



Modeling, experiments and optimization of an on-pipe thermoelectric generator



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ABSTRACT

A thermoelectric energy harvester composed of two thermoelectric modules, a wicked copper-water heat pipe, and finned heat sinks has been designed, modeled, and tested. The harvester is proposed to power sensor nodes on heating/cooling, steam, or exhaust pipes like these in power stations, chemical plants and vehicle systems. A model to analyze the heat transfer and thermoelectric performance of the energy harvesting system has been developed and validated against experiments. The results show that the model predicts the system power output and temperature response with reasonable accuracy. The model developed in this paper can be adapted for use with general heat sink, heat pipe, and thermoelectric systems. The design, incorporating a heat pipe and two 1.1" by 1.1" Bi₂Te₃ modules generates 2.25 W ± 0.13 W power output with a temperature difference of 128 °C ± 1.12 °C and source temperature of 246 °C ± 1.9 °C, which is more than enough to operate wireless sensors or some actuators. The use of a heat pipe in this design increased the power output by 6 times over conventional designs. Based on the model, further improvement of the power output and energy harvesting efficiency of the system has been suggested by optimizing the number of thermoelectric modules.

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1. Introduction

A thermoelectric module is a solid-state heat engine consisting of multiple P/N legs connected electrically in series and thermally in parallel. Modules are mechanically simple enabling them to operate quietly and stably over long lifetimes. This gives them a significant advantage over conventional heat engines for specific applications, even though their efficiency is low due to their figure of merit (ZT) [1]. Traditionally, thermoelectric generators (TEGs) have been used in aeronautical engineering, military, and medical fields. However, with the rapid development of nanotechnology, new materials with higher efficiency and special characteristics have been discovered, broadening the applications of TEGs. Recent designs include wearable TEGs for powering small carry-on electronics, solar thermoelectric energy harvesting, and automobile exhaust pipe energy scavenging [2–4]. In order to advance the field, this paper investigates a simple, versatile thermoelectric based energy harvester built to utilize thermal energy from high temperature pipes and exhausts as are found in power stations, chemical plants, and transportation systems.

There have been extensive studies on harvesting energy from high temperature pipes. The first attempt to harvest energy from

an exhaust pipe using a TEG was in 1963 [5]. Since then, Haidar and Jamil [6] built a TEG system with commercially available Bi₂Te₃ modules, in which an aluminum spreader block was designed to mount modules on an exhaust pipe. This system generated a maximum power of 12.2 W under a temperature difference of 237 °C using four modules with 2" × 3" surface area. Ikoma et al. [7] developed a SiGe module with eight pairs of legs for use in an elevated temperature, and applied it to a generator system with a heat exchanger on a rectangular exhaust pipe. Using 72 modules, they obtained a maximum power of 35.6 W with a 563 °C temperature difference. Hsu et al. [8,9] developed two generations of exhaust-based thermoelectric generators, and conducted an extensive study on system performance in low-temperature range with prototypes. Goncalves et al. [10] and Martins et al. [11] proposed a heat pipe assisted thermoelectric generator design, which included multiple heat pipes to absorb heat from an exhaust pipe and transport it to the hot end of thermoelectric modules (TEMs). Dell et al. [12] constructed a prototype that can be implemented onto steam pipes robustly. Using six Bi₂Te₃ thermoelectric modules with 1.57" by 1.73" surface area, the approximate power output is 6.9 W at a temperature gradient of 63 °C. Tewolde et al. [13] proposed a design that could be directly mounted onto the outer surface of a steam pipe, producing a matched load power of 1.0 W during real application. However, there still has been a lack of research done on steam pipe thermal energy harvesting. To address this problem,

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Nomenclature

A	surface area (m^2)
$C_1 \sim C_4$	constants
h	convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
I	current (A)
k	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
K	thermal conductance (W K^{-1})
$\bar{K}$	thermal conductance mean value (W K^{-1})
L	length (m)
m	total number of exposed surfaces
n	total number of leg pairs in two TEMs
N	total number of TEM at each side
Nu	Nusselt number
P	power output (W)
Pr	Prandtl Number
q	heat flux (W m^{-2})
Q	overall heat (W)
r	radius (m^2)
R	thermal resistance (K W^{-1}); electrical resistance (Ω)
$\bar{R}$	electrical resistance mean value (Ω)
Re	Reynold's number
t	thickness (m)
T	temperature (K)
ΔT	temperature difference (K)
V	voltage (V)
W	width (m)

Greek symbols

α	seebeck coefficient (V/K)
$\bar{\alpha}$	seebeck coefficient mean value (V/K)
ϵ	aspect ratio
ε	surface emissivity
σ	Stefan-Boltzmann constant ($\text{W m}^{-2} \text{K}^{-4}$)
η	system efficiency

Subscripts

a	adiabatic section
amb	ambient
b	base plate of heat sink
c	cold side of TEM leg
co	condenser
cv	convection
C	cold side of TEM
ce	ceramic
D	pipe diameter
e	evaporator
ex	external surface
f	fin area
h	hot side of TEM leg
H	hot side of TEM
hp	heat pipe
hs	heat sink
i	exposed surfaces
in	internal material of TEM
los	loss
L	load at external side
N	N-type leg
o	open circuit
p	adaptor plate
pr	primary area in heat sink
P	P-type leg
PN	PN pair
r	radiation
sp	spreading
S	source
$tg1 \sim tg4$	thermal grease layers
TEM	thermoelectric module
$0 \sim 10$	different sections in heat pipe

the presented novel system is able to provide enough power for wireless sensing and monitoring systems within power plants. It is easily integrated, and highly adaptable for any high temperature pipe installation.

To predict thermoelectric energy harvesting systems performances, many studies have been published regarding the mathematical modeling of these systems [14–18]. The thermoelectric process is indeed coupled by heat conduction, the Peltier Effect, the Thomson Effect, and Joule Heating. The conventional 1-D model [16] is the most commonly used, in which a constant heat flow is assumed. However, it is not accurate enough due to its neglect of the energy conversion process. Zhao and Tan [14] summarized the current materials, modeling methods, and applications of thermoelectric generators. Fraisse et al. [15] summarized the prevailing modeling techniques for thermoelectric processes based on an order of complexity, and compared the accuracy of all models. Thermos-pellets are the core component in a TE module, and Sahin and Yilbas [19] studied the influence of thermos-pellet geometry on the performance of the device. They indicated that trapezoid shape could improve the efficiency but reduce the power generation. Chen et al. [20] performed an optimization towards a two-stage thermoelectric generator by searching for the optimal heat transfer surface and the pair numbers using non-equilibrium thermodynamics and finite-time thermodynamics.

There have been several mathematical models made for integrated designs of specific applications [21–23]. In the simplest case, researchers do not consider the fact that energy conversion within the module may cause a large deviation in performance

anticipation [16]. Many existing models do not take into account the impact of sealing material (gas gap between thermos-pellets in the TE modules) in the TE modules, which can reduce the efficiency and power output of the system. Finally, the variation of the thermal resistance of heat sinks with temperature and heat flow through them is generally over-looked. Hsiao et al. [21] investigated the detailed mathematical modeling techniques for waste heat recovery from automobile engines based on a design integrating two heat sinks, in which they treated the thermal resistance of heat sinks as constant. However, due to a reduction in accuracy, this should not be treated as a constant. Gou et al. [22] conducted modeling and an experimental study on a design targeting for harvesting energy from a flow channel, and optimized the design by enhancing heat transfer capacity at the cold side.

The modeling addressed here is of a thermoelectric energy harvesting system used to extract energy from a high-temperature pipeline (Fig. 1) in order to power a wireless sensing and monitoring system. A heat pipe was chosen for its excellent thermal conductivity in order to conduct heat out of insulation layer through a penetrated (Fig. 1a) or unpenetrated (Fig. 2b) connection. A lab-based experiment was carried out to test the characteristics of the system, and validate the modeling.

In the following sections, the prototype is described, and a highly applicable model is constructed, which combines the coupled effects of heat sink thermal resistance, energy conversion, and sealing material in commercial TEG modules on system performance. This model agrees with lab based experimental tests of the prototype with promising accuracy, and an optimization of the

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