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Effects of glass cover on heat flux distribution for tube receiver with parabolic trough collector system

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ABSTRACT

A solar receiver is designed for operation under extremely uneven heat flux distribution, cyclic weather, and cloud transient cycle conditions, which can induce large thermal stress and even receiver failure. In this study, the effects of a glass cover (GC) on heat flux distribution are analyzed by Monte Carlo Ray Tracing (MCRT) method. In order to minimize the heat flux gradient, which in turn can reduce the thermal stress of tube receiver, a GC with elliptic–circular cross section is proposed in this study. The effects of refractivity and characteristic parameters on the heat flux distribution are also investigated. The numerical results indicate that the magnitude and distribution of heat flux are affected only slightly when concentrated sunlight passes through the GC with circular cross section, and adopting a GC with elliptic–circular cross section for the tube receiver can effectively decrease the heat flux gradient, the peak heat flux reduction is up to 32.3%.

1. Introduction

With the continuous increase in CO_2 emission and energy consumption from conventional sources, interest in alternative sources of energy has been strengthened [1]. The solar thermal power plant (STPP) with optical concentration technology is a candidate renewable energy resource [2]. STTP with optical concentration technology shows higher efficiency at high temperature than those without optical concentration technologies [3].

As known, solar energy is an intermittent energy source [4,5]. Solar receivers for STTP with optical concentration technology need to operate under extremely uneven heat flux [6,7], cyclic weather, and cloud transient cycle conditions, which can result in high temperature gradients [8,9]. High temperature gradients can induce large thermal stress, which may cause the rupture of the glass cover (GC, also known as glass envelope), or even solar receiver damage [10–12]. For example, in the STPP of the National University of Mexico, which had parabolic trough concentrator, large deflection was observed in the tube receiver during experimental test and operation, and the GC had ruptured several times [13].

Numerous studies have been conducted to develop methods to suppress thermal stress in solar receivers. Flores and Almanza proposed a bimetallic Cu–Fe receiver and showed that it had a lower temperature gradient and less thermal strain than those of stainless-steel tube receivers [13]. In order to reduce the thermal stress of cavity receivers, Agrafiotis et al. [14] employed porous monolithic multi-channeled SiC honeycombs as the material of an open volumetric receiver. Lata et al. conducted a low-cycle fatigue test of receiver materials at different temperature conditions, and the experimental results showed that high nickel alloys had excellent thermo-mechanical properties compared to austenitic stainless steel [15]. An eccentric tube receiver was introduced by Wang et al. [16] to reduce thermal stress, and the numerical results indicated that adopting the eccentric tube as the solar receiver for a parabolic trough concentrator system can effectively reduce the Von-Mises thermal stress by up to 41.1%.

Studies by Ifran and Chapman [17] indicated that minimizing the heat flux gradient of solar receivers is an effective way to reduce thermal stress. Based on the concept of equivalent radiation flux, an upside-down pear cavity receiver was proposed by Shuai et al. [18,19]. A computer program for calculating the heat flux distribution of parabolic dish concentrators was developed by David et al. to obtain the homogeneous radiation flux on cavity receiver surface [20]. A cavity receiver with a plano-convex quartz window was proposed by Shuai et al. based on the directional characteristics of focal flux and the redistribution effects of the quartz window, parametric studies showed that the cavity receiver with a quartz window had a more homogenous flux distribution [21].

STTPs with parabolic trough collector (PTC) technology are currently one of the most mature and prominent applications of solar

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energy, which have the advantages of high plant efficiency and low electricity production cost [22]. For example, most of the new STTPs built in Spain feature PTC technology [23]. As shown in Fig. 1, a PTC collects the radiant energy from the sun and concentrates it on the bottom periphery of the GC and transmits the concentrated solar energy to the tube receiver. The tube receiver, which is a tube heat exchanger, converts the incoming concentrated solar energy into heat and transfers the heat to the heat-transfer medium [24]. Generally, tube receivers are covered by a GC with selective coatings to minimize convection and radiation losses [25–27]. The selective coatings simultaneously exhibit high sunbeam transmissivity (τ) in the solar wavelength range of 0.2–3.0 μm and low sunbeam transmissivity in the infrared region of 3.0–20 μm [28,29].

Because of the important role played by the GC for solar thermal utilization, numerous studies had been performed on GC. Mahboub et al. proposed a modified equation to calculate GC temperature and top heat-loss coefficient, and this equation can be used in energy analysis [30]. A two-dimensional model was proposed by Cui et al. for cavity receivers with quartz GCs, and the effects of the GC on heat loss were investigated [27]. Vicente et al. investigated the application of a surface modification process for increasing the durability of GCs [31]. Giovannetti et al. proposed and fabricated a high-transmittance, low-emissivity GC and analyzed its performance [32].

A literature survey review indicates that few studies have been published about the effects of GCs on the heat flux distribution of tube receiver for PTC. In this study, the effects of a GC on heat flux distribution are analyzed by MCRT method, and a new GC shape is proposed to minimize the heat flux gradient on tube receiver surface, which in turn will reduce the thermal stress of tube receiver.

2. Methodology

In sunlight concentration and transmission problems, MCRT involves the stochastic trajectories of a huge amount of sunlight, as they intersect with the solar collector and receiver (reactor) [33,34]. The fate of sunlight is determined by emissive, reflective, and absorptive characteristics on the surface, which described by a set of statistical relationships, and the reflection of sunlight follows the Fresnel optics rule [35,36].

As a matter of fact, the solar PTC surface is a non-gray surface, and the PTC surface reflectivity varies with wavelength. Non-gray effects are addressed in this manuscript through band approximation [37]. In this method, the spectrum is broken into several bands, over which the reflectivity properties of the PTC surface are constant.

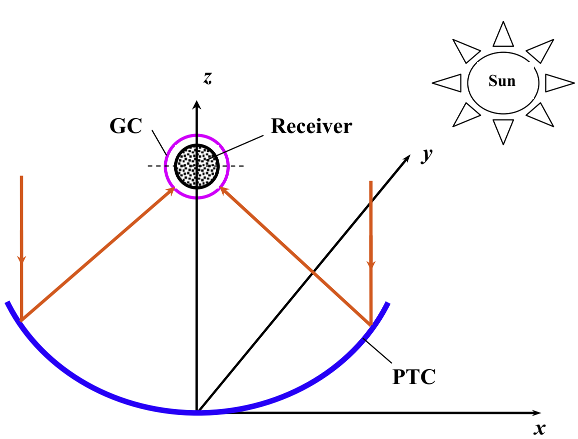

Fig. 1. Schematic of the parabolic trough collector with tube receiver.

Fig. 2 presents the spectral reflectivity of the PTC surface, which varies with wavelength [37]. Five bands are adopted for band approximation: 0.3–0.38 μm, 0.38–0.76 μm, 0.76–1.5 μm, 1.5–3 μm, and 3 μm–∞. Table 1 lists the calculated parameters of band approximation for the PTC surface.

The geometrical parameters of the parabolic trough solar concentrator and the tube receiver used in this paper are listed in Table 2. For more information about MCRT method, please refer to Ref. [16,38–40].

As the transmissivity of the GC is highly close to 1.0, little concentrated sunlight would be absorbed by the GC and its temperature variation is small. In addition, since the main purpose of this study is to compare the effects of the GC with the new shape to those of conventional GCs under the same calculation conditions, the effects of temperature on sunlight transmission are not considered in this study.

3. Results and discussion

3.1. Effects of GC on heat flux distribution

Fig. 3 illustrates the effects of GC on heat flux distribution on the bottom periphery of tube receiver. The transmissivity of GC is set to be 0.95, the refractivity of GC is 1.4, the GC thickness is 1.0 mm and the absorptivity of tube receiver is set to be 0.90. As shown in this figure, the heat flux distribution of the tube receiver with 1 mm GC thickness is very similar to that of tube receiver without the GC, and both heat flux distribution profiles on the bottom-half periphery of the tube receiver exhibit a spike distribution. As indicated in Table 1, the GC transmissivity is very close to 1.0, and its thickness is very less. Therefore, the magnitude and distribution of heat flux are affected only slightly when concentrated sunlight passes through the GC. Hence, some researches had neglected the effects of GC on concentrated heat flux distribution in numerical calculations [16,41]. However, because of the combined effects of absorption and refraction of GC, the peak magnitude of the heat flux distribution of the tube receiver with δ = 1 mm is a little lower than that of the tube receiver without a GC. The peak magnitude of the heat flux distribution of tube receiver with δ = 1 mm is 39,432 W/m^2, and the peak magnitude of the heat flux distribution of the tube receiver without GC is 41,707 W/m^2.

3.2. Effects of GC thickness

As dimensionless results are more universal, effects of dimensionless GC thickness ($\xi = \frac{\delta}{r}$) on the heat flux distribution on the bottom periphery of tube receiver are plotted in Fig. 4. Four

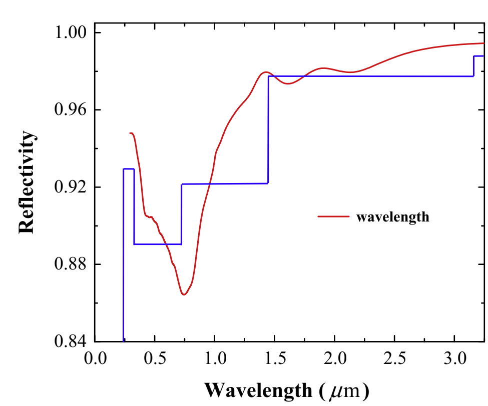

Fig. 2. Spectral reflectivity of PTC mirror varied with wavelength.