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Experimental Evaluation of Thermoelectric Generators for Indoor Autonomous Sensors

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Summary:

This work aims to identify potential indoor thermal energy sources and assess the feasibility of using a Thermo-Electric Generator (TEG) to generate electrical energy for powering indoor autonomous sensors. A commercial small TEG (4×4 cm^2) was tested with two heatsinks of different dimensions and at several values of temperature difference (ΔT) between the thermal source and the surrounding environment, so as to determine the amount of power available. The highest power outputs achieved by the TEG were 1.83 mW and 33.0 mW with the small and large heatsinks, respectively, at $\Delta T = 40$°C, which are suitable to power most sensor nodes.

Keywords: Autonomous sensor, energy harvesting, thermoelectric generator, indoor applications, maximum power point.

Introduction

In the era of Internet of Things (IoT), many sensor nodes are deployed to collect data from, for example, the industry 4.0. In the coming future, it is foreseen that half of these sensors will be located indoors [1]. One of the main challenges right now is finding suitable ways to power these sensors, especially in places where it is hard or costly to wire them to the electrical grid. While batteries are usually employed, these have some limitations such as limited energy capacity, environmental challenges, shorter lifespan, and maintenance issues [2]. An attractive alternative to power these sensors autonomously is by harvesting energy from the environment, such as from sunlight, vibrations, radio frequency, and heat [3]. In such cases, the corresponding energy harvester must work close to the maximum power point (MPP) so as to leverage the available energy.

In order to harvest thermal energy, a Thermo-Electric Generator (TEG) is generally employed. A TEG is a solid-state device (and, hence, it operates silently without any moving parts [4]) composed of p-type and n-type semiconductors which are connected electrically in series and thermally in parallel. The resulting output power of a TEG depends on the temperature difference between its hot side and cold side.

This work has two main objectives: (1) identifying indoor thermal sources to power a sensor, and (2) characterization of a TEG at specific temperature differences provided by the previous thermal sources, with the goal of quantifying the available output power and assessing the feasibility of powering sensor nodes.

Indoor thermal sources

Several indoor sources of thermal energy have been investigated, such as hot water pipes, various types of lamps, a laptop charger, and a window frame. RTD thermal sensors (Labfacility DM-314) were employed to measure the temperature of each source and the ambient, with the data recorded by a Data Acquisition System (Keysight DAQ970A). Tab. 1 shows the resulting values of temperature difference (ΔT) between the heat sources and the ambient temperature.

Tab. 1: Temperature difference obtained by several indoor thermal sources.

Thermal Energy Source	ΔT (°C)
Hot pipe	40
Compact Fluorescent Lamp (CFL)	25
Linear Fluorescent Lamp (FL)	29
LED lamp	11
Laptop charger	27
Window frame	13

The objects indicated in Tab. 1 cause the specified ΔT when they are turned on. When those are turned off, the temperature steadily drops until it reaches the ambient temperature. As for the window frame, it undergoes such a ΔT when it is exposed to sunlight. In lamps and chargers, the optimal location for a high Δ*T* is near the electronics block that control those. The maximum Δ*T* observed was 40 ºC for a hot pipe of the heating conditioning system of the building.

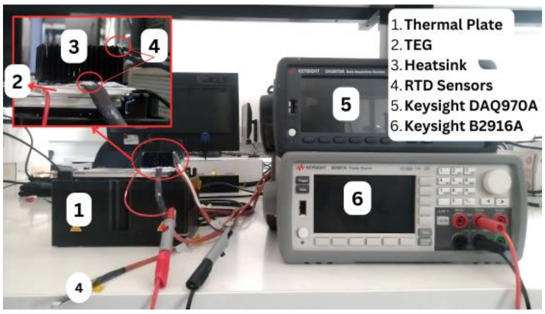

Fig. 1. Experimental setup

TEG in-lab characterization

In order to evaluate the power that can be extracted from the Δ*T* indicated in Tab. 1, a small commercial TEG of 4 × 4 cm^2 (EURECA TEG1-40-40-10/100) was in-lab characterized using the setup shown in Fig. 1. This TEG was heated on a thermal plate (QInstruments ColdPlate 2016-0110) and a heatsink was attached on the other (cold) side. The test was conducted at a room temperature of 23-24 °C, and Δ*T* was set by the thermal plate. Two heatsinks with different size were tested: a) heatsink #1 (Spreadfast SFH4001-21L) with 40 × 40 × 21 mm, and b) heatsink #2 (FischerElektronik SK-92-100 SA) with 100 × 100 × 40 mm. For each testing condition, the current-voltage characteristic of the TEG was extracted using a source and measure unit (Keysight B2961A), whereas thermal measurements (including the temperature at the hot and cold sides of the TEG) were carried out again using RTDs connected to the DAQ.

The experimental results are shown in Fig. 2 (for heatsink #1) and Tab. 2 (for both heatsinks), including the measured temperature difference (ΔT_{TEG}) between the two sides of the TEG. Accordingly, higher values of Δ*T* generate higher values of ΔT_{TEG}, and these are higher for heatsink #2 thanks to its larger dimensions. The power generated approximately increased proportionally to $(\Delta T_{\mathrm{TEG}})^2$. The TEG with heatsink #1 produced a maximum power (P_{max}) of 1.83 mW at $\Delta T = 40$°C, whereas it was 33.02 mW with heatsink #2. The corresponding power density is 0.11 mW/cm^2 and 2.06 mW/cm^2 for heatsinks #1 and #2, respectively. The experiment demonstrates that a larger heatsink results in a higher output power from the TEG, since this helps to decrease the temperature at the cold side and thus increases ΔT_{TEG}. This is, however, with the limitation that more space is required for the heatsink.

The power levels in Fig. 2 and Tab. 2 seem to be sufficient to power IoT sensor nodes, as the average power consumption of such sensors can be typically around 1 mW [2]. To generate 1 mW, $\Delta T \approx 30$ °C is required with heatsink #1, whereas Δ*T* lower than 10 °C is needed with heatsink #2, which can be obtained using the objects tested and reported in Tab. 1.

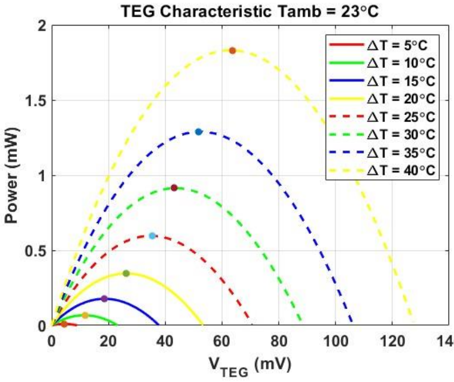

Fig. 2. Power-voltage characteristic of the TEG using heatsink #1.

Tab. 2: Maximum power at the TEG output for different values of ΔT and for two different heatsinks.

Δ*T* (°C)	TEG – heatsink #1		TEG – heatsink #2	
	ΔT_{TEG} (°C)	P_{max} (mW)	ΔT_{TEG} (°C)	P_{max} (mW)
5	1.20	0.011	2.05	0.55
10	1.83	0.068	4.17	2.09
15	2.25	0.18	5.84	4.20
20	2.90	0.35	7.95	7.12
25	3.65	0.60	9.84	12.00
30	4.44	0.91	12.09	17.96
35	5.21	1.29	14.30	24.80
40	6.15	1.83	16.50	33.02

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