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Thermoelectric energy harvesting for the gas turbine sensing and monitoring system

Yongjia Wu[a], Haifeng Zhang[b], Lei Zuo[a,*]

[a] Energy Harvesting and Mechatronics Research Lab, Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24060, United States
[b] Department of Mechanical and Energy Engineering, University of North Texas, Denton, TX 76210, United States

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ABSTRACT

A compact thermoelectric energy harvester is developed to harvest the thermal energy from the hot surface of the gas turbine, providing continuous and reliable power for the sensing and monitoring system in the gas turbine. An experimental prototype is built and the performances of the energy harvester with different electrical load resistances and source temperatures are characterized. A mathematical iterative method, taking account of Thompson Effect, line spacing gap heat leakage, material property variations, and thermal resistance of the ceramic covering layer, is used to analyze the performance of the segmented thermoelectric generator (TEG) module with good accuracy. Based on this model, the temperature profiles and heat fluxes along the thermo-elements, efficiency, and heat leakage through the filling gap material are analyzed. The prototype, with a source temperature of 325 °C, has a voltage output of 2.4 V and power output of 0.92 W, which is more than enough to power a sensor node in the gas turbine. A higher power output can be expected with some improvement on the prototype design.

1. Introduction

1.1. Thermoelectric energy harvesting

The TEG, using electrons (for N-type) and holes (for P-type) as the “working fluid”, is an attractive energy harvesting technology to convert thermal energy to electricity without any moving components [1]. The efficiency of the TEG varies with the temperature difference and ZT value, typically ranging between 1 and 20% at the current state. The primary effort to improve the efficiency of TEG device was focused on improving the materials’ figure-of-merit guiding by phonon and electron transmission theory [2,3]. Since the observation of Seebeck effect in 1821, the development of thermoelectric materials was quite slow till the discovery of semiconductors in the1950s. In 1993, Hicks and Dresselhaus [4,5] predicted that, taking advantage of the quantum effect, it was possible to achieve a ZT value higher than 10.0 in the low dimensional thermoelectric materials, including supper lattice, nanowire, and nanoparticles. This inspiring prediction significantly stimulated the research of nanostructured thermoelectric materials in the next decades. Since then, various materials with ZT values higher than 1.0 were found [6,7]. According to the newest research by Harman et al., the highest ZT reported was 3.5 in Bi-doped n-type PbSeTe/PbTe quantum-dot super-lattice [8]. Though low dimensional thermoelectric materials are theoretically predicted superior to bulk materials, fabrication of nanomaterials with stable and reliable performance can be challenging [9]. Besides nanomaterials, the highest ZT value of bulk thermoelectric material was reported to be as high as 2.6 ± 0.3 at 923 K in SnSe single crystals measured along the b axis of the orthorhombic unit cell [10]. To develop the third generation thermoelectric materials with high ZT values, researchers proposed several potential strategies, including band convergence [11,12], composition and microstructure manipulations [13], strained endotaxial nanostructuring [14], matrix/precipitate band alignment [15], and compositionally alloyed nanostructuring [16]. However, some researchers claimed that it was only when the ZT value of the commercial bulk thermoelectric material was higher than 3.0, would the TEG be able to compete with the conventional thermal engines [17]. Currently, the TEG is still restricted on relatively small scale, decentralized energy harvesting [18,19].

The system level thermal design should be equally important to achieve high performance [2,20]. To enhance the efficiency of the TEG, a large temperature difference should be sustained between the two ends of the thermo-elements. Conventionally, optimization-designed heat sinks/exchangers are mounted on the hot and cold ends of the TEG to maximize the temperature drop. For the high temperature range application, the segmented TEG, consisting of low-, medium- and high-

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[*] Corresponding author.
E-mail address: leizuo@vt.edu (L. Zuo).

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Nomenclature

Symbols

RH	thermal resistance (K/W)
L	the length of the thermos-pellets (m)
k	thermal conductivity (W/(K m))
A	cross-section area (m^2)
ε	absorption coefficient
σ	Stefan-Boltzman constant
F	relative view factor
T	temperature (K)
q	heat flow (W/m^2)
α	seebeck coefficient (V/K)
I	current (A)
V	voltage (V)
R	electrical resistance (Ω)
N	the number of thermos-couple
ρ	electrical resistivity(Ω m)
P	power output (W)
J	electrical density (A/m^2)
x	coordinate position (m)

Subscript

$P1,P2$	P-type thermo-element near to the hot/cold side
$N1,N2$	N-type thermo-element near to the hot/cold side
H,C	Hot/Cold side
G	air filling gap
h,c	hot/cold side of the thermo-element
P,N	P/N-type thermos-pellet
Ph,Nh,Pc,Nc	hot/cold side of the P/N-type thermos-pellet
$m1,m2$	the intersection of the thermo-element segments
H,C	hot/cold side of the TEG module
L	load
M	module
i	coordinates

Abbreviations

TEG	thermoelectric generator
MEMS	microelectromechanical system

temperature thermoelectric materials, are combined to maximize the overall conversion efficiency of the thermo-element by taking full advantage of the characteristics of different thermoelectric materials [21,22]. When design segmented TEG, compatibility factor issue should be carefully handled [23].

TEG technology was heavily researched in the past decades, such as harvesting waste heat from the automobile exhaust to recharge the battery thus reducing the load on the engine [24–26]. In recent years, TEG applied to energy harvesting for wireless sensor nodes has attracted increasing attention [18,27,28]. The self-powered wireless sensor nodes can provide redundant and independent measurements of operation parameters for the nuclear power plant, bridges, high building, aircraft, gas turbine, etc. TEG energy harvesters with various size and power output were designed to meet the demand of different electrical devices [17,29–31]. Inspired by the Fukushima nuclear power plant accident, Clayton et al. [32] proposed the possibility to develop a wireless sensing and monitoring system based on TEG energy harvester in the nuclear power plant. Taking advantage of the ubiquitous pipes in the plant, the TEG can extract thermal energy from the hot pipe to power the system even during station blackout accidents. In the aerospace industry, composite material like glass fiber reinforced plastics and carbon fiber reinforced plastics are widely used to improve the aircraft efficiency. A network of sensors is distributed over the structural area of interest to monitor the material health. To power these sensors, a thermoelectric solution was introduced by Samson et al. [27] to harvest energy from the aerospace engine. Kousksoua et al. [33] investigated the electric power extractable from a helicopter conical nozzle equipped with TEG. They developed a numerical model to analyze the performance of the TEG energy harvester under different operating conditions. With an exhaust gas temperature of 900 K, the output power was more than 400 W. However, they did not do any experiment to examine their result. In Ref. [34], a wearable glass fabric-based flexible TEG fabricated by a screen printing technique was presented. The research aimed at harvesting energy from the human body to power the mobile devices and health monitoring sensors. Hudak and Amatucci [18] reviewed the recent progress in three different energy harvesting technologies for small-scale devices, including thermoelectric power generation, vibration-to-electric power conversion, and radiofrequency power conversion. In most situation, when compared with kinetic and radiated energies, the thermal energy that can be harvested has a higher energy density, making it extremely suitable for energy harvesting in an environment with thermal source available.

To minimize the impact of sensing and monitoring system on the performance of the operating device, the sensing and transmitting components continue to be scaled down along with the decrease in the energy consumption. To make the whole system compact and reliable, there is an urgent need to shrink the size of energy harvester. The “Smart Dust” project [35,36] supported by DARPA (The Defense Advanced Research Projects Agency) set an arbitrary goal of 1.0 mm^2 per node. With the development of MEMS techniques, including electrochemical MEMS, chemical vapor deposit (CVD), and sputtering, the thermo-element of TEG has been miniaturized to μm-scale, which can be easily embedded in various systems. In the work of Huesgen et al. [28], they fabricated a MEMS TEG with high integration density using thin-film processing technologies on the wafer surface. A novel thermal connector was designed to guide the heat flow to pass the thermo-elements perpendicular to the chip surface. Though losing some heat due to thermal shorting of the substrate, the device can benefit from the longer thermo-elements, having a higher voltage output. Substituting the wafer with a polyimide substrate, the device can be adapted to make a flexible μm-scale TEG, harvesting milli-watts energy with a small temperature difference to power a wristwatch [19,37]. The website of Thermo Life Energy Corporation reported an energy density of 40 $\mu W/cm^2$ and voltage output of 2.7 V at $\Delta T = 5$ K for a similar design [38].

To analyze and optimize the performance of TEG more accurately, the analytical models were more and more sophisticated [39–41], taking account of the radiation heat transfer, heat leakage, contact resistance, temperature-dependent material properties, and Thompson Effect. However, analytical solutions exist only for simple scenarios. In most situation, some reasonable assumptions were made to simplify the modeling. Numerical models are more widely used to simulate thermal systems with TEG integrated. Commercial finite element method (FEM) software, such as ANSYS and COMSOL, were widely used to do thermoelectric simulations [42,43]. Jang et al. [43] simulated a TEG waste energy harvesting system using the commercial ANSYS FLUENT software. Their simulation coupled the TEG with the well-validated turbulence flow models and the radiation models imbedded in the software. The simulation result matched very well with the experimental result. Ming et al. [22] studied a geometry-optimized segmented TEG module operating between 300 K and 780 K using commercial ANSYS package. Different heat flux conditions were tested, the segmented TEG model achieved a peak efficiency of 11.2%. For even complicated cases where TEG simulation coupled with heat and mass transfer processes,