Metal-Metal Thermoelectric Harvester

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Abstract. A 3-couples proof-of-concept harvester (55×6 mm^2) was assembled by spot welding 0.1 mm thick molybdenum foil and 0.15 mm thick nickel foil together. To insulate the foils from each other at the hot side a 0.1 mm thick glass fiber sheet was placed between the foils. At the cold side the harvester was insulated with 0.1 mm polyimide tape for easier handling and fabrication of the harvester. The load resistance measurement gave impedance match of approximately 0.24 Ω at 28°C, which slowly decreased to approximately 0.1 Ω as the temperature increased to 172°C. With a temperature gradient of 172°C (0-172°C) and 0.125 (±0.025) Ω load resistance, a power output was measured to 450 (±85) µW at 7.2 mV.

1. Introduction

For wireless sensors the harsh and inaccessible environment in a gas turbine poses a challenge for battery powered solutions. However, the excessive temperatures could potentially be utilized by thermoelectric energy harvesting [1]. For this specific purpose, the possibility to harvest waste heat should be categorized into areas without cooling and areas with active cooling (e.g. oil- or air-cooled). Thermoelectric energy harvesters thrive in actively cooled areas where high thermal gradients can be maintained with little effort, by utilizing the active cooling. In areas without active cooling a thermoelectric harvester can still function but will require some method to dissipate the heat to maintain a temperature gradient, usually in the form of a heat sink. Introducing a heat sink or heat pipes will inevitably be heavy and/or complex in these locations. This paper investigates the feasibility to stretch a thermoelectric harvester between the heat source and the active cooling in a gas turbine, with a proof-of-concept thermoelectric energy harvester made of strips of molybdenum and nickel, capable of reaching (and utilizing) the active cooling locations due to its long thermocouples, see figure 1.

A 3-couples 55×6 mm^2 proof-of-concept harvester was assembled from molybdenum foil and nickel foil. The harvester was measured with various temperature gradients (with cold side in ice bath, thus at 0°C) and under various load resistance. As a comparison, a longer 300×3 mm^2 15-couples thermoelectric harvester was also considered and analyzed in Matlab, based on the heat transfer through the harvester [2].

2. Method

A 3-couples harvester (55×6 mm^2) was assembled by spot welding 0.1 mm thick molybdenum foil and 0.15 mm thick nickel foil together. To insulate the foils from each other at the hot side a 0.1 mm thick glass fiber sheet was placed between the foils. For easier handling and fabrication of the harvester, the cold side of the harvester was instead insulated with 0.1 mm polyimide tape (capable of 260°C), see figure 2. For the proof-of-concept harvester, the

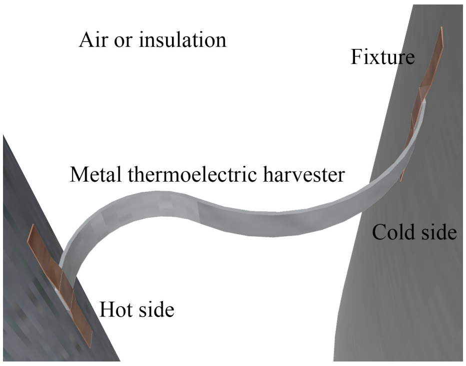

Figure 1. Example of bendable thermoelectric energy harvester made of thin metal stripes. The harvester is connected between the heat source (right) and the active cooling (left).

choice of materials are molybdenum and nickel. Both molybdenum and nickel are non-toxic, easily available, inexpensive, and corrosion- and temperature resistant with a connected Seebeck coefficient that is acceptable (for metals) at approximately 25 μV/°C [3, 4].

Figure 2. A 3-couples thermoelectric energy harvester with the hot side insulated with glass fiber sheet and the cold side insulated with polyimide tape. The thermoelectric materials are Mo and Ni with a size of 55×6 mm^2. The hot side was clamped in place during measurements and the cold side was placed in an ice bath.

2.1. Measurement setup
The hot side of the harvester was clamped between two 30×30×15 mm^3 copper blocks, heated from both sides. The cold side was placed inside an ice bath with mechanical stirring. The measurements where conducted at thermal equilibrium and with different load resistance.

2.2. Analytic model
To estimate the power output of longer thermoelectric harvesters an analytical model was used, based on the thermal transfer through the harvester [2]. The analytical harvester was based on the same 0.1 mm molybdenum strips and 0.15 mm nickel strips, but with half width (3 mm) of the proof-of-concept harvester. The calculations were primarily focused on power output and voltage output versus load resistance, with calculations at different temperature gradients. The material properties of molybdenum and nickel were simplified, and only room temperature properties were used. This could skew the result slightly, especially at high temperatures. However, the Seebeck coefficient was based on the measured proof-of-concept harvester (average 27.8 μV/°C).

3. Results

3.1. measurements

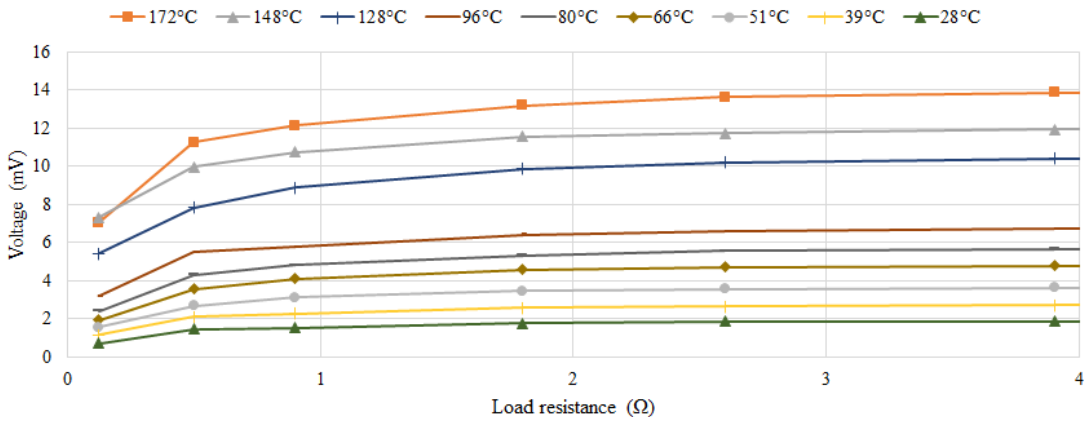

Figure 3. Voltage output as a function of load resistance. Impedance match at 28°C was approximately 0.24 Ω which reduced to approximately 0.1 Ω at 172°C. The voltage reached 14.35 mV with open circuit and 172°C.

The voltage measurement gave load resistance match at approximately 0.1 Ω with the temperature on the hot part at 172°C, see figure 3. The voltage reached 14.35 mV with 172°C temperature gradient and open circuit, which means that the combined average Seebeck coefficient is 27.8 μV/°C. With a temperature gradient of 172°C (0-172°C) and 0.125 (±0.025) Ω load resistance, this corresponds to a power output of 450 (±85) μW, see figure 4.

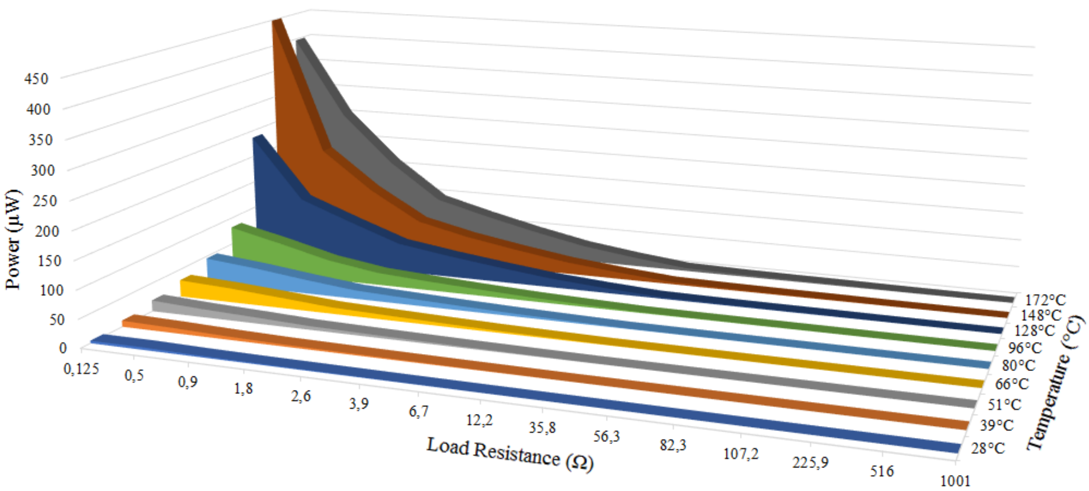

Figure 4. Power output as a function of load resistance. The 0.125±0.025 Ω measurement had big uncertainty giving a power output of between 450 (±85) μW. 0.5 Ω load resistance gives a power output of 250 μW at 172°C.

Based on the analytical model, the estimated power output from a load resistance matched 15-couples harvester with 300×3 mm^2 stripes is approximately 0.49 mW with a voltage of 47 mV with 172°C temperature gradient, see figure 5. The increased number of couples, the half width and the increased length of the harvester all contribute to an increased internal resistance, with a load resistance match at 2.95 Ω. To validate the analytical model a 55×6 mm^2 harvester was analyzed with 172°C temperature gradient, see figure 6. When comparing the calculated values with the measured values of power and voltage the model shows higher voltage and power close to load match, 34% higher at 0.125 Ω, 18% higher at 0.5-0.9 Ω and 8% higher at 2.6 Ω. Using temperature dependent material properties in the calculations could help to reduce this mismatch.

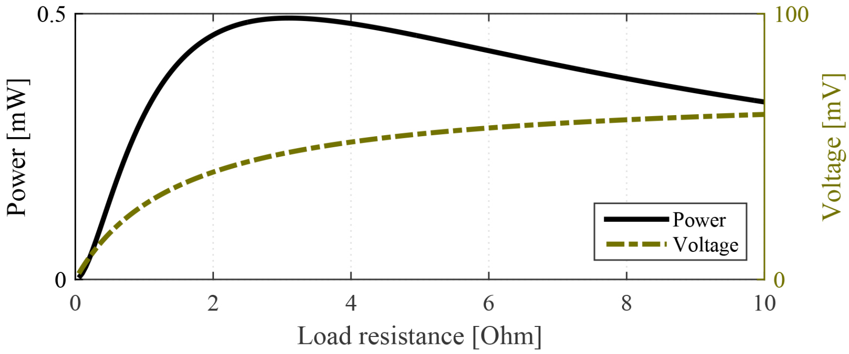

Figure 5. Analytical calculation of power output (black solid line) and voltage (yellow dotted line) as a function of load resistance, of a 300×3 mm^2 15-couples thermoelectric harvester made from 0.1 mm molybdenum and 0.15 mm nickel.

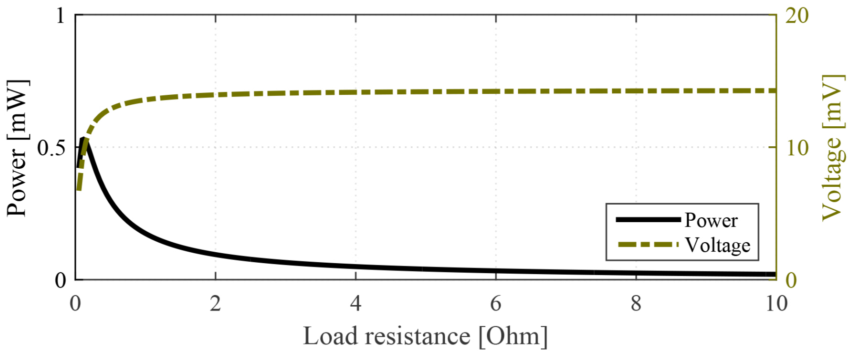

Figure 6. Analytical calculation of power output (black solid line) and voltage (yellow dotted line) as a function of load resistance, of a 55×6 mm^2 3-couples thermoelectric harvester made from 0.1 mm molybdenum and 0.15 mm nickel.

4. Discussion

Using a 55 mm long harvester as a proof-of-concept harvester might be enough to validate results and possibly for harvesting in some locations in the gas turbine. However, the harvester idea is a custom solution that require a 300 mm long harvester and is therefore examined as well through an analytical approach. The harvester power output is respectable, but the output voltage is low and huge losses (more than 70%) will come from DC-DC voltage boosting. When comparing the metal-metal harvester with a semiconductor harvester, the result is substantially lower efficiency and lower voltage. The power output can however match the semiconductor version because of the access to active cooling. The biggest advantage by far is however the simplicity of the metal harvester, no handling of brittle or sensitive materials and the simplicity of spot welding the couples together.

5. Conclusion

This paper investigates and shows the feasibility of a full metal based thermoelectric harvester that stretch between the heat source and the active cooling in a gas turbine. The analytic model estimates that the power output of a 15-couples harvester with 300 mm length would reach 490 μW (47 mV) at 172°C temperature gradient and load resistance match of 2.95 Ω. A proof-of-concept harvester with 55 mm length and 3-couples measured 450 (±85) μW with 172°C temperature gradient. As a control, the analytical model based on the 55 mm harvester gave a maximum power output of 533 μW.

Acknowledgments

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