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Solar intensity measurement using a thermoelectric module; experimental study and mathematical modeling

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ABSTRACT

The present study is intended to design, manufacture, and modeling an inexpensive pyranometer using a thermoelectric module. The governing equations relating the solar intensity, output voltage, and ambient temperature have been derived by applying the mathematical and thermodynamic models. According to the thermodynamics modeling, the output voltage is a function of solar intensity, ambient temperature, internal parameters of thermoelectric module, convection and radiation coefficients, and geometrical characteristics of the setup. Moreover, the solar intensity can be considered as a linear function of voltage and ambient temperature within an acceptable range of accuracy. The experiments have been carried out on a typical winter day under climatic conditions of Semnan (35°33′N, 53°23′E), Iran. The results also indicated that the output voltage is dependent on the solar intensity and its maximum value was 120 mV. Finally, based on the experimental results, two correlations, with the accuracy of 10%, have been proposed to predict the solar intensity as a function of output voltage and ambient temperature. The average values of total heat transfer coefficient and thermal resistance of the heat-sink have been also calculated according to the thermodynamic modeling and experimental results.

1. Introduction

Thermoelectricity is generally connected with thermal and electrical phenomena. Thermoelectric modules are able to convert thermal energy into electrical energy or vice versa [1]. One of the most important applications of thermoelectrics is to generate electrical power from thermal sources, especially dissipated heat or free thermal sources such as solar energy. Although the low conversion efficiency of thermoelectric modules, according to their low producing power, however due to the high speed of technology and hope of acquiring advanced technologies as well as new material in the near future, it is expected that this technology can be used as one of the alternative technologies for generating electrical power. In this regard, more attentions has been focused on the applications of thermoelectric in various industries, recently [2–5].

Thermoelectric modules are classified into thermoelectric coolers (TECs), and thermoelectric generators (TEGs). Thermo-electric modules are environment friendly, modular, highly reliable, and they have very long life. The most important advantage is their ability to convert low amounts of heat into electricity. [6,7].

One of the first investigations in the area of generating power from the solar energy using thermoelectric generator has been reported by Goldsmid et al. [8]. They investigated the efficiency of a bismuth telluride thermoelectric used in a flat plate collector and an asymmetric stationary concentrator collector on the generation of electrical power from solar intensity. Their results indicated that the overall efficiency of them is one percent for the former system and three percent for the later one. Omer and Infield [9] designed a two stage solar energy concentrator and used thermoelectric generator to generate electrical power from the system. The found out that in addition to improving the concentration efficiency, the second stage compound parabolic concentrator improves the overall performance of the solar concentrator. In another study, the effects of using thermoelectric modules on the power generation from solar energy have been experimentally investigated by Maneewan et al. [10]. According to their results, using ten thermoelectric modules in solar intensity of 800 W/m^2 and ambient temperature of 30 °C, 1.2 V of the output voltage can be achieved. The applications of solar thermoelectric generator in the micro-power systems have been investigated by Amatya and Ram [11]. Their results indicated that the efficiency and the output power of their system were 3% and 1.8 W, respectively. In another

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Nomenclature

A	area, m^2
a	accuracy
h	heat transfer coefficient, W/m^2 K
I	electrical current, A
$I(t)$	solar intensity, W/m^2
K_m	thermal conductivity of thermoelectric module, W/K
W	electrical power, W
q	heating Transfer, W
R_m	electrical resistance of thermoelectric module, Ω
$R_{Heat\ sink}$	resistance of heat sink, $K{\cdot}W^{-1}$
T	temperature, K
u	uncertainty
V	voltage, V

Greek symbols

α_m	Seebeck coefficient, $m^2\ s^{-1}$
α_{ab}	absorptivity
ΔT	temperature difference, K

Subscripts

a	ambient
c	convective
g	glass
H	hot
C	cold
oc	open circuit
T	thermoelectric
r	radiative

experimental investigation, Chen et al. [12] studied the effects of thermoelectric modules on power generation at different operating conditions. They found that by increasing the number of modules in series, the output power increases. Shanmugam et al. [13] conducted an experimental study on energy and exergy efficiency of a solar parabolic dish using thermoelectric generator. Their results showed that the maximum and daily average temperature of the receiver plate were approximately 190 °C and 127 °C and the energy and exergy efficiency were in the range of 0.94–1.68% and 1.01–1.81%, respectively. Hasan Nia et al. [14] experimentally studied the performance of a preheated water heater cogeneration system combined with thermoelectric modules. They used a Fresnel lens with an area of 0.09 m^2 to concentrate solar energy to the absorber plate. They reported a load output power of 1.08 W with 51.33% efficiency under radiation intensity of 705.9 W/m^2. Moraes et al. [15] studied the performance of a solar thermoelectric generator under different wind speeds and reported higher performance for the system in low wind speeds. Apart from what has been mentioned above, there are other investigations reporting different aspects of thermoelectric modules [16–18].

A pyranometer can be defined as an instrument, which is able to measure the total amount of solar radiation reaching a horizontal plane on the surface of earth. The data collected by a pyranometer can express a vast range of information including location, diurnal cycle, weather, seasons, and climate, which are used in different applications such as meteorology and agriculture. Pyranometers are divided into two categories; the expensive kind and the much less expensive type. First type pyranometers uses thermopiles while in second type small silicon-based photo-detectors are used. Researchers using high accuracy pyranometers in developing countries often experience some problems due to the higher price of these instruments. On the other hand, high radiometric accuracy is not required in some applications such as agriculture and environmental monitoring or even some experimental applications, therefore the price would play an important role in selecting the instruments. As mentioned before, thermoelectric coolers are inexpensive, reliable, and noiseless, with no moving part and they are long lasting. Designing and fabricating of a pyranometer using thermoelectric coolers would be useful and practical in broad range of applications due to their inexpensiveness and the acceptable range of accuracy.

From what has been discussed above and to the best of the authors' knowledge, although many experimental and numerical investigations have been conducted on thermoelectric coolers, there is not enough comprehensive and detailed scientific report on their application in solar radiation measurements. On the other hand, commercial pyranometers are patented facilities, and the detailed scientific idea behind them for solar intensity measurement is confidential.

Hence, the main objective of the present study is to design, fabricate, and modeling a pyranometer using the valuable characteristics of thermoelectric coolers. Another goal of this study is to reveal the possible design details lies behind solar pyranometers. To this end, mathematical and thermodynamics modeling have been conducted. Furthermore, experimental tests under real climatic conditions have been carried out. Finally, two correlations for predicting the solar intensity with respect to the output parameters of the setup as well as ambient conditions have been proposed.

2. Theoretical background

Fig. 1 illustrates a schematic view of a thermoelectric generator. In this device, heat is entered from the hot side of thermoelectric and exited from the cold side. The temperature difference between the two sides would result in a potential difference in the thermoelectric module.

The value of the input and output heat from two sides of a thermoelectric generator can be calculated as follows [20–22]:

$$q_h = \alpha_m I T_H - 0.5 R_m I^2 + k_m \Delta T$$
$$q_c = \alpha_m I T_C + 0.5 R_m I^2 + k_m \Delta T \quad (1)$$

where

$$\Delta T = T_H - T_C \quad (2)$$

The generated voltage difference in the module due to the temperature difference can be calculated as follows:

$$V = \alpha_m \Delta T - I R_m \quad (3)$$

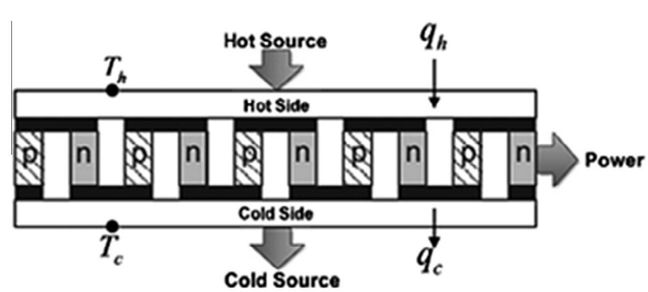

Fig. 1. Schematic view of a thermoelectric generator [19].