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Citation: Yun, Maxwell et al. "Thermal Energy Harvesting for Self-Powered Smart Home Sensors." 2016 MIT Undergraduate Research Technologies Conference November 4-6 2016, Cambridge, Massachusetts, USA

As Published: http://sites.ieee.org/r1/r1_event/2016-ieee-mit-undergraduate-research-technology-conference/

Publisher: Institute of Electrical and Electronics Engineers (IEEE)

Persistent URL: http://hdl.handle.net/1721.1/112117

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

Thermal Energy Harvesting for Self-Powered Smart Home Sensors

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***Abstract*—This paper investigates the use of thermoelectric energy harvesting for embedded, self-powered sensor nodes in smart homes. In particular, one such application is self-powered pressure sensing in vacuum insulation panels for buildings. The panels greatly improve heating and cooling energy use, and the thermal difference developed across them could be used to drive a wireless sensor to monitor their pressure level. We first created a model for the available power using historical weather data. Then, we measured the thermoelectric generator's actual power output by combining the generator with a vacuum insulation panel and mounting it inside a window for experiments. Finally, we determine the feasibility of using the established thermal gradient to power a sensor node. We show that thermoelectric energy harvesting could enable a new class of embedded, maintenance-free, self-powered sensors for smart homes.**

***Keywords*—energy harvesting, IoT, Internet of Things, sensor, smart building, thermoelectric generator, TEG**

I. INTRODUCTION

Smart homes promise great reductions in energy consumption as well as the eventual full automation of appliances and home systems. Progress is marching towards completely automated smart homes, which rely on less and less human input. For complete automation, smart homes require additional data provided from hardware sensors distributed around the home.

Advances in sensors, wireless transceivers, and low-power microcontrollers have enabled the proliferation of sensors to help realize this vision of smart homes. However, powering sensors has remained a major constraint for embedded applications. Batteries only have a finite lifetime and must be replaced, and often it is expensive or infeasible to provide wired power to every node when thousands of them may be present in a building. One solution is energy harvesting, which does not require any energy sources. For example, a temperature gradient can be used to power ultra-low power sensor nodes, making them self-sufficient and enabling a new class of embedded applications.

Recently, vacuum insulation panels (VIPs) have shown promise to increase the thermal efficiency of homes and lower heating and cooling energy costs. VIPs consist of a vacuum supported by a porous core surrounded by an impermeable barrier material. VIPs have up to 6x higher thermal resistance compared to conventional extruded polystyrene (EPS) foam insulation. However, the vacuum inside VIPs can leak incidentally or over the building's lifetime, resulting in a decrease in the thermal resistance [1]. To counter this problem, an absolute pressure sensor powered by the temperature difference across the VIP could wirelessly transmit the panel's pressure over the building's lifetime, triggering a warning that the panel is in need of replacement.

In this paper, we present our findings on testing the feasibility of using thermoelectric generators to harvest electricity from the temperature gradient across VIPs to power sensors. This project consists of four main phases: modeling power generation with weather data, determining the best power harvesting setup, gathering data from an insulated panel installed inside an apartment window, and powering a sensor that wirelessly transmits sensor data. In the end, we were able to receive sensor data from a self-powered sensor in simulated conditions as a proof of concept.

II. THERMOELECTRIC GENERATOR THEORY

Thermoelectric generators (TEGs) harvest electricity from a temperature difference by utilizing the charge carriers of doped semiconductor materials. When a temperature difference is present across either side of the TEG, charge carriers in doped semiconductors will migrate from the hot side to the cold side. This principle is called the Seebeck Effect, which is the operating principle of thermoelectric generators.

TEG modules consist of alternating p-type and n-type bismuth-telluride semiconductor legs connected in series electrically and in parallel thermally. This dissimilar semiconductor joint generates a small voltage across each leg in the module. The series electrical connection adds these small voltages to result in a much higher usable voltage [2].

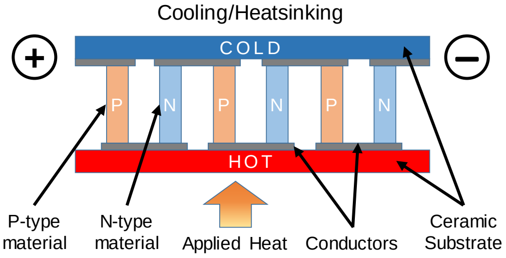

Fig. 1- Components of a thermoelectric generator.

TEG modules have three main design considerations: Seebeck coefficient, electrical resistance, and thermal resistance. The module's Seebeck coefficient (S) represents the voltage generated per degree of temperature difference and is dependent on the number of semiconductor legs and their electrical configuration.

$$V_{harv.} = S \cdot \Delta T_{harv.} \tag{1}$$

Electrical resistance affects the maximum power point, where the most usable power can be extracted from the TEG. The electrical resistance increases with the number of semiconductor legs (represented by n), electrical resistivity of the material (ρ), and length of each leg (L), and decreases with area of each leg (A).

$$R_{electrical} = n\rho \cdot \frac{L}{A} \tag{2}$$

The thermal resistance affects the heat flux across the TEG and the ability to maintain a large temperature difference. A higher thermal resistance translates to less heat flux and a higher temperature difference. Absolute thermal resistance increases with thermal resistivity (R_λ) and the length of each leg (L) and decreases with the area of each leg (A) and the number of legs (n).

$$R_{thermal} = R_\lambda \cdot \frac{L}{n \cdot A} \tag{3}$$

The actual temperature difference across the TEG depends on the thermal resistance of the TEG and its heatsinking, which interface the TEG with its surroundings. This is shown in Eq. 4.

$$\Delta T_{harv.} = \frac{R_{thermal}}{R_{thermal}+R_{heatsink}} \cdot \Delta T_{actual} \tag{4}$$

For such energy-constrained applications, one must harvest energy at the maximum power point of the TEG, which occurs at half of the harvested voltage, when $R_{load} = R_{electrical}$. The power extracted from a TEG at the maximum power point is listed below.

$$P = \frac{(V_{harv.})^2}{4R} = \frac{(S \cdot \Delta T_{harv})^2}{4 \cdot R_{electrical}} \tag{5}$$

Hence, to obtain the maximum power, we first selected a thermoelectric generator with a high thermal resistance in order to present as high ΔT as possible. We used a Laird OptoTec OT08,32,F0T,0707 thermoelectric generator. We then selected a matched electrical load to obtain the maximum electrical power point. Thermoelectric generators have potential as energy harvesters, and it is important to optimize their design for the application in order to maximize their small power output.

III. WEATHER MODELING

In order to approximate the available power from passive thermoelectric harvesting, power generation for the city of Boston was characterized over the course of the year and day, with monthly and hourly power generation, respectively, using historical weather data. For monthly data, we averaged daily temperature highs and lows over each month from 2006-2016. For hourly data, we averaged hourly temperature data for each day, by month, for 2015. All weather data is from the National Center for Environmental Information [3].

For hourly and monthly reports, temperature differences between outside and inside were then calculated, using a constant room temperature of 22°C inside. Voltage was calculated using Seebeck's law, assuming perfect heatsinking ($\Delta T_{harv} = \Delta T_{actual}$) (Eq. 1), and the calculated voltage was used to calculate harvested power at the maximum electrical power point (Eq. 5). Electrical resistance for our module at 25°C was 4.17 Ω [4].

The monthly data (Fig. 2) shows that power harvesting capability is the greatest in January/February and falls to a minimum in May and September. This directly follows from the result that the temperature difference is greatest in the winter months and least during the spring/fall months. Additionally, the harvested voltage becomes negative during summer, when it is hotter outside than inside; however, given bipolar harvesting capability, then harvesting is still possible and the power is shown to be positive.

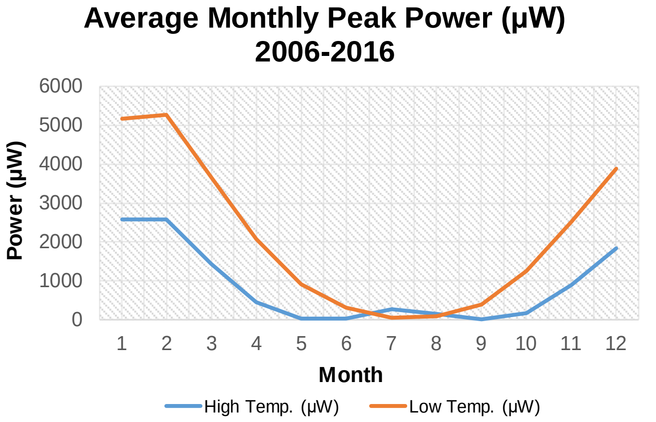

Fig. 2- Avg. monthly peak power harvesting, with temperature highs and lows

Likewise, in the hourly power generation data (Fig. 3), power generation is greatest in the morning and least in the afternoon, when the temperature delta decreases. Most of the power generation curves are the same shape, but slightly offset. In the summer months, afternoon is the peak generation time because the temperature delta reverses, but harvesting is still possible.

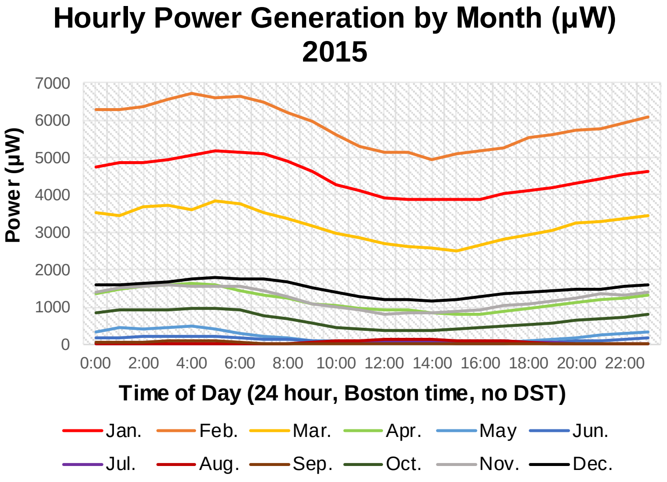

Fig. 3- Hourly power generation by month.

These simulations show that it is feasible to power a sensor with TEGs, especially in the winter months. However, this is a simplistic model; it does not take into account the actual temperature difference across the TEG, which is affected by heatsinking. For this reason, a TEG setup was inserted into an apartment window to measure the actual power generation and validate our model.

IV. EXPERIMENT SETUP

We measured TEG power generation between inside and outside temperatures with a test setup mounted inside an apartment window with a VIP panel used to establish a thermal gradient. The test setup consisted of a TEG thermally connected to a sheet of aluminum (0.8mm thick) that covered the VIP panel for improved heatsinking to the ambient. The assembly was mounted inside a sheet of extruded polystyrene (EPS) foam insulation for ease of installation into the window. The experiment ran for one week, during which we collected open circuit voltage, power generated, and temperature.

A. *Vacuum Insulation Panels*

Vacuum insulation panels (VIPs) consist of a porous core containing a vacuum surrounded by an impermeable barrier material. Advantages include far greater energy savings over conventional foam insulation. However, the main weaknesses of VIPs are price and vacuum leakage, namely incidental punctures and gradual leaks. As a result, self-powered absolute pressure sensor installed inside the vacuum insulation panel could report internal panel pressure and report issues, while being maintenance-free over the building's lifetime.

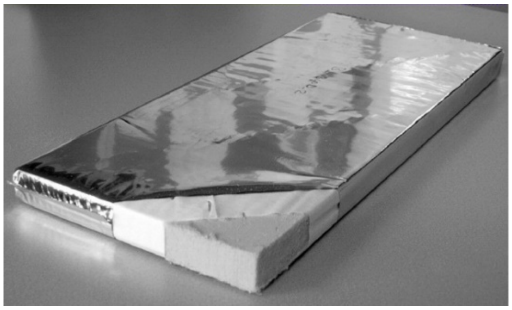

Fig. 4- A cutaway of a VIP showing the impermeable barrier layers and the porous core material [5].

B. *Window Tests*

A test setup with a TEG was mounted inside an air-conditioned apartment's window over one week to monitor power generation. In each test, open circuit voltage, inside and outside temperature, and power generated at the maximum power point were measured. For temperature measurements, a Raspberry Pi computer connected to a DHT22 temperature sensor from Aosong Electronics was used. The room temperature was held constant at 22°C with the apartment's air conditioner. All electrical measurements were taken with a Keithley SourceMeter.

A VIP and a TEG were mounted next to each other inside a sheet of EPS foam insulation the size of the window. One aluminum sheet is layered on either side of the VIP, covering the panel's entire area, to improve heatsinking qualities and maintain the temperature difference. On either side of the setup, the aluminum heatsink and TEG are thermally connected via a narrow aluminum shim and thermally conductive tape. The EPS insulation board was mounted inside, flush with the window, with one side facing inside and one side facing outside. A cutaway diagram and picture of the setup are attached below.

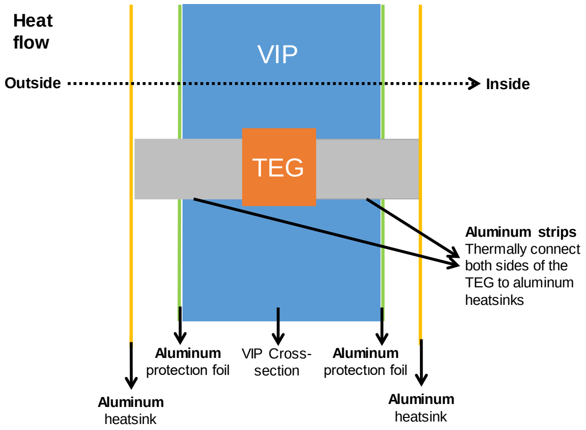

Fig. 5- Cutaway diagram of window setup, not to scale [6].

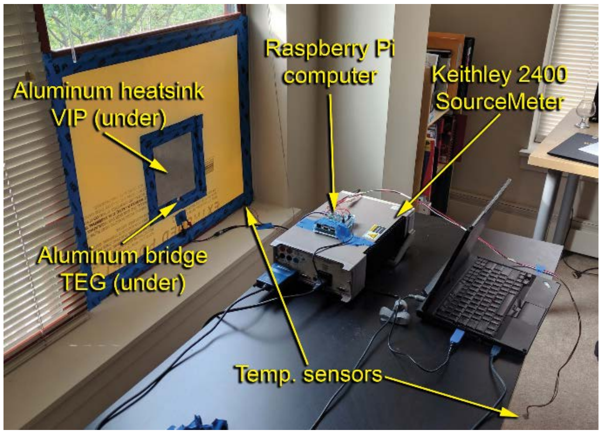

Fig. 6- The setup

The data for this experiment are listed in the next section.

V. MEASUREMENTS

A. *Window Tests*

Data was gathered over the course of one week, and the results are shown below. The outside temperature, shown in red, fluctuates over the course of the day, while the inside temperature stays fairly constant. The power generation is a square function of the temperature delta. Power generation likely peaks at around 5:00 PM due to the sun striking the building wall, causing a localized temperature spike.

This data (Fig. 7) shows an average output of 28.7 µW of power over the course of a summer day, enough to charge a capacitor and power a sensor node that duty-cycles measurements and transmissions [7]. The average power generation is expected to be far greater in the winter months due to a greater temperature difference. Powering a sensor node using this harvested power is feasible, and this will be shown as a proof-of-concept in the next section.

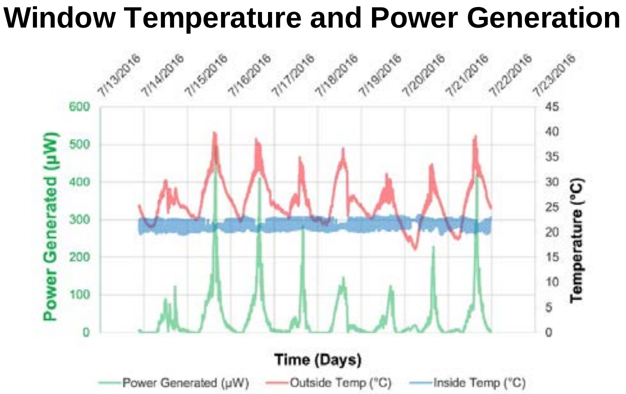

Fig. 7- Data from the window experiment. The green curve is peak power generated. The red and blue curves are outside and inside temp., respectively.

B. Powering the Sensor Node

To show conceptually that the power can be used to power a sensor node, we created a controlled setup in the lab to experiment with temperature difference versus power generation capability for a commercial harvester This is a proof-of-concept showing the feasibility of low-ΔT TEG-powered sensor nodes.

The TEG module was thermally connected to a hot plate at 35°C and a heatsink, cooled by a fan. It is electrically connected to a LTC3108 ultralow voltage boost converter and power manager from Linear Technology, which accumulates the energy in a 2 mF ceramic storage capacitor and powers the sensor node. The sensor node uses the LTC3108's 3.3V output and P_{GOOD} pin, which signals when the output voltage is within an acceptable range.

The sensor node contains a PIC12LF1840 microcontroller (MCU) with an integrated temperature sensor and wireless transmitter from Microchip. The MCU's power pin is connected to the LTC3108's 3.3V pin and is interrupted by a switch connected to the LTC3108's P_{GOOD} pin.

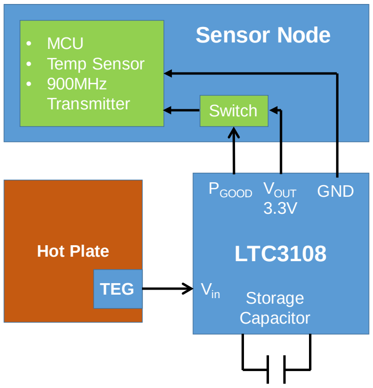

Fig. 8- A block diagram of the self-powered sensor node setup.

When the voltage drops below 3.0 V, the P_{GOOD} pin is brought low, the switch turns off, and the MCU is shut off, allowing the storage capacitor to charge. Once the P_{GOOD} pin is brought high and voltage is greater than 3.2 V, then the MCU takes a temperature reading and wirelessly transmits the data. The data measurement and transmission cause a drop in the output's and storage capacitor's voltages, but the P_{GOOD} pin remains pulled high. With the P_{GOOD} pin pulled high, the microcontroller samples the V_{DD} voltage every 2 seconds and performs a measurement if it is higher than 3.2 V.

In simulated conditions using a hot plate with a ΔT of 15°C, the frequency of data transmission was every 2 seconds, which for this sensor node, represents a power delivered of 109 µW. While the MCU's onboard temperature sensor was used in this test, any low-power sensor under 100 µW could be used, enabling a new class of embedded, self-sufficient sensor nodes.

VI. CONCLUSION

This paper investigates a novel application for thermoelectric generators in an embedded application. Using the temperature difference across an insulation panel, one can harvest ~100 µW of power to run an ultralow power sensor node. We have demonstrated the feasibility of this approach, which can enable a new class of self-powered smart home sensors, and in the future we would like to integrate the boost converter with the sensor to obtain long term measurements from a window setup.

VII. ACKNOWLEDGEMENTS

I would like to thank Phillip Nadeau for mentoring me and providing his apartment window for the experiment, and Professor Chandrakasan for hosting me for the summer.

VIII. CITATIONS

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