Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

materialstoday: PROCEEDINGS

Materials Today: Proceedings 2 (2015) 823 – 832

12th European Conference on Thermoelectrics

A thermoelectric energy harvester with a cold start of 0.6 °C

P. Mullen*[a], J. Siviter [a], A. Montecucco [a], A. R. Knox [a]

[a] *School of Engineering, College of Science and Engineering, University of Glasgow, U.K.*

Abstract

This paper presents the electrical and thermal design of a thermoelectric energy harvester power system and its characterisation. The energy harvester is powered by a single Thermoelectric Generator (TEG) of 449 couples connected via a power conditioning circuit to an embedded processor. The aim of the work presented in this paper is to experimentally confirm the lowest ΔT measured across the TEG (ΔT_{TEG}) at which the embedded processor operates to allow for wireless communication.

The results show that when a temperature difference of 0.6°C ΔT_{TEG} is applied across the thermoelectric module, an input voltage of 23 mV is generated which is sufficient to activate the energy harvester in approximately 3 minutes. An experimental setup able to accurately maintain and measure very low temperatures is described and the electrical power generated by the TEG at these temperatures is also described. It was found that the energy harvester power system can deliver up to 30 mA of current at 2.2 V in 3 ms pulses for over a second. This is sufficient for wireless broadcast, communication and powering of other sensor devices.

The successful operation of the wireless harvester at such low temperature gradients offers many new application areas for the system, including those powered by environmental sources and body heat.

Selection and peer-review under responsibility of Conference Committee members of the 12th European Conference on Thermoelectrics.

Keywords: Thermoelectric Generator; Energy Harvesting; Low Power

1. Introduction

---

* Corresponding author. Tel.: +441413302180; fax: +0-000-000-0000 .
E-mail address: paul.mullen@glasgow.ac.uk

2214-7853 © 2015 Published by Elsevier Ltd.
Selection and peer-review under responsibility of Conference Committee members of the 12th European Conference on Thermoelectrics.
doi:10.1016/j.matpr.2015.05.106

The rapidly growing demand for sensors has led to significant developments in maximising both the power and energy density of battery technology as described by Powers [1] and Anastasi et al. [2]. A difficulty in implementing sensors for use in remote locations for e.g., seismic monitoring, weather and military surveillance is the dependence on a power source with finite capacity. Often the environmental conditions in these locations (desert, ice packs, etc) are such that battery capacity is severely compromised. Hence, future development as identified by Dewan et al. [3] and Sudevalayam et al. [4] aims to eliminate the dependence on such battery powered devices and exploit more of the energy potentially available from the environment. This has led to the development of many different energy harvesting systems, described in a review of the literature conducted by Yick et al. [5]. These systems derive their energy requirements from sources traditionally thought of as "waste". Work by Vullers et al. [6] has shown that with the miniaturisation of solid-state electronics and advanced manufacturing techniques, the operational energy requirements are now so low that powering of these devices by exploitation of vibrations, electromagnetic waves and heat is viable. Systems operating on this principle are classed as "energy harvesters".

Energy harvesting enables the development of new sensor systems which can be deployed to areas where wired infrastructure may be expensive or impractical to install. Further, the use of energy harvesting systems may also lead to improvements in the sensor's operational lifetime, as noted by Jiang et al. [7] and Akyildiz et al. [8]. The use of energy harvesters also enables the upgrade of existing sensor systems with the addition of self-powered wireless communications modules such as those described by Kausar et al. [9]. Most of these systems have focussed on a variety of 'waste' energy sources; the focus on this paper is the use of thermal energy to generate electrical power by the use of thermoelectric devices.

Thermoelectric devices are fabricated from semiconductors that have been optimised for their thermal and electrical properties. The relationship between thermal and electrical energy exchange in thermoelectric devices can be described by three physical effects: the Seebeck effect, Peltier effect and Joule-Thomson heating. The Seebeck effect relates the voltage generated when two dissimilar semiconductors are in contact and simultaneously subject to a temperate gradient. The Peltier effect relates the current flow in the thermoelectric device and the heat transfer through it. Joule-Thomson heating is a consequence of the current flowing in the device and the semiconductors' electrical resistance. Whenever an electrical current is flowing in the device all effects are present to varying degrees and influence the temperature difference and amount of thermal power transferred between the hot and cold sides of the device.

The thermal energy transfer through the device is an important consideration when selecting the thermoelectric couple characteristics: a low number of couples with large pellet dimensions, e.g. 128 couples and individual pellet cross sectional area $>5mm^2$ would lead to a module with high thermal conductivity and result in large amounts of heat transferring from the hot side to the cold side, potentially reducing the effective temperature difference across the device and hence the voltage generated. This is usually the case in any energy-limited application.

Work by Wang et al. [10] reflects this challenge. The authors have manufactured a module with a large number of pellets (~2300 couples) in order to overcome the problem of low voltage generated because of limited cooling on the cold side. Su et al. [11] describe a watch-sized device for application on the human body that also uses a large number of thermoelectric couples (~1000 couples) to obtain the voltage required to activate a pulse oximeter used to determine O_2 saturation levels.

Such micro-machined devices have high open circuit voltages (1.49 V at ΔT_{TEG}=3°C) and a very large internal resistance (20 MΩ). This leads to a low output power despite the large number of couples and high open circuit TEG voltage.

Advancements in micro-power DC-DC converter design as described by Ramadass et al. [12] and Carlson et al. [13] allow for energy harvesters to operate from thermoelectric generators producing voltages below 35 mV. These devices use a boost topology DC/DC converter to raise the input voltage from the TEG to the level required to power a sensor.

Work presented by Settaluri et al. [14] describes a watch-sized thermoelectric generator device using 254 couples that produces an open circuit voltage of 85 mV at 1.7°C temperature difference across the TEG. This application shows the critical relationship between the number of couples and the open circuit voltage that can be generated at a specific temperature difference and highlights the benefit of a large number of couples if a high open circuit voltage is needed.

Work by Roy et al. [15] describes the relationship between thermoelectric pellet geometry and output power. In order to minimise the effect of Joule heating and increased thermal conductivity due to the Peltier effect that will counter-act the applied temperature difference, a large pellet length and low pellet cross-sectional area is desirable. When considering application of TEGs at the system level, work by Moser et al. [16] details the minimum voltage and temperature difference across a TEG required to operate a wireless transmission device. The authors quote a ΔT_{TEG} of 1.2°C required to perform a data transmission.

This work presented in this paper reports a power supply with a thermoelectric module as the energy source that is able to operate with as little as 0.6°C ΔT_{TEG} across the TEG. The thermal and electrical designs are described and experimentally determined supply characteristics are presented for a variety of load conditions.

2. Experimental Setup

Experimental apparatus was designed to facilitate investigation of the performance of the power stage of the energy harvester and is shown in Figure 1. The design included the placement of a number of thermocouples to determine the temperature gradients across each part of the system. By using the apparatus the thermal design could manage the flow of energy through the TEG and this would then inform the electrical design that encapsulates all the electronics required to utilise the power generated from the TEG.

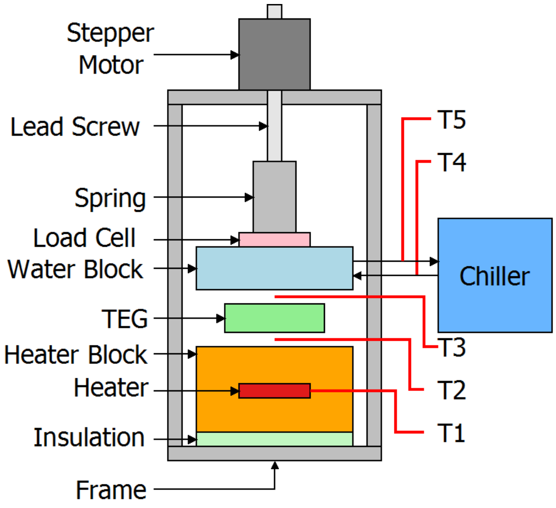

Figure 1: Physical Test Structure for TEM Characterisation

With reference to Figure 1, a stepper motor is used to apply a clamping force on the TEG. Clamping force determines to some extent the thermal resistance between the TEG faces and the water and heater blocks. A load cell is used to measure the pressure exerted and feeds data back to a software controller implemented in Agilent VEE Professional. Use of a PID loop within the controller then enables a constant pressure to be maintained despite changing test rig geometry due to thermal expansion and contraction effects. Energy extraction is by a water block connected to a chiller unit. The chiller can provide water at a constant temperature. Water temperature is measured before and after the heat exchanger (T4 and T5) and, coupled with measurement of the flow rate and heat capacity of the working fluid can be used to determine the quantity of energy removed from the apparatus. The TEG is sandwiched between the heat source and sink and the temperatures on its outer surfaces (T2 and T3, respectively) are measured. The heater is placed inside a copper block that ensured uniformity of temperature on the TEG's "hot" face. The temperature of the block is measured directly below the surface in contact with the TEG (T1). Using this apparatus enabled the accurate measurements required when working at temperature differences below 1.0 °C.

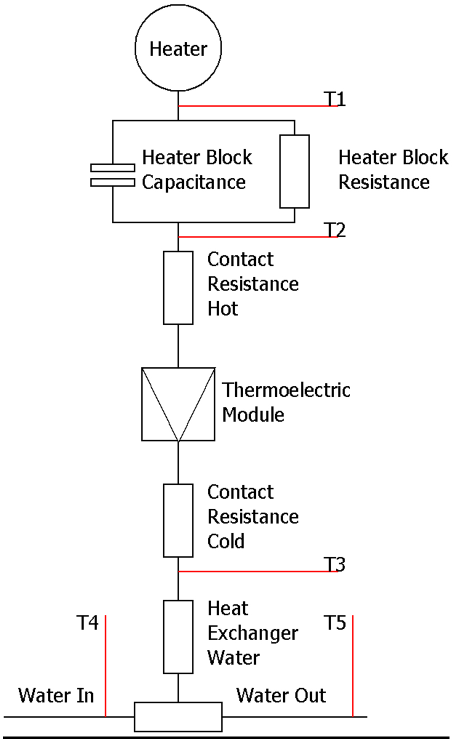

Figure 2: Equivalent Thermal Circuit for Harvester

The thermal design of the harvester describes the flow of energy through the system. Figure 2 presents the equivalent thermal circuit for the energy harvester. Energy from the heater flows through each stage until it is absorbed by water flowing in the cooling loop. The copper heater block has significant mass such that the time taken to reach operating temperature introduces a delay in the temperature rise which is represented by a thermal capacitance in the figure. Thermocouples are used to determine the temperature differences across the TEG and elsewhere in the system as shown in the Figures 1 and 2. The ΔT_{TEG} of the harvester is specified as the temperature difference between T2 and T3.

Component	Cold Start Activation Voltage	Max Input Voltage	Energy Storage	Voltage Regulation	MPPT
LTC3108 [17]	20 mV	500 mV	Supercapacitor	2.2V	None
BQ25504 [18]	330 mV	3 V	Battery	No Regulation	Programmable
MAX17710 [19]	750 mV	5.3 V	Battery	Programmable	None
SPV1050 [20]	180 mV	8 V	Supercap/Battery	Programmable	Hardware Set

Table 1: Energy Harvester Power Converters

The electronic design of the energy harvester has three key components: the TEG, the power converter and the energy store. A 449 couple TEG was used which has an open circuit voltage of 130 mV/°C. Table 1 compares several key parameters between different commercial energy harvesting ICs. The LTC3108[†] was chosen for the work presented here due to it having the lowest activation voltage and the ability to charge a supercapacitor. One major disadvantage of using the LTC3108 is that it has a fixed input resistance, which acts as a constant load to the TEG. Maximum power point tracking algorithms have the effect of matching the internal impedance of the TEG to the impedance of the load and therefore MPPT system are not used in this system While this reduces the system efficiency, the primary constraint in low ΔT_{TEG} systems is a maximising the TEG voltage.

The LTC3108 is able to regulate at 2.2 V, however, is only able to supply up to 10 mA of current. When dealing with high current events such as a wireless radio data transmission the current drawn can be up to 30 mA. A bulk storage capacitor was fitted to this voltage rail to provide charge for sufficient time for a short communications burst. The main compromise with using the LTC3108 is that its maximum input voltage is fairly low when compared to alternative power systems in table 1. When the LTC3108 is operating at ΔT_{TEG} over 16 °C, overvoltage protection is needed to ensure correct operation of the power supply. This is conveniently provided by a pair of (back to back) diodes across the input from the TEG. A 0.22F supercapacitor was used as the primary energy storage for the harvester. The size of this device has a minimum recommended value of 330μF and has no upper limit (other than the time taken to charge the capacitor to 20 mV from a cold start). A system diagram is presented in Figure 3, demonstrating the flow of charge from the TEM and how the energy harvester can supply power to a host system.

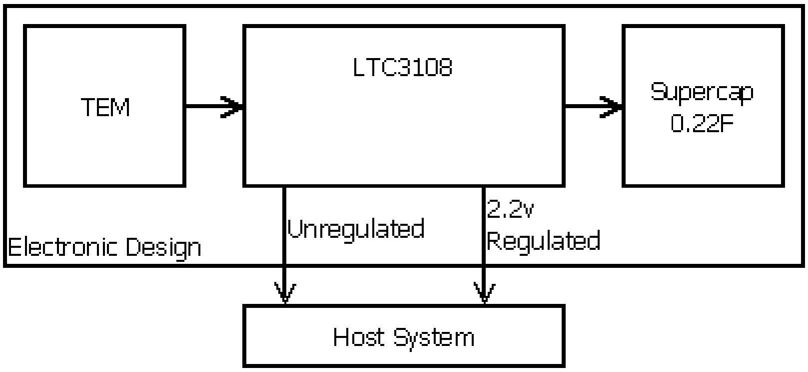

Figure 3: System Diagram

3. Method

Before the power system characterisation tests the TEG was measured to determine its output voltage under different load conditions. During these tests the TEG was mounted in the test rig shown in Figure 1 and the temperature gradient across the device was varied between 0°C and 1°C.

Three tests were carried out to characterise the complete energy harvester power system:

1. Identify the ΔT_{TEG} to allow the energy harvester to power with no prior stored charge in the supercapacitor, i.e., a cold start.
2. Determine the impact of a transient current pulse of up to 30 mA on the 2.2 V regulated voltage.

[†] This controller only accepted a fixed polarity voltage input, hence the direction of the temperature gradient on the TEG is also fixed. Regulators with a higher startup voltage (e.g. LTC 3109) can accept either voltage polarity and hence direction of temperature gradient.

3. Determine the effect of transient current pulses at regular intervals.

Test 1 was undertaken by varying the ΔT_{TEG} across the TEG between 0°C and 1°C. The harvester was found to be active if the regulated voltage was ≥ 2.15 V, meeting the device specification. Activity on the energy harvester was confirmed while this test was underway by monitoring the state of charge on the storage capacitor. The mechanical pressure applied to the TEG during this test was 100 kg. The harvester was then connected to a high accuracy bench power supply to determine its exact activation voltage. This activation voltage was then correlated with the data from the TEG characterisation tests to determine the actual ΔT_{TEG} required for system activation. This was measured to be 23 mV, slightly higher than the nominal specified value for the device.

Test 2 varied the mechanical pressure across the TEM while sweeping the ΔT_{TEG} across the TEG from 0°C to 1°C. The open circuit voltages from the TEG were monitored and compared to the results from Test 1. Two sets of data were compared, 50 kg and 100 kg. By increasing the mechanical pressure on the TEG the open circuit voltage produced increased. However, above 100kg of applied pressure the effect is reduced. There is a significant improvement in TEG open circuit voltage increasing the pressure above 100kg when compared to 50kg

.

Test 3 required the energy harvester storage capacitor to be fully charged before the test commenced. A MOSFET driven by a pulse generator was used to cause a 30 mA current pulse to be drawn from the regulated voltage line. Different pulse durations were applied by the MOSFET to experimentally determine the length of time that the harvester could supply this power for without dropping out of regulation which occurs at 1.8 V. Using a 220 µF electrolytic capacitor with a low ESR on the 2.2 V regulated output, pulse durations of over 5ms were achieved.

Test 4 evaluated the system's ability to provide a repetitive train of current pulses. The pulse current was 30 mA. The duration and the interval between pulses was varied as shown in Figure 7. Test 3 was repeated with the pulse generator using bursts of pulses rather than a single pulse. The recovery time of each pulse was four times longer than the "on" time, giving a duty cycle to a host system of 20%.

4. Results

Test 1 determined the output voltage from the TEG was 35 mV/°C when the harvester was connected, as shown in Figure 4. The activation voltage for the energy harvester was determined to be 23 mV which from figure 4 gives a temperature gradient of 0.6 °C. The voltage on the 2.2 V regulated supply rail of the energy harvester is shown in figure 5. Low power charging conditions refers to a temperature gradient of 0.6°C and it takes nearly 200 seconds to become charged. The maximum charge conditions used the bench power supply set to 480 mV and, as shown, it takes under 2 milliseconds for the regulated output to stabilise.

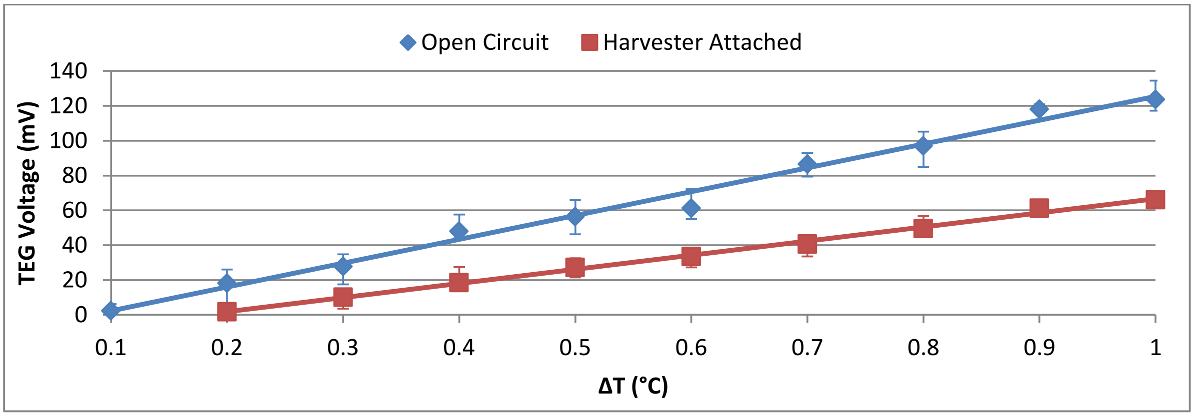

Figure 4: Output voltage from the TEM at 100 kg

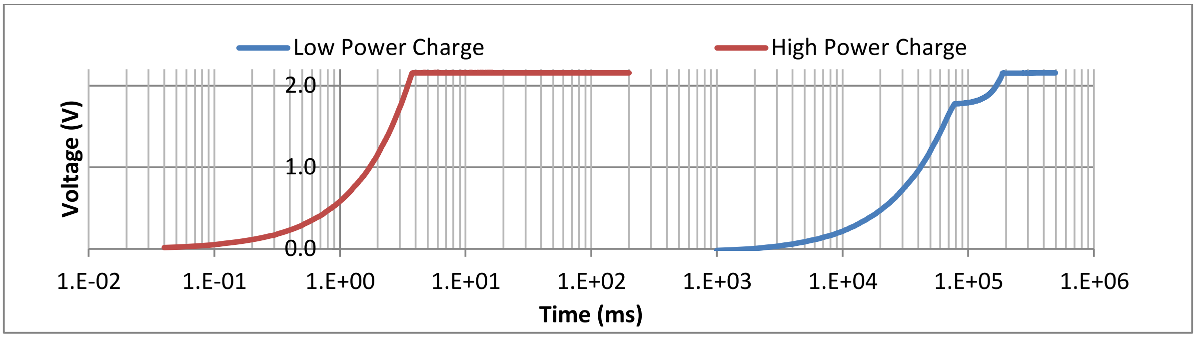

Figure 5: Charging Times for Harvester

Test 2 determined that the pressure across the device is significant at very low ΔT_{TEG}. Figure 6 shows the graphs of all three pressures applied to the thermoelectric device. At a $\Delta T_{TEG} = 1$, a 100 kg pressure is able to achieve 20 mV higher open circuit voltage than a 50 kg pressure. As the ΔT_{TEG} decreases it becomes more difficult to get accurate readings. Below 0.3 ΔT_{TEG} the error margin is large and this is down to the experimental apparatus.

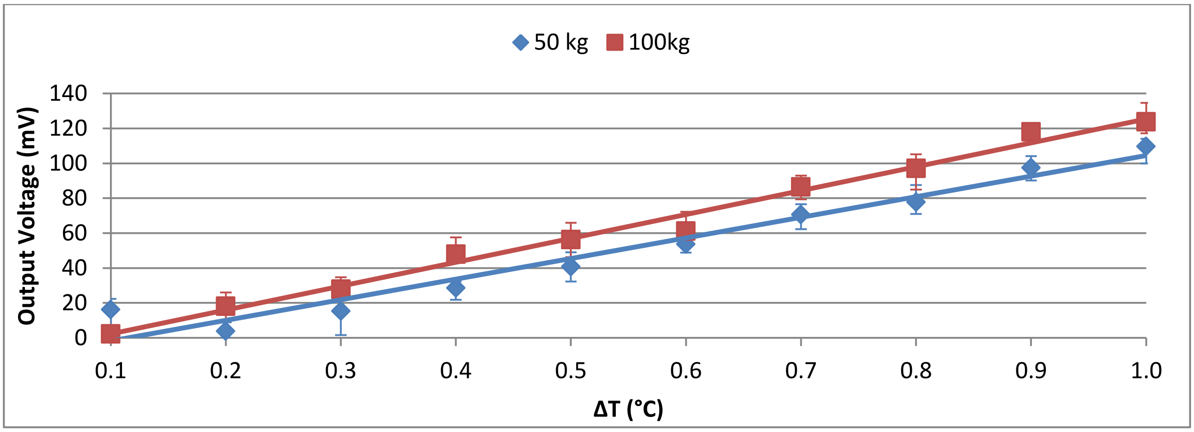

Figure 6: Effect of Pressure of Low ΔT_{TEG}

The transient discharge events in Test 3 lasted for 1, 3, 5 and 10 ms. Figure 7 shows the relationship between the length of the pulse and the reduction in voltage on the 2.2 V regulated line when the harvester was receiving 480 mV. The voltage on the bulk capacitor discharges exponentially as expected. The threshold voltage is shown at 1.8 V: this is the minimum that a typical attached microprocessor system would require to maintain normal operation. Clearly pulses of up to ~5 ms are allowable for single transient events. It is interesting to note that while the capacitor discharges at a rate of 30 mA the recovery time is very close to the discharge time, indicating that the regulator charges at a rate of nearer 15mA than the rated 10 mA.

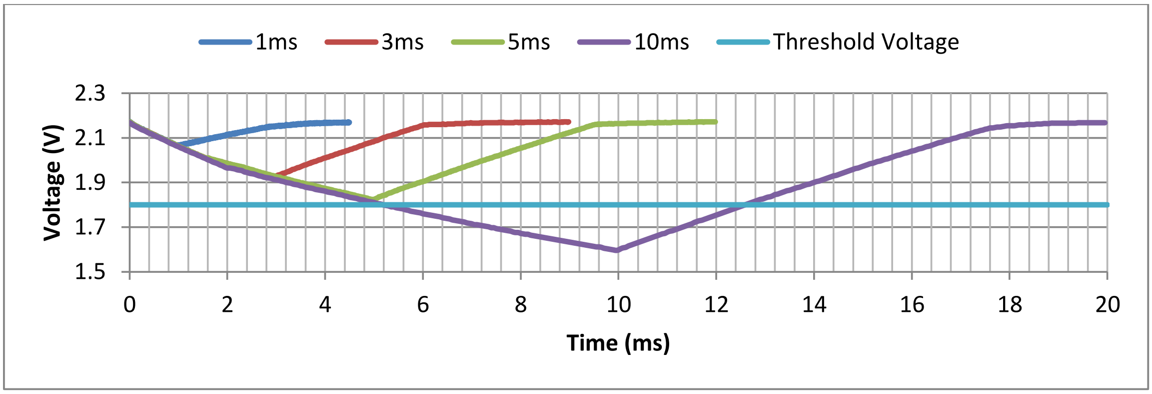

Figure 7: Transient Discharge Test Results

The fourth test undertaken was the repetitive transient discharge with recovery test. Test 3 showed that, for a charging current of ~15 mA, current pulse durations of up to 5 ms could be accommodated. The recovery period between each pulse was set at 5 times its duration. By setting a specific length of time if the duty cycle remained constant then the effective amount of work should remain constant, assuming no overhead. Repeated pulse durations of 1ms caused little effect on the regulated voltage line. Repeated pulses of 3 ms showed some variance in the voltage line but eventually fell off once the supercapacitor had lost its charge. Pulses of 5 ms were unable to maintain a voltage above 1.8 V as shown in figure 8. It is believed the reason for this is heating in the power supply chip's output stage due to an output current slightly above the recommended maximum. The inference drawn from this result c.f. that of Test 3 is that a single 30 mA pulse of 5 ms is allowable but a repetitive pulse train should be of either reduced duty cycle or of lower peak current.

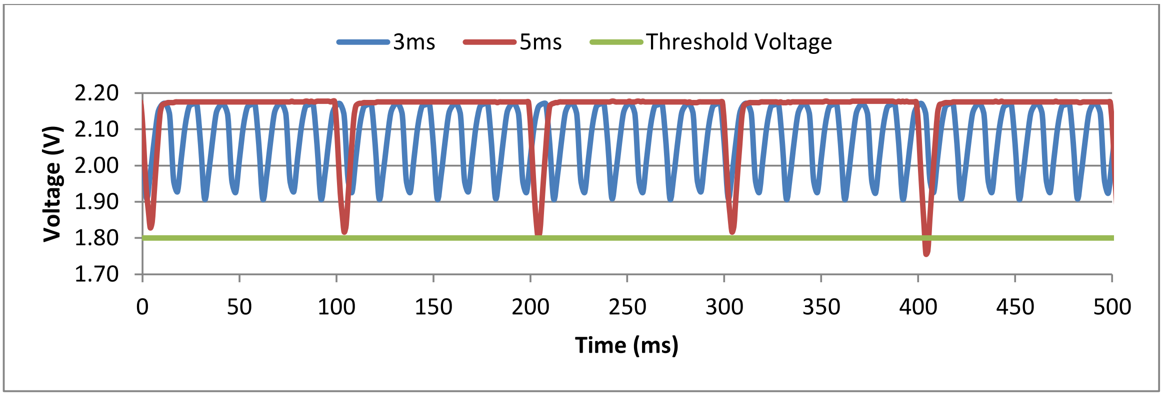

Figure 8: Repeated Current Bursts

5. Discussion and conclusions

The data presented in this paper report an energy harvester system able to operate from as little as 23 mV. This equates to a differential temperature of only 0.6 °C using the thermoelectric module specified. When the energy storage capacitor is fully charged the power supply can provide enough electrical power to run an entire low power sensor system with wireless data communication.

The use of the LTC3108 power converter allows fixed thermal gradients to be used: e.g. between a cold sink and a warmer environment or a warm source in a cooler environment. The size of TEG and the number of couples required for operation of the system depends strongly on the temperature difference available, with a higher available ΔT permitting a smaller and probably less expensive TEG to be used.

One of the concerns in developing a battery-free embedded system is the provision of sufficient energy from the power supply. The LTC3108 has an exceptionally low activation voltage but the maximum output current on its voltage regulator is only 10 mA. This is insufficient current to power a wireless data transmission system[‡] or some sensors. The bulk storage capacitor used on the regulated output rail can deliver short bursts up to 30 mA but at the expense of high ripple voltage. A larger capacitance on the regulated voltage line would reduce the variations in voltage during transient events. The trade-off is that an increased line capacitance will increase charge time and increase the leakage current – increasing quiescent power consumption. Any attached system needs to be shown to work reliability in the presence of the ripple voltage experienced.

With a functioning energy harvesting system the next stage in development would be to deploy the energy harvester as a complete unit. The suggested future setup is demonstrated in Figure 9, in this setup the thermal energy is provided by a copper hot water pipe and the cold side is a passive heat sink which is being cooled by the ambient environment. The heat will flow from the pipe into a hot block which is fixed to the pipe with a mounting bracket, this thermal interface can be improved with a thermal paste. The TEM is connected to both the heat sink and the hot block using a thermal adhesive. While the thermal performance of a thermal adhesive is not as good as a thermal paste it is able to provide the mechanical support required without creating a thermal short circuit which would happen using screws to clamp the heat sink and hot block.

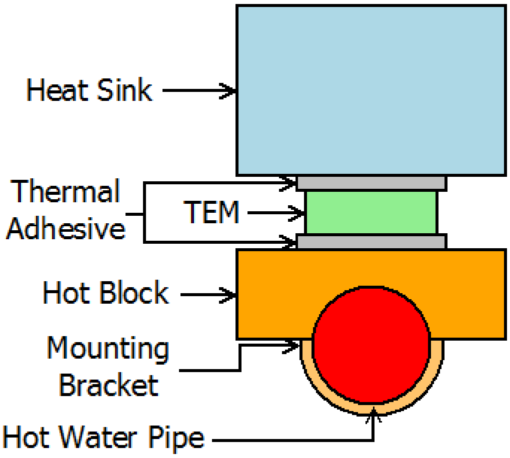

Figure 9: Suggested Future Setup

Wireless sensor systems are becoming ubiquitous but can suffer from short battery life. By scavenging energy for operation from their environment, new sensor systems can be battery-free, or can be deployed in harsh environments where traditional battery powered devices are not suitable for the task. Thermoelectric energy harvesting offers a practical way to power these autonomous sensor systems by exploiting the temperature differential available in many environments using either hot-to-cold or cold-to-hot energy flow. The work presented here demonstrates an energy harvester which is operable with less than 1°C ΔT. To the authors' knowledge this is the first time such a system has been reported.

References

[‡] For example Texas Instruments CC430 wireless SoC, requiring up to 36 mA to run

[1] R. a. Powers, “Batteries for low power electronics,” Proc. IEEE, vol. 83, no. 4, pp. 687–693, Apr. 1995.

[2] G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, “Energy conservation in wireless sensor networks: A survey,” Ad Hoc Networks, vol. 7, no. 3, pp. 537–568, May 2009.

[3] A. Dewan, S. U. Ay, M. N. Karim, and H. Beyenal, “Alternative power sources for remote sensors: A review,” J. Power Sources, vol. 245, pp. 129–143, Jan. 2014.

[4] S. Sudevalayam and P. Kulkarni, “Energy Harvesting Sensor Nodes: Survey and Implications,” IEEE Commun. Surv. Tutorials, vol. 13, no. 3, pp. 443–461, 2011.

[5] J. Yick, B. Mukherjee, and D. Ghosal, “Wireless sensor network survey,” Comput. Networks, vol. 52, no. 12, pp. 2292–2330, Aug. 2008.

[6] R. J. M. Vullers, R. van Schaijk, I. Doms, C. Van Hoof, and R. Mertens, “Micropower energy harvesting,” Solid. State. Electron., vol. 53, no. 7, pp. 684–693, Jul. 2009.

[7] J. Polastre and D. Culler, “Perpetual environmentally powered sensor networks,” IPSN 2005. Fourth Int. Symp. Inf. Process. Sens. Networks, 2005., pp. 463–468.

[8] I. F. Akyildiz, T. Melodia, and K. R. Chowdhury, “A survey on wireless multimedia sensor networks,” Comput. Networks, vol. 51, no. 4, pp. 921–960, Mar. 2007.

[9] a. S. M. Zahid Kausar, A. W. Reza, M. U. Saleh, and H. Ramiah, “Energizing wireless sensor networks by energy harvesting systems: Scopes, challenges and approaches,” Renew. Sustain. Energy Rev., vol. 38, pp. 973–989, Oct. 2014.

[10] Z. Wang, V. Leonov, P. Fiorini, and C. Van Hoof, “Realization of a wearable miniaturized thermoelectric generator for human body applications,” Sensors Actuators A Phys., vol. 156, no. 1, pp. 95–102, Nov. 2009.

[11] J. Su, V. Leonov, M. Goedbloed, Y. van Andel, M. C. de Nooijer, R. Elfrink, Z. Wang, and R. J. M. Vullers, “A batch process micromachined thermoelectric energy harvester: fabrication and characterization,” J. Micromechanics Microengineering, vol. 20, no. 10, p. 104005, Oct. 2010.

[12] Y. K. Ramadass and A. P. Chandrakasan, “A Battery-Less Thermoelectric Energy Harvesting Interface Circuit With 35 mV Startup Voltage,” IEEE J. Solid-State Circuits, vol. 46, no. 1, pp. 333–341, Jan. 2011.

[13] E. J. Carlson, K. Strunz, and B. P. Otis, “A 20 mV Input Boost Converter With Efficient Digital Control for Thermoelectric Energy Harvesting,” IEEE J. Solid-State Circuits, vol. 45, no. 4, pp. 741–750, Apr. 2010.

[14] K. T. Settaluri, H. Lo, and R. J. Ram, “Thin Thermoelectric Generator System for Body Energy Harvesting,” J. Electron. Mater., vol. 41, no. 6, pp. 984–988, Dec. 2011.

[15] G. Roy, E. Matagne, and P. J. Jacques, “A Global Design Approach for Large-Scale Thermoelectric Energy Harvesting Systems,” J. Electron. Mater., vol. 42, no. 7, pp. 1781–1788, Feb. 2013.

[16] A. Moser, M. Erd, M. Kostic, K. Cobry, M. Kroener, and P. Woias, “Thermoelectric Energy Harvesting from Transient Ambient Temperature Gradients,” J. Electron. Mater., vol. 41, no. 6, pp. 1653–1661, Feb. 2012.

[17] Linear Technology, LTC3108, http://cds.linear.com/docs/en/datasheet/3108fc.pdf

[18] Texas Instruments, bq25504, http://www.ti.com/lit/ds/symlink/bq25504.pdf

[19] Maxium Integrated, MAX17710, http://datasheets.maximintegrated.com/en/ds/MAX17710.pdf

[20] STMicroelectrics, SPV1050, http://www.st.com/st-web-ui/static/active/en/resource/technical/document/datasheet/DM00100984.pdf