Flexible Printed Thermoelectric Textiles for Low Temperature Waste Heat Energy Harvesting Systems

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ABSTRACT

The application of traditional thermoelectric generators (TEG) to large area industrial waste heat recovery is limited by high fabrication costs, the use of toxic semiconductor materials, and rigid structures. In this study, flexible thermopile structures are fabricated using conductive inks, utilizing less expensive printing techniques, and high throughput textile technology towards reducing the cost per watt. A prototype TEG device is demonstrated with 525 screen printed Ag-Ni junctions. The Seebeck coefficient per junction was 8.6 μV/°C. The open circuit voltage for the entire device was 741 mV at a temperature difference of 165 °C and the power generated with matching load resistor was 0.28 mW. The concept of embedding thermopiles into a pipe insulation and utilizing them for waste heat recovery has a large market opportunity in industrial steam pipe insulation.

Keywords: printed thermopiles, thermoelectric textiles, pipe insulation, energy harvesting, waste heat recovery

1 INTRODUCTION

The global need for clean and sustainable energy along with recent advances in thermoelectrics (TE) has improved opportunities for waste heat recovery. Waste heat accounts for >50% of energy consumption in U.S and over half of this waste heat is in low-temperature streams [1, 2]. TE power generation offers potentially unique solutions for waste heat recovery with high reliability due to no moving parts and silent operation. Printing of thermoelectric materials is one pathway towards low-cost, and flexible devices [3-7]. Taroni *et al.* [3] and Elsheikh *et al.* [4] recently reported the history of thermoelectric materials and the future direction in this technology. Madan *et al.* [5, 6] reported dispenser printed thermoelectric generator (TEG) using Bi-epoxy and $Bi_{0.5}Sb_{1.5}Te_3$ materials. The 10 couple TEG prototype produced 0.13 mW power at ΔT of 70 °C. Lu *et al.* [7] demonstrated the printability of TEG materials using inkjet printing technology. The p-type $Sb_{1.5}Bi_{0.5}Te_3$ nanoparticles and n-type $Bi_2Te_{2.7}Se_{0.3}$ nanoparticles were synthesized and formulated into inks for printing. Wearable TEGs fabricated on textile materials were reported [8-11]. A prototype consisting of 8 couples of Bi_2Te_3 and Sb_2Te_3 were deposited on a glass fabric. The prototype generated an open-circuit voltage of 90 mV at a ΔT of 50 °C [8]. A wearable TEG device fabricated on a flexible fabric material consisting of 20 thermocouple generated 20 mV at a temperature difference of 30 °C [9].

Most prior printed TEGs contained toxic materials such as tellurium and antimony. Tellurium and thallium decompose and emit toxic vapors to environment in high temperature applications. An alternative materials like metal oxides, conductive polymers, and metal inks are being investigated for fabricating low-cost flexible TEGs [11-13]. Markowski *et al.* fabricated a multilayer printed TEG based on thick-film and low temperature co-fired ceramic technology [13]. The prototype structure consists of 450 Ag/PdAg thermocouples that generated an open-circuit voltage of 450 mV. In this paper we introduce a new approach large scale screen printing of metal inks on flexible substrates as a route to integration of TEGs in pipe insulation (Figure 1).

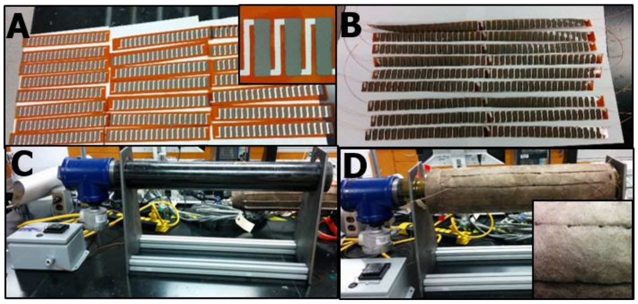

Figure 1. (A) Thermopiles printed on Kapton® film, (B) modules were prepared by attaching thermopile structures, (C) lab-scale heat pipe set-up, (D) thermopile structures embedded into pipe insulation.

2 EXPERIMENTAL

In this study, silver (Ag) and nickel (Ni) pastes were selected for printing themopile structures. Silver (5064H) paste was purchased from DuPont. Nickel paste was formulated from nickel flakes (Ni-101) purchased from Atlantic Equipment Engineers. The pipe insulation material was purchased from Carolina Plumbing Supply, Inc, and a lab-scale heat pipe set-up was constructued to replicate operating conditions.

2.1 Device Fabrication

Ag and Ni were used respectively as positive and negative Seebeck coefficient materials for forming thermocouple legs. Thermopile structures were printed on Kapton® substrates using screen printing technology. The length and width of each Ag leg was 20 mm and 2 mm. Ni legs were 20 mm x 5 mm. All silver legs were printed in 1 pass while Ni legs were printed with 2 passes. Silver legs were conductive when cured at 120 °C for 30 minutes. Nickel legs required sintering at 350 °C for 3 hours under an argon atmosphere to achieve appropriate conductivity. Screen printed structures of 37 junctions each were electrically connected in series with silver paste to form 75 junction modules. This module is pictured in Figure 1.

2.2 Thermopile - Pipe Insulation

The heat pipe was constructed by inserting a pipe heater element into a 3.5 inch diameter carbon-steel pipe. Temperature was controlled within 2 °C using a PID controller (Figure 1C). Fiber glass filled one-inch thick pipe insulation was cut lengthwise to insert thermopiles structures. Each module was embedded into the pipe insulation and leads were connected electrically in series. The embedded modules were completely buried in the insulation materials (Figure 1D).

3 RESULTS

3.1 Electrical Resistance

The electrical resistance of each module, consisting of 75 junctions, was measured using a two probe method after sintering. The protoype, consisting of 525 junctions, exhibited a total resistance of 309 Ω at room temperature. The reistance of the prototype increased with increasing temperature. This increase in resistance is at least partially due to the positive temperature coefficient of resistance for metals (Figure 2).

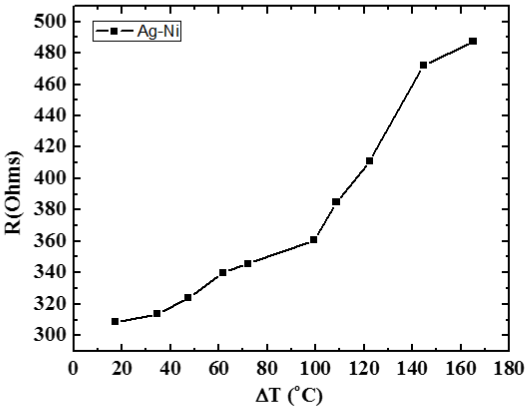

Figure 2. The TEG resistance variation with the temperature difference between hot and cold junctions.

3.2 Voltage and Power

A potential large scale industrial application of these thermopiles would be incorporating them in steam pipe insulation to recover waste heat. To mimic this application, the thermopile embedded pipe insulation was wrapped around the heat pipe. The temperature on the surface of the heat pipe was monitored with a surface mounted themocouple. A second thermocople was attached to the "cold side" of the TEG. The heat pipe temperature was systematically raised with the PID controller and the TEG's generated voltage and power performance were continuously monitored. The open-circuit voltage for the 525 junction module was 741 mV at a ΔT of 165 °C (actual pipe temperature of 300 °C). To obtain maxium output power, voltage was measured across a matching load resistor to the TEG device. The power generated from the TEG device was 0.28 mW at ΔT of 165 °C. The voltage and power trends followed expected TEG output characteristics as shown in Figures 3 and 4. These results demonstrate the feasibility of utilizing thermopile structures in pipe insulation to generate power.

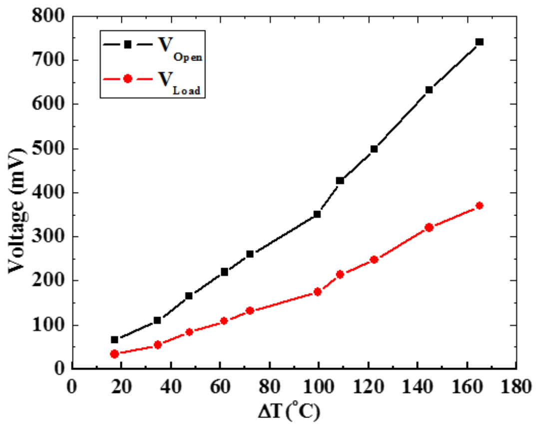

Figure 3. Voltage generated from 525 junctions of TEG device.

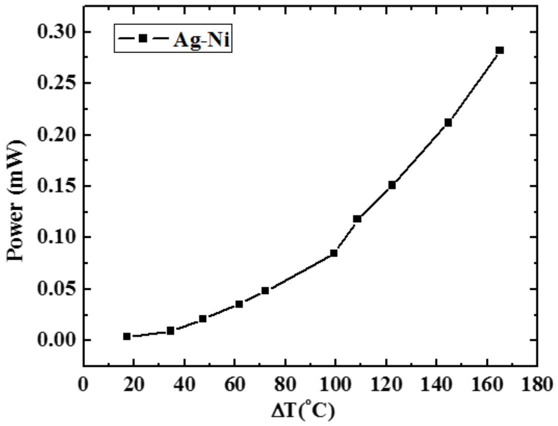

Figure 4. Power generated from 525 junctions of TEG device.

3.2 Thermal Profile

Thermal profile of the embedded thermopile structures was imaged with an infrared camera. Images were captured at each voltage measurement. One of the images is shown in Figure 5. Interestingly, the temperature from the surface of the heat-pipe radiates uniformly despite cuts in the insulation made for inserting the thermopile modules. Further investigations are underway to understand how TEG integration affect the insulation's thermal conudctivity (R-value).

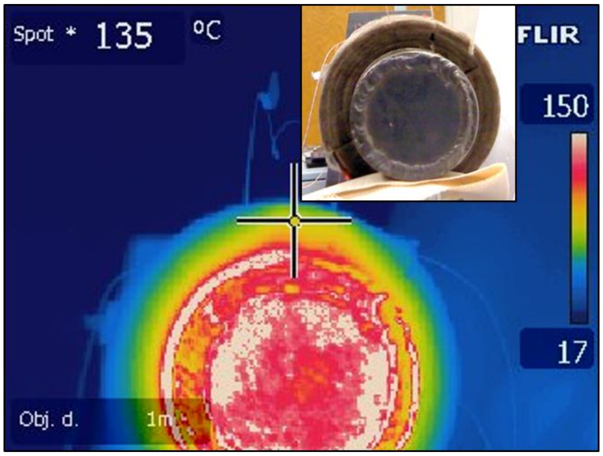

Figure 5. Thermal profile of the thermopile embedded pipe insulation (inset figure is the prototype wrapped around the heat pipe).

3.3 Performance Challenges

An important aspect of the thermocouple design lies in the choice of inks used in the thermopile. Ag paste is commercially available with low curing temperatures for printing on low-temperature substrates. However, there is a scarcity of Ni pastes that meet these same requirements. Here, Ni paste was formulated from commercial nickel flakes. This paste was tested at 350 °C curing temperature and 300 °C service temperature. The primary concern on long-term performance of the printed thermoelectric is the ability to maintain a consistent electrical resistances with thermal cycling. Further studies are being conducted to investigate the stablity in the resistance of Ni paste with temperature cycling and time. Inks also influence Seebeck coefficients and maximum performance. For example, the Seebeck coefficient obtained for the Ag-Ni junctions is approximately 8.6 μV/°C, whereas the combined Seebeck coefficient of silver and nickel bulk materials is 21.5 μV/°C. Investigations into the effects of ink composition on Seebeck coefficient are underway.

Several design features are also being considered to further optimize TEG performance, including: 1) further optimization of geometry of the legs for accommodating more junctions per unit area, 2) increase in the temperature difference between hot and cold junctions by adding heat sink material at cold junctions, and 3) optimization of Ni paste formulation for obtaining stable and lower electrical resistance. Optimization of ink and fabriation processes are critical roadblocks towards realizing a price competitive opportunity for power generation.

4 SUMMARY

Printed-thermopiles embedded in pipe insulation were constructed and demonstrated the feasibility of generating power using TEGs integrated in pipe insulation. Large area industrial application of traditional thermoelectric generators are limited by high fabrication costs, the use of toxic semiconductor materials, and rigid structures which cannot be easily installed in industrial systems. In this study, a prototype consisting of flexible thermopile structures was developed using conductive inks of Ag and Ni, utilizing less expensive printing techniques, and high throughput textile technology towards reducing the cost per watt. The prototype with 525 thermopile junctions generated an open-circuit voltage of 741 mV at a temperature difference of 165 °C and the power generated with matching load resistor was 0.28 mW. Further optimization of printing materials and leg geometry could further improve power generation. Embedding thermopiles into pipe insulation for waste heat recovery has vast market opportunity if key technical challenges can be solved.

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