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Collecting performance of an evacuated tubular solar high-temperature air heater with concentric tube heat exchanger

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ABSTRACT

A set of evacuated tube solar high temperature air heaters with simplified CPC (compound parabolic concentrator) and concentric tube heat exchanger is designed to provide flow air with a temperature of 150–230 °C for industrial production. The solar air heater system consists of 30 linked collecting units. Each unit includes a simplified CPC and an all-glass evacuated tube absorber with a concentric copper tube heat exchanger installed inside. A stainless steel mesh layer with high thermal conductivity is filled between the evacuated tube and the concentric copper tube. Air passes through each collecting unit, and its temperature increases progressively. An experimental investigation of the thermal performance of the air heater is performed, and the experimental results demonstrate the presented high-temperature solar air heater has excellent collecting performance and large output power, even in the winter. The measured thermal efficiency corresponding to the air temperature of 70 °C reaches 0.52. With the increase of air temperature, thermal efficiency reaches 0.35 at an air temperature of 150 °C, and 0.21 at an air temperature of 220 °C.

1. Introduction

New energy, especially solar energy, has been widely used in a variety of fields with the coming of the energy crisis. Solar collectors are intended to collect heat by absorbing sunlight. They may be mainly divided into three categories: evacuated tube collector, flat-plate collector, and concentrating collector. Both the evacuated tube collector and the flat-plate collector are generally designed to collect heat for low temperature applications. In the last two decades, the market for solar evacuated tube water collectors has been expanded due to the development of low-cost sputtering technology for producing an all-glass evacuated tube absorber [1]. In China, solar all-glass evacuated tube water heaters are widely applied due to their excellent thermal performance, easy installation and transportation, and low cost. Up to now, most studies concerning the all-glass evacuated tube collector have focused on low temperature applications for water and air heating [2].

CPC (compound parabolic concentrator) can receive incoming radiation over a relatively wide range of angles. Any entering radiation heat within the collector acceptance angle can find its way to the absorber surface located at the bottom of the collector by using multiple internal reflections. As a kind of highly efficient high temperature solar collector, the CPC collector has been widely researched, both in terms of analysis and design [3,4].

Nowadays, most studies of solar air collectors are based on the flat-plate absorber with CPC. The main application fields comprise air coediting, grain dry and desalination, etc., while much less attention has been paid to the study of all-glass evacuated tube air collectors. Karim and Hawlader presented a design in which heated air is subsequently used for space heating and drying [5]. Ong [6] put forward some mathematical models and solution procedures for analyzing the performance of solar flat-plate air heaters. Garg and Adhikari [7] conducted a performance calculation of a single solar air heater with several subcollectors. Carvalho and Collares-pereira [8] carried out theoretical analyses on truncation of CPC solar collectors and its effect of energy collection. Tchinda presented a mathematical model for analyzing air collector performance for quantifying heat transfer within CPC solar energy collectors with a flat one-side absorber [9]. Zukowski's study team presented a novel micro jet air solar heater and investigated thermal and flow characteristics [10]. In addition, many experimental studies concerning configuration design and thermal performance for solar air plate heaters with non-tracking type CPCs and parabolic trough concentrators (PTC) have also been reported [11–20]. Recently, a combination of air heater and phase change material energy storage system has attracted great attention. Esakkimuthu and coworkers proposed a design and carried

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out an experimental study on solar air heaters with phase change material energy storage [21]. Edward and Mohammed et al. introduced a design and optimization of a solar air heater collector with phase change material energy storage for humidification–dehumidification desalination [22].

In almost all of the experimental studies concerning solar flat-plate air heaters with non-tracking type CPC or PTC mentioned above, the highest air temperature at the system outlet has not surpassed 120 °C and largely remained in the range of in 50–80 °C. This greatly restricts applications of solar air heaters in wider industrial fields. However, the all-glass evacuated tube collector with non-tracking CPC possesses the potential ability to provide high-temperature air with good operational performance, due to the low heat dissipation owing to the vacuum encapsulation around the absorber surface. Nevertheless, up to now, there have been few studies related to all-glass evacuated tube air heater for heat-temperature applications. We have carried out an experiment and simulation concerning a novel all-glass evacuated tubular solar air heater with simplified CPC [23]. This system is made up of 10 linked collecting panels, each of which includes a simplified CPC and an all-glass evacuated tube with a U-shaped copper tube heat exchanger installed inside. Calculated and experimental results demonstrate that this experimental system can provide heated air exceeding 200 °C in the summer.

In this study, the experimental system is further improved to increase air collecting temperature and collecting thermal efficiency, and decrease costs. The present solar air collector system consists of 30 linked collecting units. Each unit includes a simplified CPC and an all-glass evacuated tube with a concentric tube heat-exchanger installed inside. The concentric tube made of copper is installed in the inner tube of the all-glass evacuated tube. A resilient stainless steel mesh layer is filled between the concentric tube and the inner glass tube, instead of the previous paste-like mixture of high temperature oil and graphite powder as the thermal conductivity medium. This structure can further improve the collecting efficiency and reduce costs. Air passes through all of the 30 collecting units and is progressively heated in each unit. This solar collector system is designed to provide high-temperature air with great output power for a relatively long time in industrial processes. The experimental results realize the expected study goals and offer meaningful guidance for designing solar all-glass evacuated tube air collectors with simplified CPC for application in industrial air heating processes.

2. Experimental apparatus

2.1. Geometry of simplified CPC

CPC is capable of collecting solar radiation for relatively long periods without tracking the sun. A design method of standard CPC has been put forward by Winston [24] and improved by Rabl [25–27] and Khonkar and Sayigh [28]. Recently, Seo and coworkers [29] and Panse and coworkers [30] carried out some evaluations of the thermal performance of a novel CPC solar air collector. The solar absorber is a tubular all-glass evacuated tube consisting of two concentric glass tubes sealed at one end, with a selective absorbing coating layer on the outer surface of the inner tube and an annular vacuum space.

The CPC-type concentrator utilized in this study is the same as that in the authors' previous study [23]. Fig. 1 presents a simplified CPC profile after truncation and cutting the involute shape for reducing processing difficulty and cost. According to the designed calculation and test result, the concentrating efficiency of the simplified CPC with a flat curve bottom decreases by about 15% compared with the truncated CPC with an involute bottom [23].

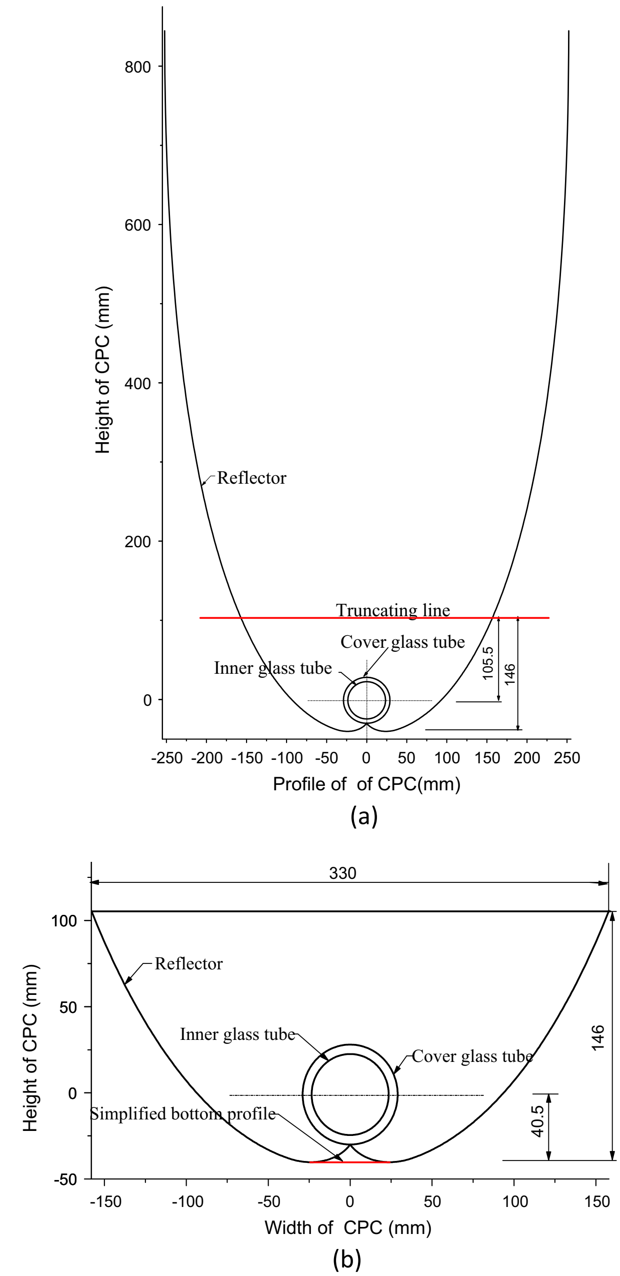

Fig. 1. Profiles of the CPCs; (a) standard CPC and (b) simplified CPC (unit: mm).

Design of acceptance half angle and concentrating ratio were carried out as the below.

In first, the concentrating ratio, C which is the ratio of the aperture area of the CPC to the over area of tubular absorber, was calculated according to the designed highest flow air temperature of 200 °C on noon in summer that is almost independent of both air flow rate and number of colleting units. In the present study, C was fixed 2.16 (aperture width is 330 mm).

For the standard CPC, there is a simplified function relation between C and θ_a, $\sin\theta_a = 1/C$. Therefore, $\theta_a = 27.6^{\circ}$ for $C = 2.16$.

For the truncated CPC, after C is fixed, θ_a can still be changed in a limited range whose maximum is $\theta_{a,\max} = 27.6°$ for $C = 2.16$. The litter θ_a corresponds to the shorter height of the CPC, i.e., the lower material and making costs. Therefore, the selection of θ_a and the height of the CPC needs a comprehensive consideration.