Energy Conversion and Management 142 (2017) 286–295

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermal performance of a transpired solar collector updraft tower

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ARTICLE INFO

Article history:
Received 7 January 2017
Received in revised form 6 March 2017
Accepted 15 March 2017

Keywords:
Solar updraft tower
Solar air collector
Transpired solar collector

ABSTRACT

A novel solar updraft tower prototype, which consists of transpired solar collector, is studied, its function principle is described and its experimental thermal performance is presented for the first time. A test unit of transpired solar collector updraft tower was installed at the campus of Trakya University Engineering Faculty in Edirne-Turkey in 2014. Solar radiation, ambient temperature, collector cavity temperatures, and chimney velocities were monitored during summer and winter period. The results showed that transpired solar collector efficiency ranges from 60% to 80%. The maximum temperature rise in the collector area is found to be 16–18 °C on the typical sunny day. Compared to conventional solar tower glazed collectors, three times higher efficiency is obtained. With increased thermal efficiency, large solar collector areas for solar towers can be reduced in half or less.

1. Introduction

Solar updraft tower (SUT) power plant also called solar chimney power plant, is a renewable energy system that produces electricity from solar heated air. Since the idea first appeared, many researchers and entrepreneurs such as Bennet [1], Cabanyes [2], Dubos [3], Günther [4], Schlaich et al. [5] and many others, proposed different applications of SUT [6]. In 1982, a 50 kW, 200 m tall chimney experimental test unit of a solar draft tower was built in Manzanares, Spain [7,8]. The power plant operated for almost eight years for the purposes of testing solar collectors and validation of mathematical models. In the past decades, after the construction of the Manzanares pilot plant prototype, some small and large experimental setups were built and tested for operational parameters and commercial projects for large scale electricity production are being developed in several countries [6].

From the first concept of solar updraft tower, all test units have incorporated transparent collectors as the roof using the greenhouse effect to produce heat which creates updraft in the chimney. Since the tests at Manzanares were completed, further development worldwide has been minimal and no scientific or technical research has been carried out on the use of different solar air collectors in solar chimney plants. One of the most efficient and successful solar air collectors in history was developed after Manzanares and is referred to as transpired solar collector (TSC). Transpired collectors are unglazed, all metal solar collectors and are used in a wide range of applications such as drying, space heating and cooling. Since John Hollick [8] first developed TSC for heating outside air in 1989, millions of square feet of panels have been installed and many installations were monitored; independent data and numerous research articles has shown solar efficiencies of 80% [10]. A transpired collector is a perforated solar absorber plate which allows the external heat boundary layer to be drawn into the air cavity without the need for glazing [18–22].

In a conventional SUT systems, the air is heated by a greenhouse type glazed solar collector. The glazing of solar collector can consist of a glass or transparent material [6]. There are problems with greenhouse type glazed collectors used with solar towers including high costs, very low efficiencies (25% range), low temperature rise and large land masses (many square kilometers) required to generate thermal energy to create sufficient air movement, high collector costs (collector costs can exceed 50% of total costs) and the glass roof will accumulate dust easily over its entire surface, so its solar-optical efficiency will be decreased over time. The durability of the glass roof is uncertain as glass roofs can be broken easily; plastic or polymer glazing used as roofs will degrade over time when exposed to UV rays and thin plastic sheets may tear apart under strong wind conditions. As stated by various researchers, cost-saving performance efforts should be focused on the collector for greater cost reduction, because of high cost and low efficiency of SUT solar air collector [23–39]. Bernardes et al. [23] studied heat transfer mechanism for translucent solar collectors in SUT and determined heat transfer coefficients within collector. Guo et al. [24] calculated collector's efficiency for SUT prototype in

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http://dx.doi.org/10.1016/j.enconman.2017.03.052
0196-8904/

Nomenclature

Abbreviations

A	area (m^2)
c_p	specific heat capacity ($J\,kg^{-1}\,°C^{-1}$)
I	Solar irradiation ($W\,m^{-2}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
T	temperature (°C)

Subscripts and abbreviations

coll	collector
g	ground
in	inlet
out	outlet
TSC	transpired solar collector
TSCUT	transpired solar collector updraft tower
SUT	solar updraft tower

Greek symbol

η	efficiency

Manzanares and showed that collectors efficiency ranges from 15.6% to 28.9% when the solar radiation is changed from 200 to 1000 W/m2. To improve thermal performance of conventional SUT, various collector arrangements have been proposed and examined by researchers: Schlaich [25] reported that double glazing of the collector roof increases annual plant output by approximately 28.6%, compared to the same plant using a single glazed roof. Double glazed roof is studied by Bernardes et al. [26], and they showed that double cover area has no significant effect on SUT performance, power output is only increased by approximately 5–6%. On the other hand, Pretorius [27] exhibited that compared to the single roof, double glazing the entire collector roof increases the annual power output by 38%. Pretorious also studied different single-double configurations and showed that, in terms of annual power output, double glazing a quarter, half or three-quarters of the collector roof area (with the rest single glazed) increases power outputs to 15.3%, 26.1% and 33.8% respectively, compared to a fully single glazed reference plant. Preterious and Kröger [28] reported better quality glass provides a better transparency, allowing more solar radiation transmission, and it increases the annual plant power output by 3.4%. Stamatov [29] studied performance of a non-transparent roof material for SUT, made an analysis for trapezoidal shaped metal collectors, and reported that SUTs with trapezoidal-shaped collectors may experience less energy dissipation and better flow stability in the existence of side-wind at lower solar conversion, compared with flat collectors. Guo et al. [30] studied the effect of turbine speed and zenith angle on collector efficiency numerically by using discrete ordinate radiation model for transparent collectors, and found that collector efficiency ranges from 33% to 47%. Okeye et al. [31] analyzed the variation of collector efficiency on performance and feasibility of SUT, and they found that, if the collector efficiency is greater than 35%, SUT application can be feasible within given specific example project, which shows the importance of collector efficiency in SUT applications. They also showed that collector efficiency has a big impact on overall SUT cost: Increasing the collector efficiency from 20% to 60% decreases total SUT cost by 50% in their example project. Guo et al. [32] showed that the efficiency of the transparent solar collectors in SUT applications is overrated when radiation model is not taken into consideration, which negatively effects the review of collector performance and also the cost of SUT systems in general.

The present study provides experimental thermal performance of a solar updraft tower using for the first time a transpired solar collector. The transpired solar collector updraft tower (TSCUT) test unit was installed at the campus of Trakya University Engineering Faculty in Edirne-Turkey in 2014. Solar radiation, ambient temperature, collector cavity temperatures, and chimney velocity data were monitored during summer and winter period. The thermal performance results are presented and compared with data from conventional SUTs.

2. The transpired solar collector updraft tower concept

2.1. Principle

A conventional solar updraft tower or solar chimney power plant has a simple operation principle as shown in Fig. 1a: The ambient air which enters from the open perimeter of a large transparent collector, is heated via "solar greenhouse effect" and flows into a centered position chimney with turbines to produce electricity by using the air flow to turn turbines. The faster the air flow, the more power produced. The transpired solar collector uses metal in place of the traditional glazing covers and air enters over the entire surface instead of the perimeter in, as seen in Fig. 1a and b.

The use of TSC is an important difference and can be a game changer in future projects with limited land area. In conventional SUT, ambient air enters from open perimeter of the roof collector and is heated generally by convection along the hot ground under the roof. With transpired collectors, air enters through millions of perforations along the entire surface of the collector and air is heated directly by TSC, not along the ground. Consequently, the function and definition of solar collector is changed with this new concept for SUT applications: "Direct heating" of ambient air is achieved via TSC, while conventional glass collectors have an indirect heating mechanism as the ground is heated first and then the ground heats the incoming air.

2.2. Heat transfer mechanism for glazed and transpired solar collectors

The main difference of heat transfer mechanism for conventional SUT and TSCUT is illustrated in Fig. 2. The transparent roof of the solar collector admits direct and diffuse solar radiation and retains long-wave radiation from the ground. This produces greenhouse effect in the collector. The ground under the roof heats up and transfers its heat to the airflow above it [6,23–42]. Because of the indirect heat exchange mechanism of greenhouse type collectors and losses, the collector efficiency is as low as 15% to 30% [23–32].

Heat transfer mechanisms for the transpired solar collectors are relatively simple and the reverse of a glazed system as the transpired collector heats the air directly and the ground is heated indirectly by the moving air stream. Air enters through perforations in the absorber plate, and solar energy from the absorber is transferred to it directly. This solar heated air is drawn into chimney to produces electricity in the classical way. The ground is heated indirectly by solar radiation in TSCUT concept by the warm air passing over the ground on its way to the chimney. At night, the ground or geothermal energy, is several degrees warmer than the night air temperature which creates continual air flow to the chimney.

Another important consideration is that the lack of glazing eliminates the transmission and reflection losses associated with glazing, which may be 10% to 15% for clean glazing [41]. In arid zones glazings get dirty from dust accumulation and the light