-section of absorber tube, a cylindrical coordinate system is used to count the photon distribution and heat flux distribution (Fig. 2). Because the absorber tube is located along the focal line and the parabola is symmetric, the photon and heat flux distribution is symmetric along the z axis. So the range of circle angle φ is from -90° to 90°.

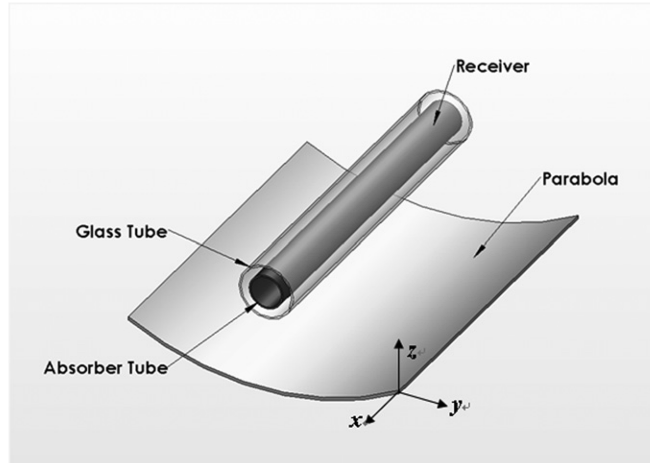

Fig. 1. Schematic of a parabolic trough collector.

2.2. Details of MCRT

The flowchart for MCRT is shown in Fig. 3. The diamond boxes can be considered as judgments for position relation of straight and curve, such as judgments of “Shadowed region by absorber”, “Reflected region by parabola”, “Hit glass tube” or “Hit absorber tube”. If those judgments are “YES”, the hitting locations are determined, such as processes of “Count hitting position on glass tube and absorber tube”. All those judgments and processes are easy events as solving quadratic equations. So details of those boxes are not shown in following sections. However, in several processes, new trace directions should be decided, such as “Initialize photon distribution”, “Reflect” and “Transmit”. Monte Carlo Method is used in those sections which will be detailed in following sections. Other processes which are statistic events, such as “Absorb photon”, “Count photon distribution” and “Count heat flux distribution”, are also discussed in following sections.

2.2.1. Initialize photon distribution

Initializing photon distribution is used to decide the location of photon hitting the parabola, the direction of photon tracing and the energy weight carried by each photon packet. The location is described by the Cartesian coordinates (x,y,z) and the direction is described by the directional cosines (u_x,u_y,u_z) [16]. The location where photon hits the parabola is specified as follows:

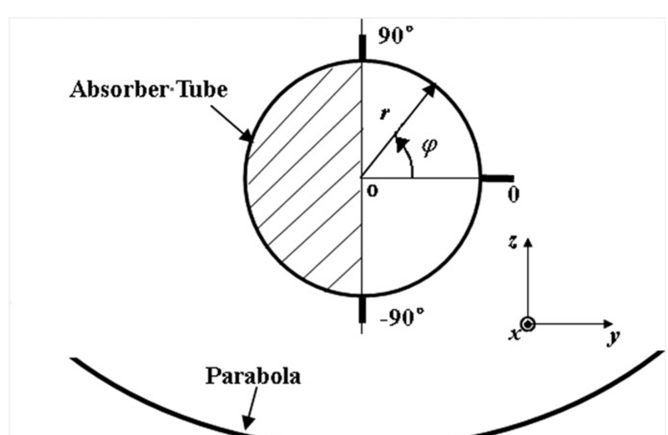

Fig. 2. The cylindrical coordinate system.