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Multiphysics simulations of thermoelectric generator modules with cold and hot blocks and effects of some factors

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ABSTRACT

Transient and steady-state multiphysics numerical simulations are performed to investigate the thermal and electrical performances of a thermoelectric generator (TEG) module placed between hot and cold blocks. Effects of heat radiation, leg length and Seebeck coefficient on the TEG thermal and electrical performances are identified. A new correlation for the Seebeck coefficient with temperature is proposed. Radiation effects on the thermal and electric performances are found to be negligible under both transient and steady-state conditions. The leg length of the TEG module shows a considerable influence on the electrical performance but little on the thermal performance under transient conditions. A nearly linear temperature profile on a leg of the TEG module is identified. The temperature profile of the substrate surfaces is non-uniform, especially in the contacted areas between the straps (tabs) and the substrates.

1. Introduction

An integrated or hybrid compound parabolic concentrator (CPC) with photovoltaic (PV) and other thermal techniques have been proposed recently to improve the solar energy utilisation efficiency potentially. Conventional concentrated solar power technologies were reviewed and applicability particularly in West African countries was discussed in [1]. The effects of a CPC trough and thermal collector on the electrical performance of a solar panel were analysed in [2], and a solar cell with a CPC trough was cooled by two air streams through the CPC and fins installed on the back cover of the cell as demonstrated in [3,4].

A hybrid photovoltaic-thermal water heating system was developed recently for residential applications [5,6]. The system was subject to 37.6–48.65% thermal and 10.3–12.3% electrical efficiencies. In [7], a silicon thin-film solar cell, thermoelectric generator (TEG) and heat collector were integrated together. A solar TEG was also proposed by Amatya and Ram [8] for micro-power applications by means of a cheap parabolic concentrator. CPC, solar module and thermal collectors were incorporated together in [9], resulting in a 62–67.9% averaged optical efficiency per day. An analytical model for solar module with CPC and TEG devices was established in [10] and the effects of thermal conductance between the module and the TEG, current of module, irradiance, concentration ratio and figure of merit of TEG on performance were studied. In [11], a TEG, CPC and heat exchanger were integrated together to form a hybrid electric/thermal energy conversion device with the best conversion efficiencies, 0.6% and 43.3% in

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electricity and thermal energy at a water flow rate of 0.24 kg/s, respectively.

In our funded project, we aim to develop an integrated CPC, PV, TEG and other thermal techniques for a further increase working efficiency of a PV module. In doing so, a numerical method is needed to characterize the steady-state and transient thermal and electrical performance of a TEG module when the temperature, geometrical and electrical parameters of the TEG are varied.

Previously, the modelling of the TEG module was carried out by using 1D simulation methods usually applied to a single thermocouple (two legs) [12–16]. These models were developed for simulator software such as SPICE [12,13], Modelica [14], and MATLAB/Simulink [15,16] and they were capable of predicting electrical and thermal performance of the TEG. An unsteady heat conduction model with Joule heat generation for a TEG was also developed in [17] to study the transient thermal performance, while Alata et al. [18] developed a hyperbolic heat conduction model and investigated the dynamic thermal behaviour of a TEG. Nguyen and Pochiraju [19] considered both the Joule heating and Thomson effects. The TEG model with constant thermal and electrical properties was subject to variable heat sources.

More recently, thermal and electrical finite element methods were applied into TEG modules without a heater and heat sink in [20–26]. The method in [20] was applied to a single pellet and a parametric analysis of a multi-stage Peltier cooler was presented. The steady cooling performance of a thermo-electrical micro-cooler was analysed in [21] using COMSOL. The geometrical parameters of the cooler were optimised under various temperature differences without thermal and electrical contact effects. The leg and thermal and electrical properties of the TEG were inversely determined with an approach based on experiments and finite element least squares in [22]. Chen et al. [23] used the 3D finite volume method in ANSYS 12.0.1 and investigated steady-state performance of a miniature thermo-electrical cooler with and without considering the Thomson effect. The thermal and electrical properties of the legs were variable with temperature, however, the thermal and electrical contacts were neglected. ANSYS was also applied by Xiao et al. [24] to characterise the steady electrical performance of one- and two-stage TEGs with different materials, but the thermal and electrical properties were constant again and without thermal and electrical contact effects. Thermal stress and deformation in TEG module legs were estimated by using finite element analysis in [25,26] and high stress concentration and large deformation were found on the edges of the TEG contact with the hot substrate.

The studies above are obviously fruitful and respected. However, in these steady thermal and electrical performance simulations, the heater (hot block) and heat exchanger (cold block) of a TEG module have not been considered. Even though a transient thermal and electrical performance of a TEG module with heater and heat exchanger was conducted in [27], the effects of leg length and the Seebeck coefficient, steady performance, and mesh independence study were not involved. The temperature along the leg of the TEG was also not demonstrated.

In this article, we study the transient thermal and electrical performance of a TEG system comprising a TEG, heater (hot block) and heat exchanger (cold block) by means of ANSYS 15.0 Thermal-Electric System. Additionally, the thermal and electrical contacts as well as radiation effects are taken into account. To characterise the TEG module performance, results are presented for a number of important variables such as temperature, Joule heat, electrical current and voltage profile in the TEG. The temperature along one leg of the TEG is shown to demonstrate the thermal and electrical coupling effect. A new scaled Seebeck coefficient for Bi_2Te_3 is also proposed.

2. Models, boundary conditions and methods

2.1. Computational models

The experimental test rig and instrument shown in Fig. 1(a)–(c) were developed in [28] to characterise various TEG modules suitable for solar energy harvesting systems. The experimental set-up consists of a cold block with cooling water pipes, TEG module, hot block with an electric heater, a vermiculite insulating layer, a bottom steel plate, and a top load cell/sensor which is used to measure a force applied on the cold block. By using this force the hot block, TEG and cold block can be held together firmly. Experimental data were collected from the load cell, thermal couplings installed in the heat exchanger inlets and outlets, on the TEG top substrate contacted with the cold block, on the TEG bottom substrate attached to the hot block and on a surface of the heater by a data logger connected to a PC. This set-up allows measurement of both transient and steady-state thermal and electric performance of the TEG module.

The method for measuring the electric performance of a TEG module has been described completely in [28]. The main idea is to pick up the current and voltage through and across a TEG module when the electrical current load in an external electrical circuit connected with the module is changed with a certain step from open-circuit operating point to short-circuit point at a specific temperature difference across the module. The control program used in the electrical experiment was able to check the temperature difference based on the signals from the thermocouples and control the current in the heater. The prescribed mechanical loading generated by a spring applied on the load cell/sensor remains constant during the electrical experiment.

We characterised the thermal and electrical performance of the TEG model GM250-127-14-10 (European Thermodynamics Ltd) by means of ANSYS 15.0 Thermal-Electric System and compared results with those presented in [29]. The computational model includes a load sensor, a cold block, a TEG module, and a hot block, as shown in Fig. 1(d). The hot and cold blocks are subject to conductive heat transfer, while the TEG module experiences a coupled thermoelectricity process.

The governing equations of conductive heat transfer and thermoelectricity are detailed in [20], including the Peltier and Thomson effects. The steady continuity of electrical current density and the coupled heat transfer and thermoelectricity equations in the isotropic and homogenous legs, copper straps and leads are as follows [20]: