Solar Energy Materials & Solar Cells 92 (2008) 1105–1109

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Performance analysis of a double-pass thermoelectric solar air collector

C. Lertsatitthanakorn [a,*], N. Khasee [a], S. Atthajariyakul [a], S. Soponronnarit [b], A. Therdyothin [b], Ryosuke O. Suzuki [c]

[a] Faculty of Engineering, Mahasarakham University, Khantarawichai, Mahasarakham 44150, Thailand
[b] School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Bangmod, Thungkru, Bangkok 10140, Thailand
[c] Engineering of Eco-Processing Laboratory, Department of Material Science, Hokkaido University, Sapporo, Hokkaido 060-8628, Japan

ARTICLE INFO

Article history:
Received 4 January 2008
Accepted 25 March 2008
Available online 15 May 2008

Keywords:
Thermal efficiency
Conversion efficiency
Overall efficiency
Power output

ABSTRACT

The thermoelectric (TE) solar air collector, sometimes known as the hybrid solar collector, generates both thermal and electrical energies simultaneously. A double-pass TE solar air collector has been developed and tested. The TE solar collector was composed of transparent glass, air gap, an absorber plate, thermoelectric modules and rectangular fin heat sink. The incident solar radiation heats up the absorber plate so that a temperature difference is created between the thermoelectric modules that generates a direct current. Only a small part of the absorbed solar radiation is converted to electricity, while the rest increases the temperature of the absorber plate. The ambient air flows through the heat sink located in the lower channel to gain heat. The heated air then flows to the upper channel where it receives additional heating from the absorber plate. Improvements to the thermal and overall efficiencies of the system can be achieved by the use of the double-pass collector system and TE technology. Results show that the thermal efficiency increases as the air flow rate increases. Meanwhile, the electrical power output and the conversion efficiency depend on the temperature difference between the hot and cold side of the TE modules. At a temperature difference of 22.8 °C, the unit achieved a power output of 2.13 W and the conversion efficiency of 6.17%. Therefore, the proposed TE solar collector concept is anticipated to contribute to wider applications of the TE hybrid systems due to the increased overall efficiency.

1. Introduction

Every energy generation and transmission method affects the environment. It is obvious that conventional generating options can damage air, climate, water, land and wildlife, landscape, as well as raise the levels of harmful radiation. Renewable technologies are substantially safer offering a solution to many environmental and social problems associated with fossil and nuclear fuels. Solar energy is one type of renewable energy, which provides obvious environmental advantages in comparison to conventional energy sources, thus contributing to the sustainable development of human activities [1]. Not counting the depletion of the exhausted natural resources solar energy's main advantage is related to reducing CO_2 emissions, and normally it is absent in any air emission or waste product during operation. Solar energy has the potential to meet a significant proportion of the world's energy needs [2]. It can be broadly classified into two systems; a thermal energy system, which converts solar energy into thermal energy; and an electrical system, which converts solar energy into electrical energy. Normally, these two collection systems are used separately. It has been shown that these systems can be combined to form a hybrid photovoltaic-thermal (PVT) systems. The heat accumulated in the solar cells is recovered in the form of low-temperature thermal energy, resulting in improvements in the electrical conversion efficiency of PV modules. Over the last few years, different PVT systems, based on air and water as heat carrying fluid, have been studied, developed and reported in literature. For example, Kalogirou [3] has studied experimentally an unglazed hybrid PVT system under the force mode of operation for climatic condition of Cyprus. He observed an increase in the mean annual efficiency of a PV solar system from 2.8% to 7.7% with a thermal efficiency of 49%. Hagazy [4] and Sopian et al. [5] investigated a glazed PVT air system for a single and double-pass air heater for space heating and drying purposes. They have also developed a thermal model of each system. Thermal energy for the glazed PVT system is increased with lower electrical efficiency due to high operating temperature. However, there is another technology for combined electrical and thermal energies namely: thermoelectric (TE) technology. The term TE refers to solar thermal collectors that use TE devices as an integral part of the

* Corresponding author. Tel.: +66 43 754 316.
E-mail address: freeconvect@hotmail.com (C. Lertsatitthanakorn).

0927-0248/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.solmat.2008.03.018

absorber plate. The system generates both thermal and electrical energy simultaneously.

A TE device for power generation consists of n and p semiconductors connected electrically in series and thermally in parallel. Heat is supplied at one end of the TE, while the other end is maintained at a lower temperature with a heat sink [6]. As a result of the temperature difference, a current flows through an external load resistance. TE has the advantage that it can operate from a low grade heat source such as waste heat energy. It is also attractive as a means of converting solar energy into electricity. A number of simulations as well as experimental studies have been reported on solar-driven TE power generators. Chen [7] derived a thermodynamic analysis of solar-driven TE power generator based on a well-insulated flat plate collector. A thermodynamic model including four irreversibilities is used to investigate the optimum performance of a solar-driven TE generator. The example discussed by Chen is based on an extremely well-insulated flat plate collector, which, in practice, may be difficult to achieve. Gunter et al. [8] constructed a prototype of a solar thermoelectric water heater. The hot side of TE module was heated by solar hot water. Meanwhile, the heat was released at the cold side of TE module via a heat sink. Three vacuum tubes with heat pipes, each with a 0.1 m^2 absorber area and with water as the heat pipe medium, were connected via a specially designed heat exchanger to a fluid circuit acting as a heat sink. Test result showed that the electrical efficiency reached a maximum value of 1.1% of the incoming solar radiation, which is around 2.8% of the transferred heat. Scherrer et al. [9] presented a series of mathematical models based on the optimal control theory to assess the electric performance of a skutterudites-based solar TE generator as a function of sun-spacecraft distance, and optimized its design parameters (such as dimensions, weight and so on) when operating at a distance of 0.45 a.u. from the sun, for 400 W electrical output power and for a required load voltage of 30 VCD. The simulation results indicated that the skutterudites-based solar TE generator offered attractive performance features as primary or auxiliary power source for spacecraft in near-Sun missions. Maneewan et al. [10] studied a thermoelectric roof solar collector (TE-RSC) to reduce roof heat gain and improve indoor thermal comfort. Maneewan's TE-RSC combined the advantages of a roof solar collector and TE to act as a power generator. The electric current produced by the TE modules was used to run a fan for cooling the modules and improve the indoor thermal conditions. The subsequent simulation results, using a real house configuration, showed that a TE-RSC unit with a 0.0525 m^2 surface area could generate about 1.2 W under solar radiation intensity of about 800 W/m^2 and at ambient temperatures varying between 30 and 35 °C. The induced air change rate varied between 20 and 45 ACH (number of air changes per hour) and the corresponding ceiling heat transfer rate reduction was about 3–5 W/m^2. The electrical conversion efficiency of the proposed TE-RSC system is 1–4%.

In this work, an attempt has been made to develop and test a TE solar air heater to study the performance under the tropical climate of Mahasarakham, Thailand.

2. Analysis

The thermal output Q_{th} and electrical output P of the TE solar collector are calculated from the measured data by:

$$Q_{th} = mC_p(T_{aco} - T_{amb}) \tag{1}$$

$$P = I_{mp}V_{mp} \tag{2}$$

where C_p is the specific heat at the average air temperature, m is the air mass flow rate, T_{aco} and T_{amb} are the air temperature at the outlet of collector and ambient temperature, respectively. I_{mp} and V_{mp} are the maximum current and voltage of the TE modules at a matched load.

Theoretically, the maximum power output of a realistic TE module takes into account the contact resistance as given by [11]

$$P = \frac{\alpha^2}{2\rho}\frac{NA(T_h - T_c)^2}{(L+n)(1+2rL_c/L)^2} \tag{3}$$

where T_h and T_c are the hot side and cold side of thermoelectric, respectively.

Typically, $n = 0.1$ mm, $r = 0.2$, $L = 1.2$ mm, $L_c = 0.8$ mm, $\alpha = 2.1226 \times 10^{-4}\,VK^{-1}$, $N = 127$ couples, $\rho = 2.07 \times 10^{-3}\,\Omega\,cm$ and $A = 1.96\,mm^2$.

The heat released from the heat sink at the cold side of TE modules is calculated from

$$Q_w = mC_p(T_{aho} - T_{amb}) \tag{4}$$

where T_{aho} is the air temperature at the outlet of heat sink

The performance of a TE solar collector can be described by a combination of efficiency terms. The basic ones are the thermal efficiency η_{th} and the conversion efficiency η_c are calculated based on the following definitions:

$$\eta_{th} = \frac{Q_{th}}{A_aG} \tag{5}$$

$$\eta_c = \frac{P}{A_{TE}G} \tag{6}$$

where A_a is the aperture area of absorber plate, A_{TE} is the area of TE modules and G is the incident solar radiation.

The total efficiency η_o is commonly used to assess the overall performance

$$\eta_o = \frac{(Q_{th} + P - P_b)}{A_aG} \tag{7}$$

where P_b is blower power.

3. Description of the TE solar collector and experimental methodology

The schematic view of the TE solar collector is shown in Fig. 1. The TE solar collector was composed of a glass cover, air gap, galvanized iron plate and TE modules with the hot side attached directly to the back side of the galvanized iron plate acting as absorber, and rectangular fin heat sink directly attached to the cold side of the TE modules. The space between the TE modules, absorber and heat sink was insulated using the closed cell elastomeric thermal insulator (thermal conductivity = 0.039 W/mK). The collector was 1 m wide, 1.5 m long, with an aperture area of 1.5 m^2. It also had a 0.11 m flow duct height (air gap), leading to a flow area of 0.11 m^2. The absorbing sure surface in the collector was made of galvanized iron, 2.5 mm thick, painted with dull black. Twenty-four TE cooling (model TEC1—12708, China) modules are made of bismuth telluride-based alloys were used. Each module had an area of $4 \times 4\,cm^2$. The TE modules were connected in series and arranged in 4 rows with 6 TE modules in each row. The rectangular fin heat sink on the cold side was made of aluminum. The fins were 4.5 mm thick; 120 mm long in the horizontal direction and had a height of 40 mm from the base with a fin space of 7 mm. A centrifugal blower was used to circulate the air through the rectangular fin heat sink and the collector. The collector was oriented to south and tilted so as to adjust an angle of 16° from horizontal, which was considered suitable for the geographical location of Mahasarakham, Thailand (16°14′N, 103°15′E) [12].