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Multiphysics Simulations of a Thermoelectric Generator

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Abstract

Transient multiphysics simulations are performed to investigate the thermal and electric performance of a thermoelectric generator (TEG) module placed between hot and cold blocks. Effects of heat radiation, thermal and electric contact on the TEG are examined and the simulated results are compared with experimental data. The predicted temperature difference across the TEG module and the electric voltage and power are in very good agreement with the experimental data. The radiation effect on the thermal and electric performance is negligible and the temperature at the interface of the TEG module substrates is predicted to be non-uniform. The peak temperatures are found in the both ends of the legs, and the maximum Joule heat is generated at the leg ends connected with the hot substrate.

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Keywords: thermoelectric generator; TEG; transient simulation; heat transfer; thermal contact

1. Introduction

Integrated or hybrid compound parabolic concentrated photovoltaic (CPC-PV) and thermoelectric (TE) systems have been proposed recently for solar energy applications [1-3]. In our EPSRC-funded project "SUNTRAP", a key objective is to develop a novel integrated CPC, PV, TEG and thermal system capable of harvesting solar energy with an increased utilisation efficiency. Thus, it is necessary to establish a suitable numerical method for characterizing both thermal and electrical performance of a TEG module and thermal-mechanical coupling as well as optimizing its design configuration.

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A TEG system is usually composed of a TEG, a heating block and a heat sink block. Thermal and electric finite element methods (FEMs) have been applied to TEG modules without heater and heat sink [4, 5]. Thermal stresses and deformation in TEG module legs are studied in [6]. However transient thermal and electric performance of a TEG module with heating block and heat sink block has not been covered yet. Radiation effects, thermal and electric contact in each interface in the TEG module were not included.

This paper studies the overall performance of a TEG module taking into account thermal and electric contact resistance as well as thermal radiation.

2 Computational Models and Boundary Conditions

2.1 Computational Models

The experimental set-up is shown in Fig. 1(a) and consists of a water-cooled block, a TEG module, a hot block with an electrical heater inside, a vermiculite plate, a bottom steel plate and a top load generator with sensor, as well as a data logger [7, 8]. The corresponding computational model is shown in Fig. 1(b).

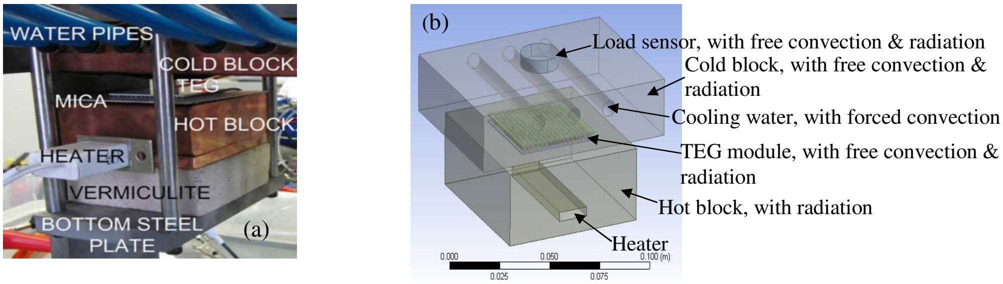

Fig. 1 (a) Experimental set-up [7] and (b) computational model.

The hot and cold blocks are subject to conductive heat transfer, while the TEG module experiences a coupled thermoelectricity process. Governing equations of the conductive heat transfer and thermoelectricity include both Peltier and Thomson effects. Thermal and electric properties of the materials used for the hot and cold block, TEG module and sensor are isotropic and listed in Table 1. Note that the thermal conductivity, resistivity and Seebeck coefficient are temperature-dependent and corresponding equations are given under Table 1.

Table 1 Thermal and electrical properties of materials

Component		Material	Density (kg/m^3)	Specific heat capacity (J/(kgK))	Thermal conductivity k (W/(mK))	Emissivity	Resistivity s (ohm m)	Seebeck coefficient α (V/K)
Sensor		steel	7750	480	15	0.35	N/A	N/A
Cold block Hot block		copper	8300	385	401	0.07	N/A	N/A
TEG	Strap lead	copper	8300	385	401	N/A	1.69×10^{-8}	N/A
	substrate	ceramic	3220	419	31	0.6	N/A	N/A
	n, p-legs	Bi_2Te_3	7740	200	a	0.9	b	c

a $k=\left(62605-277.7T+0.4131T^2\right)\times10^{-6}$, b $s=\left(5112+163.4T+0.6279T^2\right)\times10^{-8}$ and
c $\alpha=\left(22224+930.6T-0.9905T^2\right)\times10^{-9}$ after [9]

2.2 Boundary Conditions

Temperature profile against time is illustrated in Fig. 2(a) [8]. The lead connecting with the p-leg is subject to an electric current profile versus time based on the experimental data [8], as shown in Fig.2(b).

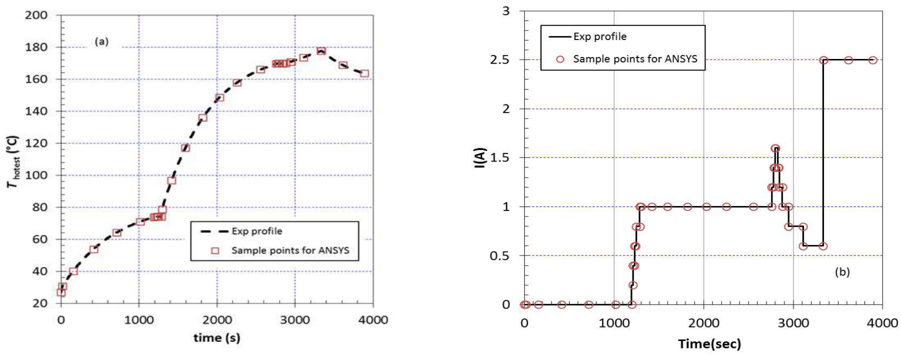

Fig. 2 Experimental temperature profile on heater five surfaces and electric current profile on the lead [8], the symbols on the curves are involved into the transient analysis, (a) temperature and (b) current.

The three holes in the cold block circulate cooling water at 19^{o}C and are subject to a forced convection coefficient of 1376.4W/(m^{2}K) based on a conjugate heat transfer analysis conducted in ANSYS CFX. All the surfaces exposed to air radiate heat with an emissivity shown in Table 1 at 19^{o}C ambient temperature. The grey radiation model is adopted in the simulation. The side surfaces of the hot block are insulated with glass fibres. Thus they are subject to a zero heat flux. However, the surfaces of the sensor, cold block, TEG and hot block exposed to the air experience a natural convection with a coefficient of 10W/(m^{2}K) at 19^{o}C ambient temperature.

There are thermal contacts in the interfaces between the sensor and the cold block, the cold block and the TEG substrate, the substrate and the strap, the substrate and the lead, the substrate and the hot block. Also, there are electric contracts in the interfaces between the leg and strap, the leg and lead. The thermal and electric contact conductance is given in Table 2.

Table 2 Thermal and electrical contact properties

Interface	Component	Thermal conductance, W/(m^{2o}C)	Electric conductance, S/m^2	Reference
1	sensor cold block	3500	×	[10]
2	cold block substrate	3500	×	[10]
3	Hot block substrate	5500	×	[10]
4	substrate strap	50000	×	[10]
5	substrate lead	50000	×	[10]
6	strap leg	×	10^9	[11]
7	leg lead	×	10^9	[11]

3 Results

3.1 Transient Thermal and Electric Performances

The transient temperature, temperature difference, electric voltage and power are shown in Fig. 3(a) and (b). The measured leg length and thickness of the TEG are 1.8mm and 1.4mm, respectively. The temperature on the hot side (hot substrate surface) of the TEG module is very good agreement with the experimental data. Unfortunately, the temperature on the cold side of the TEG is slightly over predicted when time is later than 1200sec from where the current applied starts to increase from zero. Except the time beyond 3300sec, the temperature difference across the hot and cold sides agrees well with the observation.

The predicted electric power follows the experimental curve well, but the power is slightly over estimated. Besides, even though the radiation effect is involved in the computational model, the temperature of the cold and hot sides, and the temperature difference across the sides as well as the electric power profiles do not show a notable difference from those without the effect.

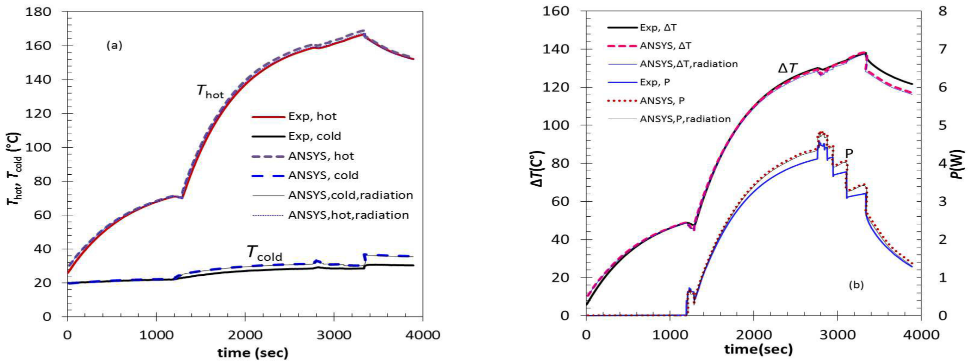

Fig. 3 (a) Temperature on the cold and hot sides of the TEG as well as (b) electric voltage and power with time.

3.3 Detailed Performance Characteristics

The detailed performance parameters refer to the temperature contours on the hot and cold blocks, the TEG module and the TEG elements, and some electric variable profiles in the TEG circuit. These parametric distributions can provide some interesting physical insights. Fig. 4 illustrates the temperature contours on the hot and cold blocks, the TEG module and the TEG elements when the heater is subject to the highest temperature of 202.9ºC and the TEG lead is at 2.4A current. This highest temperature results in the 150ºC temperature difference across the TEG module. Clearly, the temperature on the hot and cold blocks is not perfectly uniform, especially in the interfaces of the hot and cold blocks and the TEG substrates. The peak temperatures are mainly located on the two substrates of the TEG module. The temperature contour on one leg does not show any noticeable difference from the other legs.

The voltage, total current density and Joule heat profiles in the TEG module are shown in Fig.5 at the same operating conditions i.e. at the highest temperature of 202.9ºC in the heater and 2.4A current in the leads. In this case, a 150ºC temperature difference is maintained across the TEG module. Since the thermoelectric pellets are electrically connected in series, the voltage increases linearly from one lead to the other. The copper tabs are as thin as 0.2mm therefore they are subject to the maximum total current density. The maximum Joule heat occurs in the legs near the hot substrate because the tabs electric resistance is considerably lower than the legs'. These results suggest that the pellets thermal and electric properties play a vital role in the TEG module performance.

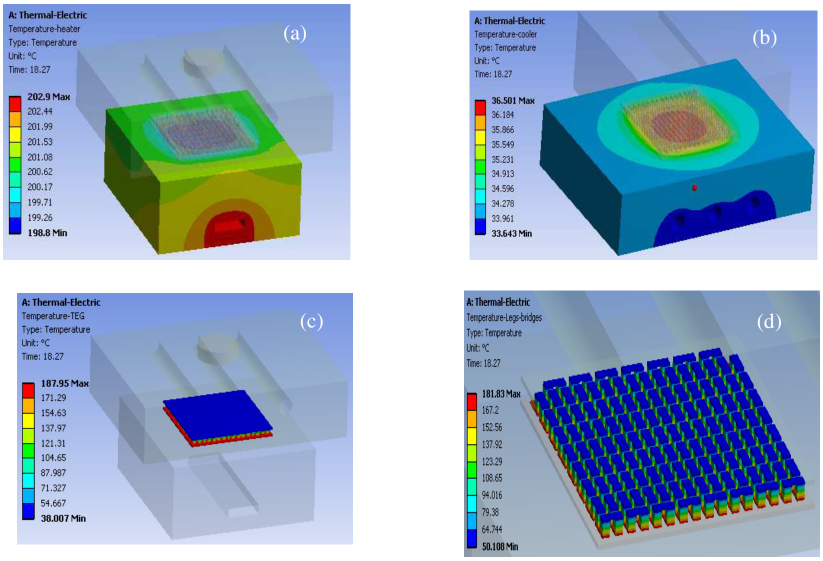

Fig. 4 Temperature contours on the hot and cold blocks, TEG module and the TEG with substrates removed at the highest temperature 202.9ºC which results in 150ºC temperature difference across the TEG module at 2.4A current, (a) hot block, (b)cold block, (c) TEG module, and (d)TEG with substrates removed.

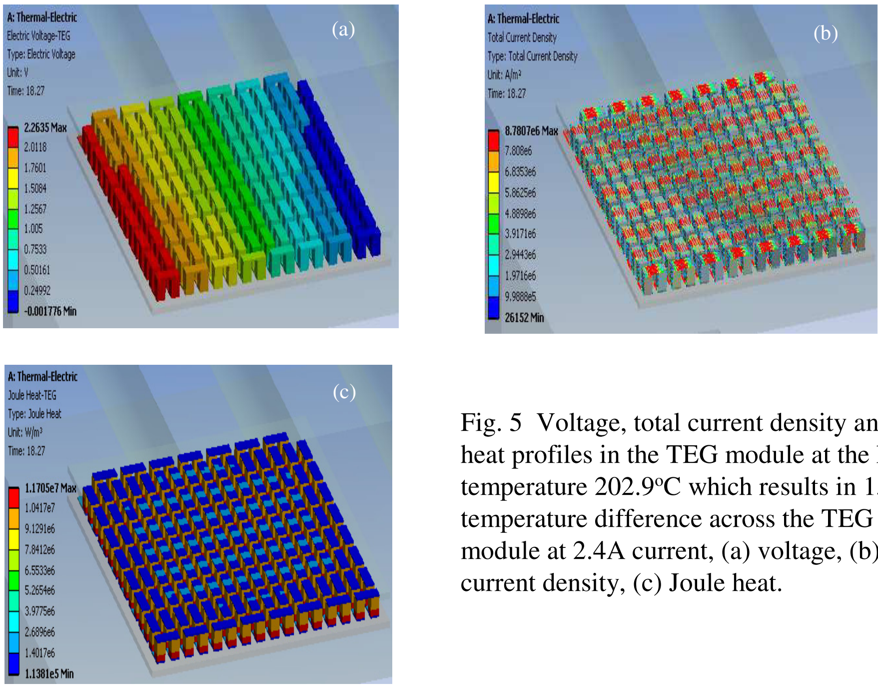

Fig. 5 Voltage, total current density and Joule heat profiles in the TEG module at the highest temperature 202.9ºC which results in 150ºC temperature difference across the TEG module at 2.4A current, (a) voltage, (b) total current density, (c) Joule heat.

4 Conclusions

Thermal and electric performance of a TEG module with hot and cold blocks is investigated numerically by using the thermal-electric coupled multiphysics analysis technique in ANSYS 15.0. The radiation, thermal and electric contact effects have been included. The performance curves and detailed performance parameters of the TEG are presented. It is identified that the predicted transient performance curves are in very good agreement with the experimental data. The radiation effect on thermal and electric performance is unnoticeable. The temperature on the interfaces of the cold and hot blocks with the TEG module substrates is not perfectly uniform. The peak temperatures are obtained at both ends of the legs; Joule heat is created inside the legs, and it is maximum at the end next to the hot substrate.

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Biography

Wenguang Li is a Research Assistant at the School of Engineering of the University of Glasgow. He has over 10-year experience in fluid dynamics, He received his PhD from the University of Sheffield, Great Britain, in 2007.