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Thermal and stress analyses in thermoelectric generator with tapered and rectangular pin configurations

Bekir Sami Yilbas [a, b, *], S.S. Akhtar [a], A.Z. Sahin [a, b]

[a] Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia
[b] Center of Research Excellence in Renewable Energy, Research Institute, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia

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Thermal stress developed in thermoelectric generators is critical for long service applications. High temperature gradients, due to a large temperature difference across the junctions, causes excessive stress levels developed in the device pins and electrodes at the interfaces. In the present study, a thermoelectric generator with horizontal pin configuration is considered and thermal stress analysis in the device is presented. Ceramic wafer is considered to resemble the high temperature plate and copper electrodes are introduced at the pin junctions to reduce the electrical resistance between the pins and the high and low temperature junction plates during the operation. Finite element code is used to simulate temperature and stress fields in the thermoelectric generator. In the simulations, convection and radiation losses from the thermoelectric pins are considered and bismuth telluride pin material with and without tapering is incorporated. It is found that von Mises stress attains high values at the interface between the hot and cold junctions and the copper electrodes. Thermal stress developed in tapered pin configuration attains lower values than that of rectangular pin cross-section.

1. Introduction

A thermoelectric generator is one of the green energy devices, which constitutes a simple mechanical system without movements. Although the efficiency of the thermoelectric generator is low, research into improvement of the device efficiency and the output power through modifying pin geometric configurations [1] and pin materials [2] are in progress. Geometrically tapering of the thermoelectric pins improves the thermal efficiency of the device [3] and increasing junction temperature of the thermoelectric generator enhances the device output power [4]. In general, the size of the thermoelectric generators is small, and temperature difference across the device junctions is high because of the quest for achieving the high Carnot efficiency of the system. The thermal efficiency and the device output power improve significantly when temperature difference increases across the thermoelectric junctions within the range of operating conditions of the thermoelectric generator pin material [4]. High temperature difference results in high strain in the thermoelectric pins, particularly in the junction regions. Thermal strains give rise to development of thermal stresses in the pins and across the pin connections in these regions. These causes pin material failure under the high thermal stress conditions during the operation. Therefore, operational life is highly influenced by the stress states in the pins, which in turn limit the practical applications of the device. Although engineered pin configurations, such as tapering, improve the device efficiency, it may have an adverse effect on the stress levels in the pins. Consequently, investigation of the thermal stress development in the thermoelectric device with and without engineered pin configurations becomes essential.

Considerable research studies were carried out to examine thermal management of thermoelectric generators. The performance of a thermoelectric generators coupled with a solar pond was studied by Ding et al. [5]. They indicated that thermoelectric generators could be used to extract heat stored from the solar ponds; however, the thermal-electrical conversion efficiency of the thermal system was low, i.e. in the range of 1%–1.5%. A waste heat recovery from the exhausted cryogenic nitrogen by using thermoelectric power generator was investigated by Weng et al. [6]. They showed that the thermoelectric generation system worked successfully despite the system efficiency remained low. The effect of radiation view factors on thermoelectric performance was

* Corresponding author. Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia.
E-mail address: bsyilbas@kfupm.edu.sa (B.S. Yilbas).

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Nomenclature

A	Cross-section area of the thermoelectric generator (m^2)
E	Energy gain (J/m^3)
I	Electrical current (A)
k	Thermal conductivity (W/mK)
$k_{e,n}$	Thermal conductivity of *n*-type semi-conductor (W/mK)
$k_{e,p}$	Thermal conductivity of *p*-type semi-conductor (W/mK)
K	Total thermal conductance in of thermoelectric generator (Ω)
K_n	Thermal conductance of *n*-type semi-conductor (W/K)
K_p	Thermal conductance of *p*-type semi-conductor (W/K)
L	Length of leg of thermoelectric generator (m)
R	Total electrical resistance in of thermoelectric generator (Ω)
R_L	External load resistance (Ω)
R_n	Electrical resistance of *n*-type leg of semi-conductor (Ω)
R_p	Electrical resistance of *p*-type leg of semi-conductor (Ω)
R_0	Reference electrical resistance (Ω)
T_1	Hot junction temperature of the thermoelectric generator (K)
T_{2n}	Cold junction temperature of the thermoelectric generator for n-type pin (K)
T_{2p}	Cold junction temperature of the thermoelectric generator for p-type pin (K)
T_{av}	Average temperature (K)
W	Power output of the thermoelectric generator (W)
Z	Figure of merit (1/K)
ZT	Dimensionless Figure of merit (−)
α	Net Seebeck coefficient of thermoelectric generator (V/K)
α_n	Seebeck coefficient of *n*-type semi-conductor (V/K)
α_p	Seebeck coefficient of *p*-type semi-conductor (V/K)
α_T	Thermal expansion coefficient (1/K)
ΔT	Temperature difference at cold junction due to p-type and n-type pins (K)
$\{\Delta\boldsymbol{\varepsilon}\}$	Overall strain vector
$\{\Delta\boldsymbol{\varepsilon}^{\mathbf{el}}\}$	Elastic strain vector
$\{\Delta\boldsymbol{\varepsilon}^{\mathbf{th}}\}$	Thermal strain increment vector
$\{\Delta\boldsymbol{\varepsilon}^{\mathbf{pl}}\}$	Plastic strain increment vector
η	Efficiency
λ	Temperature parameter
$\tau_1 = T_1/T_{max}$	Hot junction temperature ratio
$\tau_2 = T_2/T_{max}$	Cold junction temperature ratio

examined by Barry et al. [7]. The findings revealed that radiation view factor behaved non-linearly with increasing temperature ratio. In addition, increasing the leg height to width ratio of the thermoelectric pins decreased radiation view factor monolithically. The influence of Thomson effect on the performance of a two stage thermoelectric generator was studied by Manikandan and Kaushik [8]. They demonstrated that the exergy efficiency of two stage thermoelectric generator was greater than the energy efficiency of the device. Energetic and exergetic performance analyses of a solar energy-based integrated system incorporating the thermoelectric generators were investigated by Islam et al. [9]. They indicated that the maximum work done by the thermoelectric generator and cooler was increased considerably through increasing the temperature of the heat transferring fluid. The analysis of thermoelectric generator performance incorporating the pin tapering was carried out by Yilbas and Ali [10]. They demonstrated that the first and second law efficiencies were significantly influenced by the pin geometry; in which case, increasing tapering of the thermoelectric pins within the range of $2 \leq a \leq 4$ (a being the tapering slope) resulted in improved first and second law efficiencies. A multi-physics simulation of a thermoelectric generator was carried out by Li et al. [11]. They showed that the thermal radiation effect on the thermal and electric performance was negligible and the temperature at the junction of the thermoelectric module remained non-uniform. Optimal design of a novel thermoelectric generator with linear-shaped structure under different operating temperature conditions was presented by Jia and Gao [12]. They indicated that decreasing total length and/or increasing pin height could improve the device output power. Thermal characteristics of combined thermoelectric generator and refrigeration cycle were studied by Yilbas and Sahin [13]. They demonstrated that the location of the thermoelectric generator in between the condenser and the evaporator decreased coefficient of performance of the combined system. Alternatively, the location of thermoelectric device in between the condenser and its ambient enhanced coefficient of performance of the combined system. Thermoelectric device with coaxial rotated-leg configuration was examined by Erturun and Mossi [14]. They showed that the effect of rotated-leg configuration on thermal stresses and conversion efficiencies were less than 1.2% and 0.3%, respectively; therefore, considerations of rotating-leg configurations for the thermoelectric device design was not promising.

Thermal stress development in thermoelectric generator under the various operating conditions is important for the operational sustainability of the device. Therefore, investigation of the thermal stress development in thermoelectric generators becomes essential. Considerable research studies were carried out to examine thermal stress development in thermoelectric generators. A numerical simulation of the temperature gradient and thermal stress fields in a thermoelectric generator was carried out by Wu et al. [15]. They showed that under high heat flux imposing upon the hot end, the thermal stress was considerably high and it had a decisive effect on the life expectation of the device. Cracking and thermal shock resistance of the bismuth telluride based thermoelectric material was examined by Wang et al. [16]. They indicated that the maximum stress intensity factor increased with increasing of the thickness of the plate and the thermal shock resistance was improved when the plate became thinner. Thermal stress analysis of thermoelectric power generator and influence of pin geometry on device performance was studied by Al-Marbati et al. [17]. The findings revealed that the thermal efficiency improved for certain geometric configuration of the device; in which case; the maximum thermal stress developed in the pin reduced slightly indicating improved life expectation of the device. Thermally induced interfacial shearing stress in a thermoelectric module with low fractional area coverage was investigated by Ziabari et al. [18]. They demonstrated that the shearing stress could be effectively reduced by using thinner (smaller fractional area coverage) and longer (in the through thickness direction of the module) legs. Thermal stresses development in a multilayered thin film thermoelectric