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Co-generation of heat and power in a thermoelectric system equipped with Fresnel lens collectors using active and passive cooling techniques

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ABSTRACT

A Fresnel lens collector was incorporated in a thermoelectric solar system for combined heat and power (CHP) generation. Two passive (heat pipe thermo-siphon) and active (pumped circulation) cooling systems were used for transferring heat from the cold side of thermoelectric generators to a thermal energy storage. Experimental results from the solar thermoelectric (STE) CHP system equipped with passive cooling showed that the maximum output power of the thermo-siphon from the thermoelectric generators (TEGs) was 70 W/m^2. This system also generated 3.8 kW/m^2 thermal power in a clear September day from 10:30 to 15:30. The thermal efficiency of the thermo-siphon configuration was 18.05% and its total efficiency (electrical and thermal efficiency) was 18.39%. Additionally, experimental results of the STE CHP system equipped with active cooling were indicative of 33.15% thermal efficiency and 33.88% total efficiency at a flow rate of 700 ml/min. The maximum generated power and stored thermal energy of the system were 143 W/m^2 and 6.5 kW/m^2, respectively.

1. Introduction

Solar energy technologies are widely used for generating heat and power and even for cooling residential, commercial and industrial areas. The most significant of these systems are: photo biological systems, photovoltaic systems, solar chemical systems, and solar thermal systems [1]. Hybrid systems, which convert and store the excess energy, can be used as a solution to the problem of an intermittent solar energy source that is unavailable at nights and during overcast weather conditions [2]. Thermoelectric (TE) power generation is a proper technique used in hybrid systems to generate power from thermal energy [3]. Given the various colors of the solar spectrum, TEGs can be used in solar systems with a broad solar energy spectrum in order to simultaneously generate both electricity and solar heat at high temperatures [4]. To produce thermoelectric effects, there is no need for chemical changes in materials. They are highly flexible in design as they can be developed in flat, cylindrical or other shapes depending on the cooling source [5]. Besides the advantages of thermoelectric systems (*e.g.* no mechanical parts, clean and noiseless operation, small scales and light weight, and high reliability), these systems suffer from drawbacks including removal of heat from the cold side of the TEGs [6]. This can be countered by attaching a finned radiator for cooling. These cooling systems are however sizable with limited efficiency. In order to increase the electrical efficiency of these systems, heat is transferred from the hot side of the TEG. Research shows that these systems can be cooled by thermo-siphons as passive heat pipes used for transferring heat from the back of the TEG (the hot side of the thermoelectric module) with high efficiency and low cost [7,8]. Accordingly, this study used thermo-siphon heat pipes as a means for passive heat transfer from the hot surface of TEGs to a condenser located in a water tank. Moreover, in photovoltaic-thermal (PVT) systems, solar energy is used for co-generating heat and power. The performance of these systems drops within the low temperature range (30–80 °C). Results obtained from PVT systems equipped with a concentrator reveal that these systems have a higher conversion efficiency than their simpler PVT counterparts [9]. When temperature rises in these systems, there would be a considerable loss in power conversion efficiency due to the recombination of internal carriers in PV cells [10].

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On the contrary, TEGs have improved conversion efficiency at higher temperatures since they directly convert heat into electrical energy [11]. Incorporating concentrators into solar power generation systems can boost efficiency and/or reduce the number of solar cells per given generated power. The main problem of using these systems is the high temperature of solar cells that adversely affects their life and can even damage the system at high concentration ratios [12]. Fresnel lens concentrators facilitate absorption of high solar energy levels from a small surface area. In recent years, Fresnel lenses have become a top choice for developing solar concentrators, backed by their numerous advantages including small size, light weight, mass production at low cost, and effective increase in energy density [13]. Against this background, a concentrator system with a Fresnel lens was used.

There has been extensive research on Fresnel lenses mainly focusing on thermal analysis of a Fresnel lens solar collector [14], optical and thermal efficiency analyses of a Fresnel lens collector [15], comparison of thermal efficiency of a flat-plate Fresnel lens collector [16], comparison between two types of linear and spot Fresnel lenses [17], and evaluation of a greenhouse equipped with Fresnel lens and photovoltaic cover [18].

He et al. [19] studied experimental and analytical methods of incorporation of thermoelectric modules with glass evacuated-tube heat-pipe solar collectors. Results showed that a good agreement between the simulation results and experimental data. The simulation results show that for the water temperature of 45 °C and the solar irradiation of larger than 600 W/m^2, the SHP-TE unit may have a thermal efficiency of about 55% and electrical efficiency of above 1%.

Another research studied the system design of a combined thermo-syphon and thermoelectric modules (TTMs) for generation of electricity from low-grade thermal sources like a solar pond. In this case a TTM module with 16 thermoelectric cells was able to provide maximum power of 3.2 W, which was obtained at 13.4 V and 0.24 A (temperature difference of 27 °C). Open-circuit voltage and the short-circuit current values were 26 V and 0.4 A, respectively [20].

An analysis of a hybrid solar thermoelectric (HSTE) system, which uses a thermo-siphon to passively transfer heat to a bottoming cycle for various applications shows an optimum-efficiency range of 34.4%, 48.1%, and 52.6% at different temperatures [21].

Hasan Nia et al. [22] studied electricity and preheated water generation by thermoelectric cells. In their research, a Fresnel lens and a thermoelectric module were utilized. Results showed that output power was 1.08 W with 51.33% efficiency under solar radiation intensity of 705.9 W/m^2. Electrical power was 1.038 W with a flow rate of 0.002 kg/s and an initial temperature of 19 °C.

In another study, a solar concentrating thermoelectric generator using the micro-channel heat pipe array was designed. The experimental and simulation results were compared between the solar concentrating TEG with a micro-channel heat pipe array and a TEG in-series. The research findings showed that the STEG-MCHP had a higher output power than the TEGs in series with similar selective absorbing coating area [23].

Fan et al. [24] analyzed a concentrator thermoelectric generator (CTEG) theoretically and experimentally by utilizing solar thermal energy. Under maximum heat flux, a single TEC generator produced 4.9 W (temperature difference 109 °C), and electrical efficiency was 2.9%. The overall CTEG system was able to produce electric power of up to 5.9 W (temperature difference of 35 °C) with a hot-side temperature of 68 °C.

The theoretical analysis and experimental validation on the transient behavior of a proposed combined solar water heating and thermoelectric power generation system were performed. Results showed that with 75 °C temperature difference across the TEG hot and cold side, an open-circuit voltage of 3.02 V can be generated for each thermoelectric generator [25].

There is also research on different areas of a thermoelectric generator equipped with a solar concentrator [26], electricity production from a thermoelectric module by using parabolic concentrator [27], real-time study of solar thermoelectric generator [28], experimental evaluation of an active solar thermoelectric radiant wall system [29], and combination of solar cells and thermoelectric [30].

The literature review shows that there is few studies on generation of combined heat and power in a thermoelectric system that is equipped with Fresnel lens collectors using active and passive cooling techniques. In this research, a linear Fresnel lens was used for concentrating sunlight on thermoelectric cells. The absorbed heat was transferred to cold water in a heat exchanger to produce hot water. A thermoelectric generator (TEG) was also employed between the Fresnel lens and cold water for power generation. The study analyzed the effect of various cooling systems on thermal efficiency, open-circuit voltage, current and power. Theoretical and experimental analyses were also evaluated in different treatments. Thus this research aims to compare two cooling systems (active and passive) for production of combined heat and power. The main objective of this design is to study the CHP system with a solar technology in the building applications. Therefore, given the high potential of Iran in terms of solar energy, this study focused on evaluation of heat and power co-generation using a solar thermoelectric system equipped with Fresnel lens concentrators and two active and thermo-siphon cooling systems.

2. Materials and methods

2.1. Experimental Setup

Experiments were conducted in September 2015 at Vardavard (latitude 35.67° Northern and longitude 51.43° Eastern) in western Tehran. The inflow rate, solar radiation intensity, ambient temperature and water temperatures at inlet and outlet were measured in these experiments. Fig. 1a shows the experimental setup and Fig. 1b shows the schematic of thermoelectric solar CHP system.

Generally, two types of Bi_2Te_3 TECs are available: Seebeck cells and Peltier cells [31]. Experimental results indicate similar electrical and thermal characteristics for Peltier and Seebeck cells up to 150 °C [32].

Considering the temperature range of the collector's surface in the Fresnel lens concentrator, a total of ten bismuth telluride (Bi_2Te_3)-based thermoelectric modules (TEC1-12704) were used. Moreover, two-phase water-copper heat pipes (thermo-siphons) were used within the 27–227 °C temperature range, based on the temperatures experienced during the study. The condenser section of the thermo-siphon consisted of a thermal energy storage and a heat exchanger connected to the adiabatic section of the thermo-siphon using a steam hose. The vapor from the heat-transfer fluid (HTF) entered the heat exchanger inside the thermal energy storage by passing through the adiabatic section of the thermo-siphon, where it lost its energy, converted back into liquid, and was returned to the evaporator. Fig. 2 shows the schematic of energy flow.

In this study, a coil-type heat exchanger was used in the design due to its simple structure, high heat transfer rate, small size, low fouling and its applicability to highly-viscose fluids. Additionally, the helical geometry of these exchangers help bearing high temperatures and pressures. Fig. 3 presents a side view of the system's evaporator.

A total of 7 temperature sensors (SMT160) with a temperature range of -45 °C to $+130$ °C and an accuracy of 1.2 °C were used for