Milliwatt Power Supply by Dynamic Thermoelectric Harvesting

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Abstract. In this work we demonstrate a power supply that collects thermal energy from temperature fluctuations in time, to provide regulated power in the milliwatt range. It is based on the dynamic thermoelectric energy harvesting concept, in which a phase change material is used to store heat and create spatial heat flow from temperature transients. A simple, cost-effective and reproducible fabrication method is employed, based on 3D printing and off-the-shelf components. The harvester is integrated with a commercial power management module and supercapacitor storage. Output energy up to 2 J is demonstrated from temperature cycles corresponding to avionic applications. The demonstration includes harvesting while powering a 10 kΩ analogue voltmeter directly from the supercapacitor, including during cold-starting.

1. Introduction

The employment of heat storage addresses the problem of achieving a significant temperature difference in thermoelectric energy harvesters. Dynamic thermoelectric devices comprise an insulated heat storage unit (HSU) which is in thermal contact to the environment through thermoelectric generators (TEG) as shown in Fig. 1:Left. The HSU is filled with a phase change material (PCM) to increase thermal storage density and the time constant of its heat dynamics. Thereby, it can achieve substantial ΔT across the TEG, which is essential for efficient power transduction and management. This device concept was introduced in [1], studied analytically and numerically [2], and used in various implementations, including demonstrators for aircraft applications and flight tests [3] and integrated wireless sensor networks [4]. A model for phase change inhomogeneity was introduced in [5]. Recently, a practical fabrication method was proposed, based on 3D-printed double-wall insulation and water capsules [6]. In this work, a power supply demonstrator is introduced, integrating a commercially available power management (PM) system designed for low-voltage input and a supercapacitor energy storage array.

2. Fabrication of the dynamic thermoelectric harvesting prototype

The energy harvester fabrication process is described in Fig. 2 and it follows the method introduced in [3]. An insulating 32 × 32 × 26 mm HSU box with 3 mm thick walls is fabricated by Acrylonitrile-Butadiene-Styrene (ABS) 3D printing. The side walls encompass a 1 mm airgap to enhance thermal insulation. The PCM is inserted to the insulation box in an encapsulated form, using commercially available water containers made either of metal for enhanced heat bridging, or of plastic for reduced device weight. The usage of other PCMs in encapsulated form is also possible, depending on the temperature fluctuation range of the target application. A Marlow TG12-2.5 TEG with dimensions 30 × 30 × 4 mm is slid to the open side of the box. A photograph of the prototype is shown in Fig. 1:Right.

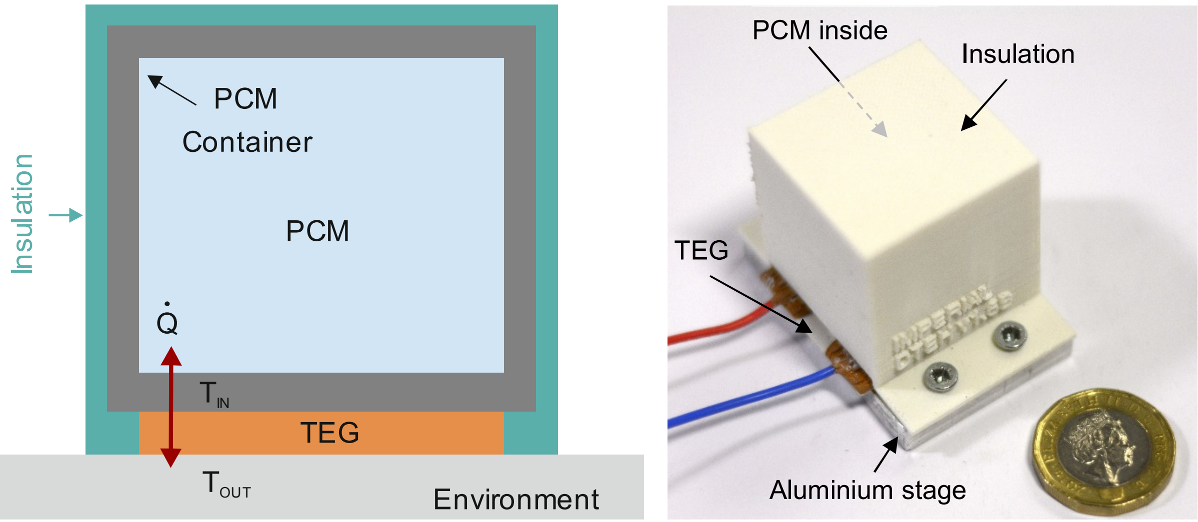

Figure 1: Left: The dynamic thermoelectric harvesting concept [6]. Right: Image of the demonstrator.

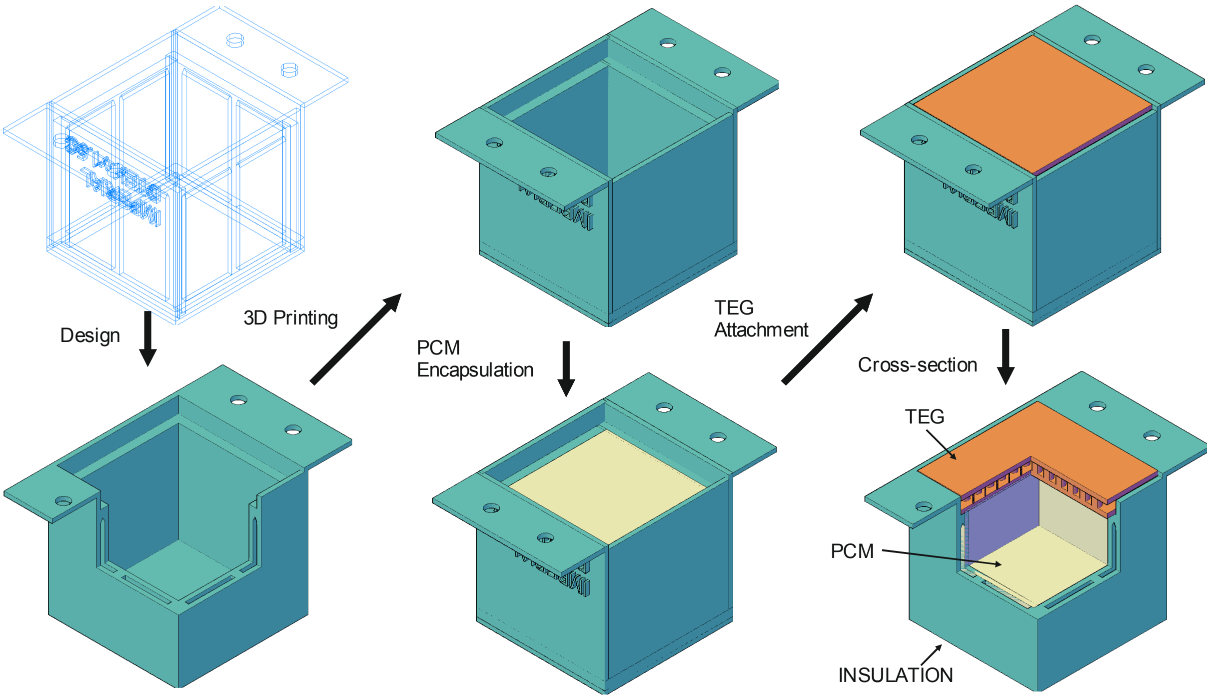

Figure 2. 3D printing and dry assembly of the dynamic thermoelectric harvesting demonstrator.

3. Power Management and Storage

The power management system block diagram is depicted in Fig. 3. It includes two 1:100 transformers to allow bipolar cold starting from very low voltages. This is key to dynamic thermoelectric harvesting, because in contrast to static installations, the polarity is varying and cold starting from either increasing or decreasing environmental temperatures is desirable. Cold starting from voltages as low as 30 mV is provided by the Linear Technology LTC3109 chip. Two 330 μF capacitors are used as power buffers for the two regulated 2.2 V and 3.3 V outputs of the system. For storage, two 2.5 V, 1 F supercapacitors are used in series, allowing an overall storage capacity of around 6 J. For testing under power dissipating loads, a 0.1 F supercapacitor was used as storage, to shorten the charging time, and a 10 kΩ analogue voltmeter was connected in parallel directly on the supercapacitor, as shown by the dashed connections of Fig. 3.

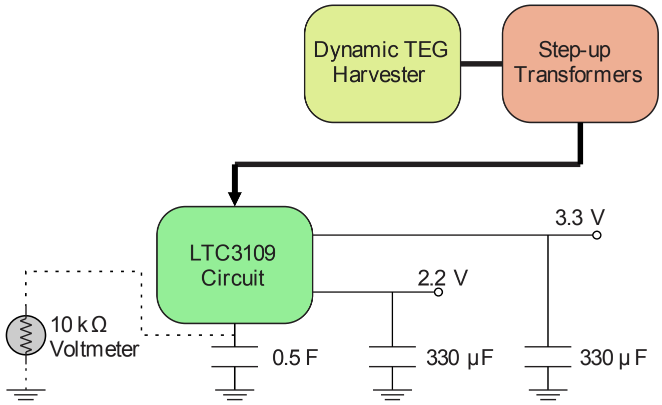

Figure 3. Block diagram of the power management and energy storage system. The dashed circuit corresponds to the dissipative load experiments, for which a 0.1 F supercapacitor was used in place of the 0.5 F array.

4. Characterisation

Experimental measurements of the storage voltage obtained from a 4 K/min temperature change between +20 °C and -35 °C are presented in Fig. 4. The total output energy of the TEGs is found to be around 18 J, assuming a 3.5 Ω input resistance for the power management board [7]. The total stored energy is 1.6 J giving a 9% overall power management efficiency. The observed efficiency was almost double during low TEG voltage operation (below 100 mV), as expected from the specifications of the used circuit [7].

To characterise the performance during power consumption, measurements using a 0.1 F supercapacitor and a 10 kΩ analogue voltmeter as a dissipative load are shown in Fig. 5. Dissipation exceeds harvesting at around 25 min., resulting in supercapacitor discharge. The slow discharge rate in comparison with the exponential RC discharge (dashed red curves in Fig. 5), demonstrates useful energy harvesting even at TEG voltage below 100 mV. In the insets, the corresponding combined storage and cumulative dissipation energy is presented. A total cumulative energy delivery of 2 J is demonstrated. The cumulative TEG output energy is 17.64 J, assuming a 3.5 Ω input resistance for the power management board, yielding a 11% overall power management efficiency for this experiment.

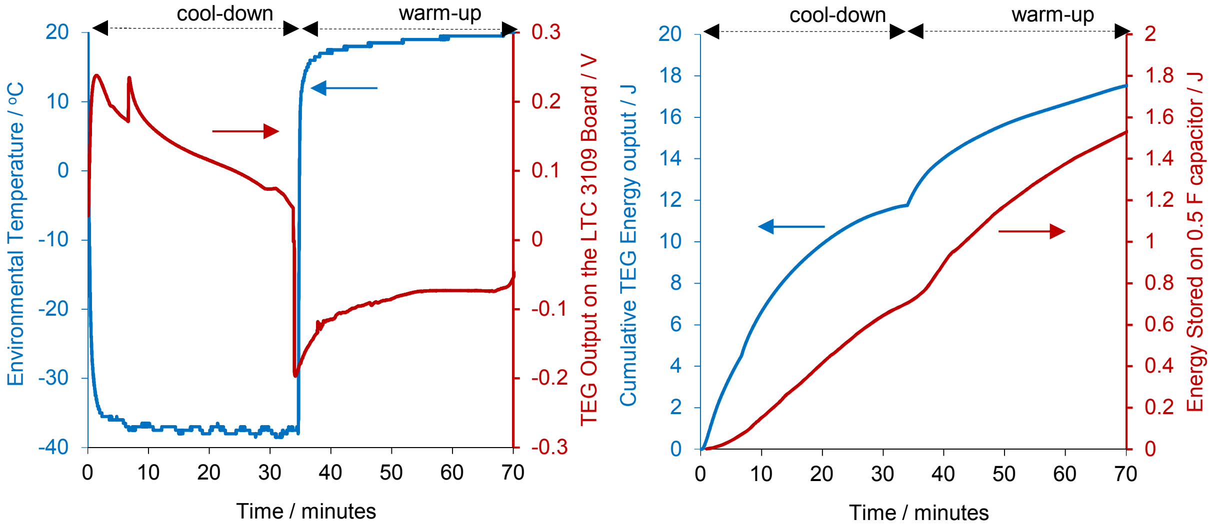

Figure 4. Left: Measured temperature and voltage on TEG output connected on the LTC 3109 board, during a temperature sweep between 20 °C and -35 °C. Right: Corresponding electrical input energy and energy stored in a 0.5 F supercapacitor array.

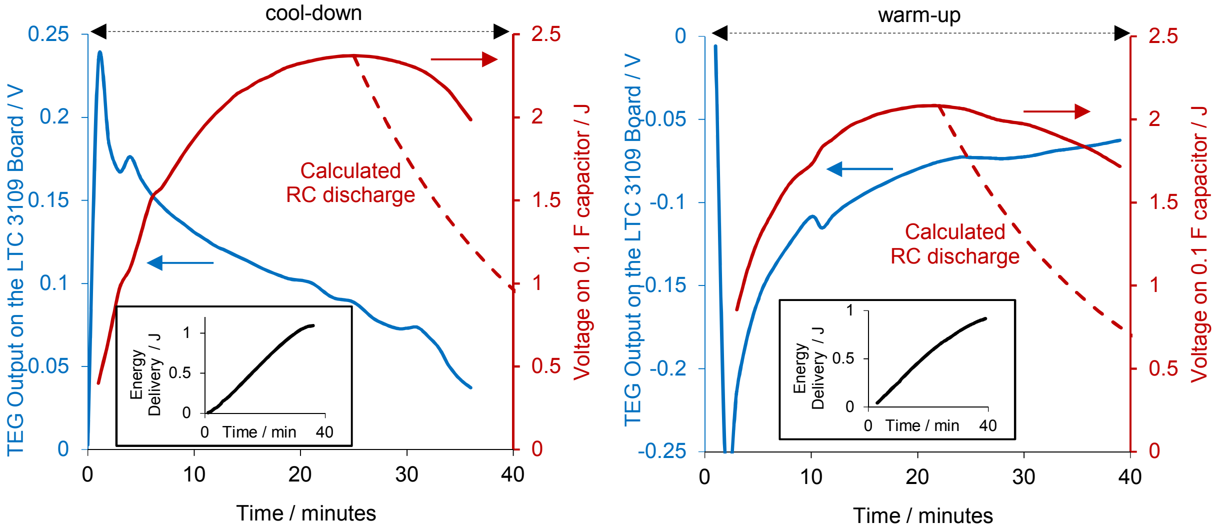

Figure 5. Measured TEG output and storage voltage using a 0.1 F supercapacitor and a 10 kΩ analogue voltmeter as dissipative load, during a cool-down (Left) and warm-up (Right) temperature sweep between 20 °C and -35 °C. The total cumulative energy delivery is shown in the insets.

5. Conclusion

A new dynamic thermoelectric harvesting power supply with a bipolar power management system optimised for low ΔT operation is introduced in this paper. Useful output energy of 2 J is demonstrated from a temperature cycle corresponding to aviation applications. Successful system operation during power dissipation in a 10 kΩ load is achieved. The low power management efficiency (~10%) is due to the optimization for start-up and operation from TEG voltages below 100 mV. This corresponds to ΔT values below 5 K, which can be easily achieved by dynamic harvesters from moderate temperature fluctuations. The improvement of thermal contacts and further customization of the power management system are expected to enable dynamic thermoelectric harvesters suitable for a broad range of applications.

Acknowledgement

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