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A detailed nonuniform thermal model of a parabolic trough solar receiver with two halves and two inactive ends

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ABSTRACT

In this paper a detailed one dimensional nonuniform thermal model of a parabolic trough solar collector/receiver is presented. The entire receiver is divided into two linear halves and two inactive ends for the nonuniform solar radiation, heat transfers and fluid dynamics. Different solar radiation and heat transfer modes can be taken into consideration for these four different regions respectively. This enables the study of different design parameters, material properties, operating conditions, fluid flow and heat transfer performance for the corresponding regions or the whole receiver. Then the nonuniform model and the corresponding uniform thermal model are validated with known performance of an existing parabolic trough solar collector/receiver. For applications, the uniform thermal model can be used to quickly compute the integral heat transfer performance of the whole PTC system while the nonuniform thermal model can be used to analyze the local nonuniform solar radiation and heat transfer performance characteristics and nonuniform heat transfer enhancements or optimizations. Later, it could also be effectively used with an intelligent optimization, such as the genetic algorithm or the particle swarm optimization, to quickly evaluate and optimize the characteristics and performance of PTCs under series of nonuniform conditions in detail.

1. Introduction

The parabolic trough solar collector is currently one of the most mature and field tested solar thermal technologies for large-scale exploitations of solar energy [1–3]. It uses mirrored surfaces of a linear parabolic reflector to focus solar radiation onto an evacuated tubular receiver placed along the focal line of the parabola. The receiver mainly includes an inner absorber tube surrounded by an outer glass cover and supported brackets [1,2]. The concentrated solar radiation reaching the absorber tube heats the heat transfer fluid that flows through it, thus transforming the radiant energy from the sun into useful thermal energy [2–7]. In the solar field, parabolic trough solar collectors are always built in modules to operate at up to temperatures of 400 °C, and synthetic oil is commonly used as the heat transfer fluid. The whole solar to thermal conversion process is coupled with large concentrated solar radiations, conjugated heat transfers and fluid dynamics, including all modes of heat transfer and temperature-dependent properties.

Since the 1970s, numerous thermal models have been proposed for the heat transfer analysis of this process, as it is very important for quickly calculating thermal losses or collector efficiencies, sizing the solar field, evaluating the effects of collector degradation and heat transfer fluid flow rate control strategies on overall solar field performance [8]. The most important ones are the study of Dudley et al. [9], Forristall [10], Padilla et al. [11] and Kalogirou [12]. In the 1990s, Dudley et al. [9] developed a significant one dimensional steady-state analytical model for an LS-2 SEGS parabolic trough solar collector after many experiments were performed on the AZTRAK rotating test platform at Sandia National Laboratories. The results showed good agreements between the theoretical and experimental collector efficiencies or thermal losses under the known tested conditions. Based on this, Forristall [10] presented a more detailed one-dimensional or two-dimensional heat transfer model for short and long receivers implemented in the engineering equation solver, to determine the parabolic trough solar collector/receiver thermal performance with various geometric parameters, fluid flows, material properties and operating conditions. In recent years, Padilla et al. [11] proposed a one dimensional numerical heat transfer analysis of a parabolic trough solar collector/receiver by applying the mass and energy balance in several segments of the

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steel absorber and glass envelope, in which the thermal interaction between neighboring surfaces for thermal radiation losses was implemented by a comprehensive radiative analysis. Kalogirou [12] also developed a detailed thermal model of a parabolic trough solar collector/receiver using the engineering equation solver. The thermal analysis of the collector receiver takes into consideration all modes of heat transfer. Up to now, all these thermal models have been thoroughly tested, experimentally validated and well applied for general parabolic trough solar collector systems. Usually, most of them assumed that the solar energy flux density, wall temperature or physical properties were uniform for the whole circumferential direction at a cross-section of the receiver.

In fact, the solar flux on the collector absorber side opposite to the parabolic trough collector receives large amounts of concentrated solar radiation but there is the opposite for the other side of the absorber [13–22], and it is no concentrated solar radiations on the two inactive ends, i.e., the part includes bellows and glass-to-metal joints at either end of the receiver. Because of this, the fluid inside the tube is heated asymmetrically and thus the temperature distributions and temperature-dependent properties are nonuniform. Some significant studies have been published recently to investigate the nonuniform heat transfers and fluid dynamics in the parabolic trough solar receivers by numerical models (three-dimensional nonuniform computational fluid dynamics (CFD) models) [4,15,19–37], but it is revealed that the numerical methods need great computation time. Especially, the time-consuming computational process is a critical question for an intelligent optimization on the PTC performance. For example, it may take several weeks or months to make a completed intelligent optimization based on these complex three-dimensional nonuniform CFD models with the genetic algorithm (GA) or the particle swarm optimization (PSO). Alternatively, a new simplified and quick thermal model that can take into account these nonuniform conditions to some extent may also be another feasible method to apply.

Furthermore, to develop an energy-efficient receiver for solar parabolic trough concentrators, various special considerations on either side of the receiver were proposed. Reddy et al. [38–43] proposed various porous inclusions inserted in one side of the inner absorber to enhance heat transfer in the receiver. Grena [44] presented a new receiver tube half-covered with an IR-reflecting layer in the non-irradiated half of the glass cover to reduce the thermal emission. As a preliminary study, this was evaluated by means of optical and thermal simulations with a simplified two halves model derived from that for a linear Fresnel solar collector [45], while the reliability and accuracy for the parabolic trough solar collector need to be further validated and investigated. Al-Ansary and Zeitoun [46] numerically investigated the conduction and convection heat losses from a proposed receiver of a half-insulated air-filled annulus with a heat-resistant thermal insulation material. Cheng et al. [47] presented three-dimensional numerical studies on the turbulent flow and coupled heat transfer enhancement in a novel unilateral multi-longitudinal vortexes enhanced parabolic trough solar receiver, where longitudinal vortex generators are only located on the side of the absorber tube with the concentrated solar radiation. Considering the complex modeling process and the numerical computing cost, mentioned above, a quick analytical model also needs to be further developed for these special cases.

Thus, a detailed one dimensional nonuniform thermal model is proposed and used in this paper, to quickly and accurately estimate the performance characteristics of the parabolic trough solar receivers for both the nonuniform conditions occurring in the parabolic trough solar collector/receiver system (i.e., the nonuniform solar flux and the corresponding nonuniform temperature distributions and temperature-dependent properties) and these special considerations made by other researchers (i.e., the nonuniform performance improvements on one half of the absorber/cover) mentioned above. The entire receiver is divided into two linear halves and two inactive ends, and different solar radiation and heat transfer modes can be taken into consideration for these four different regions respectively. The model is then validated with known performance of an existing parabolic trough solar collector, and some further studies for nonuniform heat transfer enhancements or optimizations based on the proposed model are also discussed.

2. Nonuniform thermal model

A detailed schematic diagram of the parabolic trough evacuated tubular receiver is presented in Fig. 1. It mainly includes an inner stainless steel absorber tube with a solar-selective absorbing coating on its outer surface, an outer glass cover with anti-reflective (AR) coatings on its both surfaces, an annular space, getters, bellows and glass-to-metal joints (i.e., the inactive ends). The absorbing coating combines a high absorptance for solar radiation and a low thermal emittance to reduce thermal reradiation from the outer absorber surface [10], while the AR coatings are used to reduce Fresnel reflective losses at the glass surfaces [1,2]. The glass cover and the annular vacuum space are used to significantly reduce convection heat losses and protect the coating from oxidation. The vacuum is initially maintained at about 0.0001 Torr determined by the Knudsen gas conduction range [5,21], but it may be degraded with time. The getters are placed in the annular vacuum space to absorb residual gases that permeate into the annulus over time and indicate the status of vacuum, while the vacuum-tight enclosure is sealed by glass-to-metal joints at both ends with bellows that accommodate for thermal expansion difference between steel and glass materials [1,27]. The space outside the bellows at either end provides a place to attach the support brackets.

The nonuniform heat transfer model of the parabolic trough solar receiver is based on the energy balance between the incoming solar radiation (i.e., the solar energy input on the collector opening minus the optical losses), the heat transfer fluid (HTF), the absorber tube, the glass cover and the surroundings for both the two linear halves and the two inactive ends. Figs. 2 and 3 show the heat transfer in a cross-section of the receiver and the thermal resistance model used in the heat transfer analysis. The incoming solar radiations at the two linear halves of the receiver (as side 1 and side 2 shown in Fig. 2) and the two inactive ends are nonuniform. Side 2 toward the reflector receives much higher solar flux than the side 1 because of the radiation reflected by the parabolic mirror and the two inactive ends receive no concentrated solar radiations at all. The incident solar radiation at the side 1 is directly absorbed by the upper half absorber surface and the upper half glass cover which

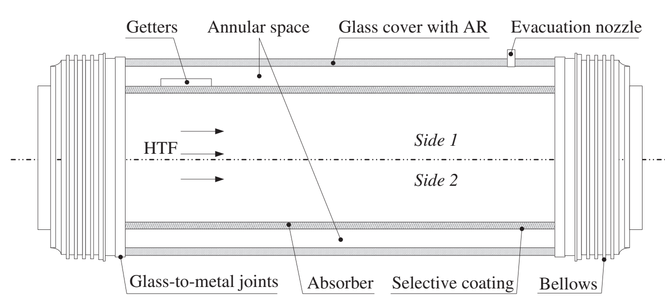

Fig. 1. Schematic of the physical model of a PTC tubular receiver.