Sensor systems

Three-Dimensional Printed Insulation For Dynamic Thermoelectric Harvesters With Encapsulated Phase Change Materials

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Abstract— Energy harvesting devices have demonstrated their ability to provide power autonomy to wireless sensor networks. However, the adoption of such powering solutions by the industry is challenging due to their reliance on very specific environmental conditions such as vibration at a specific frequency, direct sunlight, or a local temperature difference. Dynamic thermoelectric harvesting has been shown to expand the applicability of thermoelectric generators by creating a local spatial temperature gradient from a temporal temperature fluctuation. Here, a simple method for prototyping or short-run production of such devices is introduced. It is based on the design and 3-D printing of an insulating container, insertion of a phase change material in encapsulated form, and use of commercial thermoelectric generators. The simplicity of this dry assembly method is demonstrated. Two prototype devices with double-wall insulation structures are fabricated, using a stainless-steel and a plastic phase change material encapsulation and a commercial TEG. Performance tests under a temperature cycle between ±25 °C show energy output of 43.6 and 32.1 J from total device masses of 69 and 50 g, respectively. Tests under multiple temperature cycles demonstrate the reliability and performance repeatability of such devices. The proposed method addresses the complication of requiring a wet stage during the final assembly of dynamic thermoelectric harvesters. It allows design and customization to particular size, energy, and insulation geometry requirements. This is important because it makes dynamic harvesting prototyping widely available and easy to reproduce, test, and integrate into systems with various energy requirements and size restrictions.

Index Terms—Sensor systems, thermoelectric, energy harvesting, phase change materials, 3-D Printing.

I. INTRODUCTION

Finding a practical method to power off-grid wireless devices is of the uttermost importance to sensor technologies that are, in turn, key for sustainable development and improvement of quality of life [1]. Examples include monitoring industrial [2] and civil installations [3], infrastructure, networks and human health [4], [5]. Rechargeable energy storage, energy harvesting from local power sources and wireless power delivery are the main options. Systems comprising energy harvesting and storage have already been demonstrated to improve autonomy and reliability, and reduce maintenance requirements. However, these systems usually rely on very specific environmental conditions, such as vibration at a specific frequency, direct sunlight or a large temperature difference between two thermally conductive surfaces in close vicinity.

Dynamic thermoelectric harvesting, the exploitation of time-varying environmental temperature by employing a heat storage unit (HSU), has shown promise in expanding the applicability of thermoelectric power generation [6]. A conceptual illustration of this device concept is shown in Fig. 1.

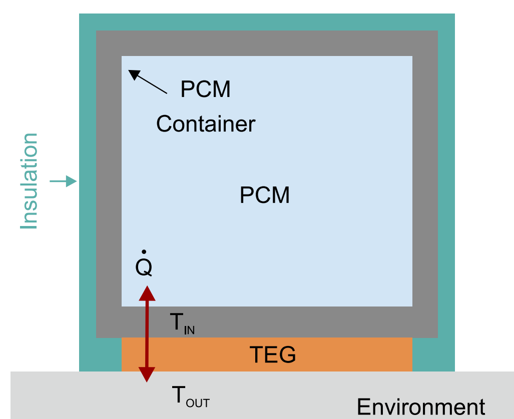

Fig. 1. Conceptual description of dynamic thermoelectric harvesting.

The HSU contains a phase change material (PCM) to increase heat capacitance. This increase has been shown to be over an order of magnitude in cumulative energy [7], [8]. The HSU is in thermal contact with the environment only through a thermoelectric generator (TEG). The dynamic response of the system to a varying outside temperature

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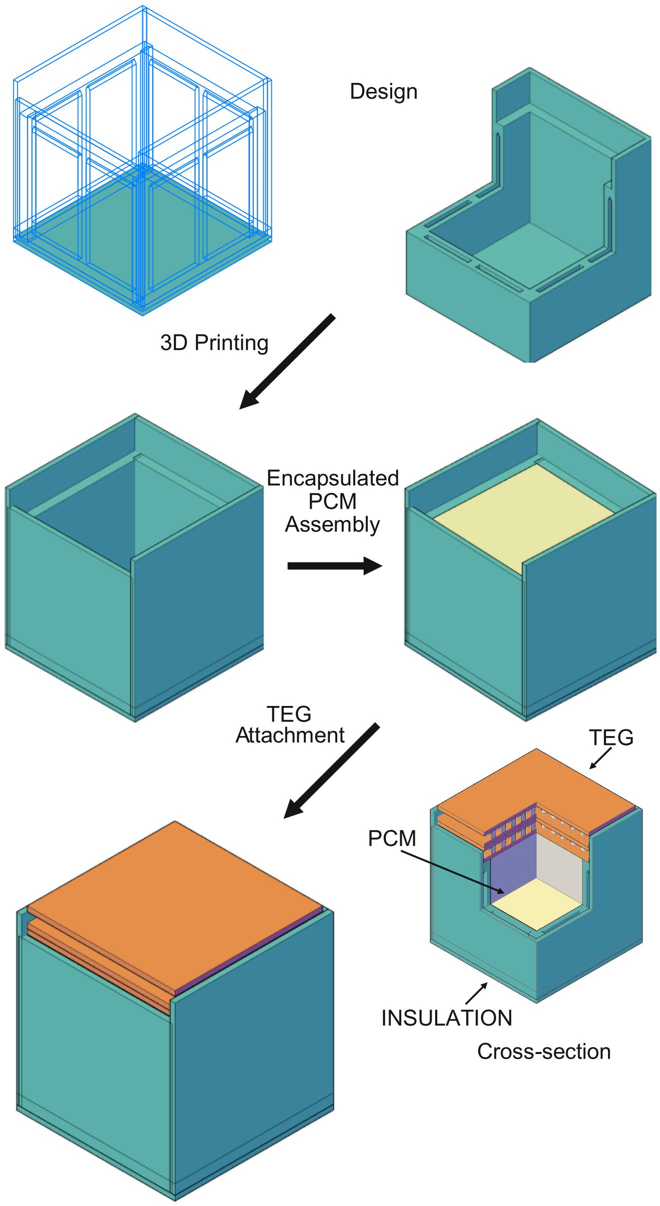

Fig. 2. Fabrication process steps for a dry-assembled dynamic thermoelectric harvesting devices.

is determined by the HSU heat capacity C, the PCM latent heat L and the thermal resistance R between the PCM and the environment. As the environmental temperature T_{OUT} fluctuates, heat flows through the TEG. The internal HSU temperature T_{IN} follows T_{OUT} with a delay that depends on the thermal RC time constant of the system. This delay builds a temperature difference $\Delta T = T_{OUT} - T_{IN}$ across the TEG which allows energy conversion at increased efficiency. During phase-change, T_{IN} remains constant further increasing ΔT. The dynamics of this device concept have been studied experimentally, analytically and numerically [9], and phase change homogeneity [10], super cooling [11], and TEG design [12] have been considered as methods of performance improvement. Suitable power management systems have been developed, including bipolar operation, maximum-power-point-tracking and battery management capabilities [13]. Various prototypes have been reported and characterized typically in the temperature range between $\pm 20\,^{\circ}$C, at a rate of 4

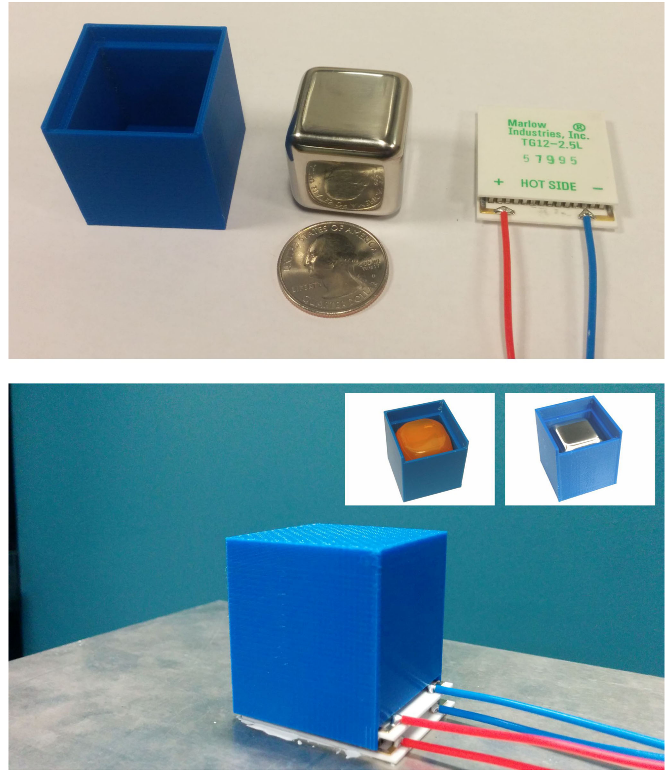

Fig. 3. Demonstration device. (Top) Device components. (Bottom) Fully assembled dynamic thermoelectric harvester. Insets: Insulation box with plastic (left) and stainless steel (right) PCM containers.

K/min, because of the high potential of dynamic harvesting devices for aircraft applications. Energy output recently reached 1 J/cm^3 per total device volume and per T_{OUT} cycle, allowing the implementation of energy autonomous strain monitoring wireless sensor nodes for aircraft [14].

While this dynamic approach removes the requirement for a locally available ΔT and broadens the applicability of thermoelectric harvesting, size customization to fit the energy demand of specific sensing applications is still required. The fabrication of such customized devices is challenging because it involves heat bridge and liquid container machining, insulation customization, which is often mold-based, and an assembly process that includes liquid filling and sealing. This process is expensive and can result in devices of reduced reliability, due to sealing limitations during assembly. In this work, a new fabrication process for dynamic thermoelectric harvesting devices is proposed. It is based on 3-D-printing the heat storage unit and a simple, dry assembly method made possible by employing commercially available encapsulated PCM containers.

II. FABRICATION

The proposed fabrication process is illustrated in Fig. 2. The HSU is 3-D designed and printed allowing prototyping at custom sizes and evaluating different structural insulation techniques, such as implementation of double-walls, low density materials and advanced, foam-like microstructures. Off-the-shelf or customized sealed PCM containers can then be fitted into the printed-to-fit HSU. These containers can be made of metal, providing an internal heat bridge, or of plastic, offering a considerably lighter implementation at the cost of

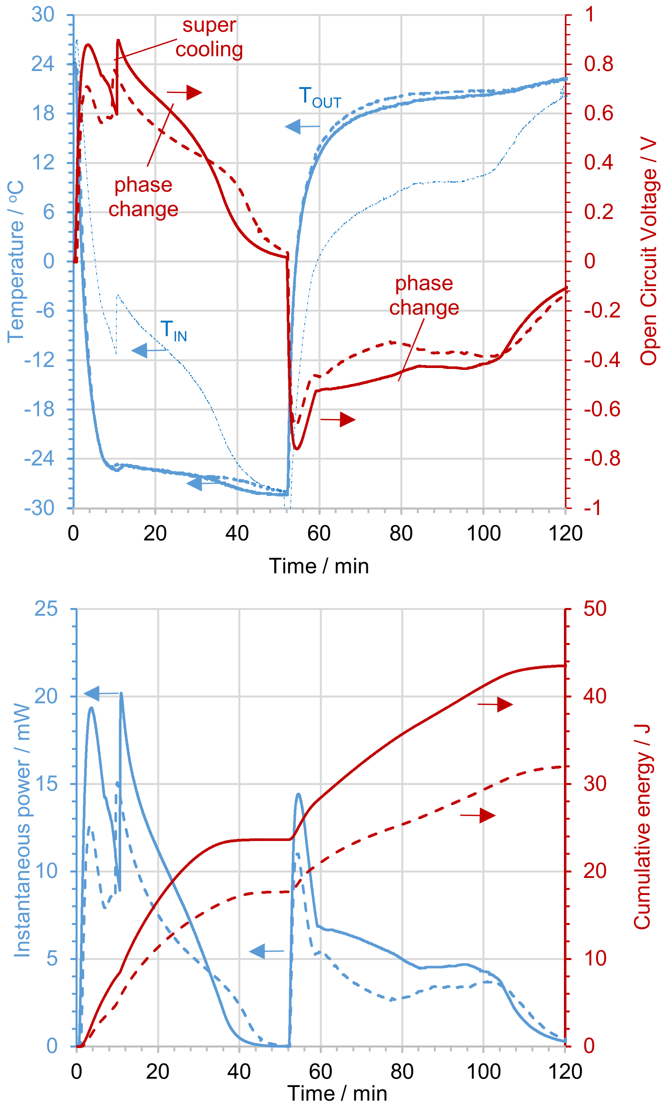

Fig. 4. Experimental measurements of device performance under a temperature cycle between $\pm 25\,^{\circ}$C with a temperature change rate of around $4\,^{\circ}$C / min. (Top) Outside temperature (T_{OUT}) and open circuit voltage output. The dash-dotted curve shows the T_{IN} calculated from T_{OUT} for an effective Seebeck coefficient of 42 mV/K [9]. (Bottom) Corresponding instantaneous power and cumulative energy output, accounting for a $10\,\Omega$ matched load across the two TEGs. The solid and dashed lines correspond to the device with a stainless steel and a plastic PCM container, respectively.

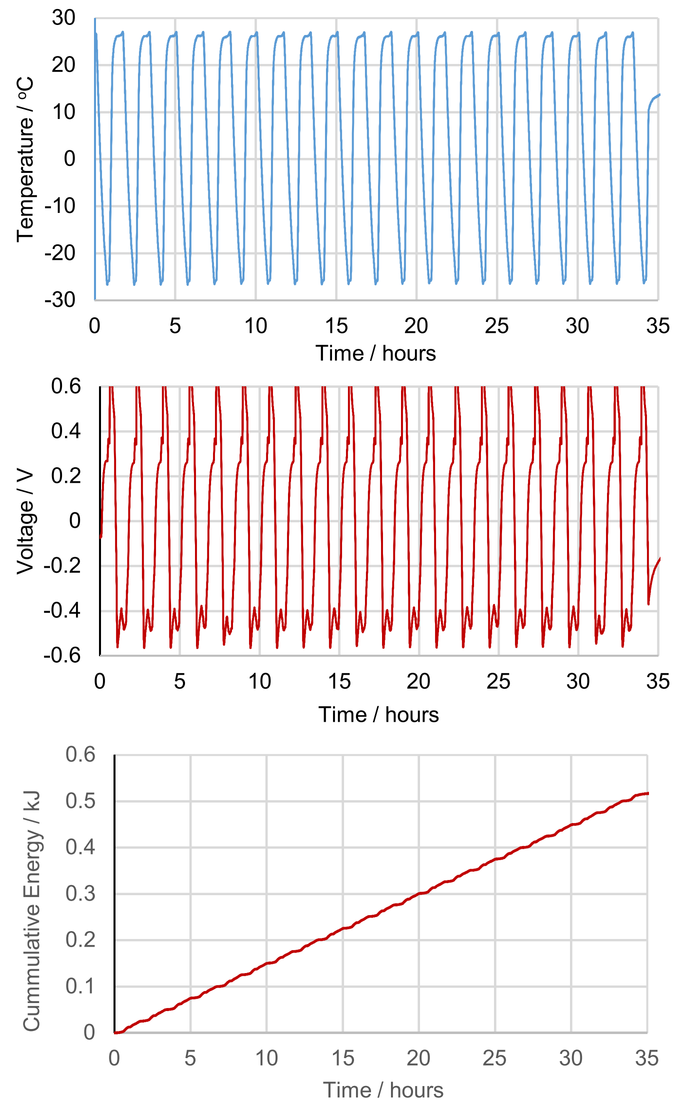

Fig. 5. Measured performance of the device with the plastic PCM container during multiple temperature cycles.

ΔT loss due to temperature inhomogeneity [10]. Finally, one or more commercial TEGs are assembled and fixed either by press-fitting or clamping. The fixing structure can be included in the 3-D design.

In order to demonstrate this fabrication method, HSUs customized to fit commercially available 26 mm side cubic water containers were designed and 3-D printed. Sealed containers from various vendors were tested for overall performance in the $\pm 20\,^{\circ}$C range. In the results presented here, Qvant stainless steel and common plastic PCM containers were used.

The design includes a double-wall insulation structure and was printed by a uPrint Stratasys printer using an Acrylonitrile-Butadiene-Styrene (ABS) filament at coarse printing mode. It allows accommodation of two 30 $\times$ 30 $\times$ 4 mm Marlow TG12-2.5 TEG which can be mounted by press-fitting in a thermally-serial orientation. This orientation doubles thermal resistance, thereby increasing the total energy output [12]. Thermally conductive paste was used to reduce interface thermal resistance. The two TEGs are electrically connected in series, giving a combined electrical output resistance of 10 Ω. The complete device can be dry assembled and disassembled, eliminating the requirement of gluing or screw-fitting of previous prototypes. An image of the device components and the fully assembled device is presented in Fig. 3.

III. DEVICE CHARACTERIZATION

The devices were tested under 4 K/min temperature cycles in a temperature range between $\pm 25\,^{\circ}$C, corresponding to the fuselage temperature during typical flights [8] in a Tenney Engineering Inc. BTR mL environmental chamber. The temperature applied to the outside surface of the TEG and the open circuit voltage output were monitored using two data-logging multimeters connected to a computer. The T_{IN}

was calculated from T_{OUT} using an effective Seebeck coefficient of 42 mV/K for each TEG [9]. The results are shown in Fig. 4. As T_{OUT} is swept towards $-25\,^{\circ}$C, the output voltage V_{OUT} increases to around 0.9 V. When T_{OUT} starts stabilizing, V_{OUT} drops but it soon increases abruptly due to the beginning of phase change. This abrupt increase is due to super-cooling [11]. During phase change the voltage drops gradually, due to T_{IN} drift caused by phase-change inhomogeneity. When phase change is complete, V_{OUT} drops exponentially to zero. The same effect occurs during warmup, but without the super-cooling effect. The open-circuit output voltage is over 0.2 V during most of the power transducing time. This voltage level is adequate for cold-starting and efficient power management by commercially available systems [14]. The cumulative energy output for the stainless steel and plastic container implementations are 43.6 J and 32.1 J respectively. The total device volume is 37 cm^3 and the total weight is 69 g and 50 g for the stainless steel and plastic container implementations respectively. These values correspond to energy density of 1.17 J/ cm^3 and 0.86 J/ cm^3 or 0.63 J/g and 0.64 J/g respectively at the device level. This performance could be increased if the insulation at the interface between the two TEGs is improved, by eliminating the protruding TEG substrates and enclosing the connections into a modified HSU design.

As mentioned, the proposed fabrication method is expected to provide enhanced reliability even for prototype implementations. To experimentally assess this anticipation, the devices were tested under multiple T_{OUT} cycles. Indicative results for the plastic box device undergoing twenty cycles between $\pm 25\,^{\circ}$C at 1 K/min are shown in Fig. 5. A consistent voltage output is observed throughout the experiments, though lower than that of Fig. 4 due to the moderate sweep rate, without any signs of performance degradation.

The sudden voltage increase due to super-cooling is observed during cool down. The voltage ripple during warm-up is due to the limitation of temperature uniformity in the environmental chamber. The total cumulative energy output during this experiment was around 0.5 kJ.

IV. CONCLUSION

A new prototyping method for dynamic thermoelectric harvesters was introduced, based on 3-D printed insulation, encapsulated phase change material containers and off-the-shelf thermoelectric generators. The demonstrator devices show energy density similar to that of state-of-the-art implementations fabricated by other methods. Testing under multiple temperature cycles demonstrated the repeatability and reliability of performance, as well as its functional stability under normal operating conditions.

The proposed method addresses the challenges of including a wet step in the final assembly process of these prototype devices. In addition, it provides a simple way to develop new dynamic thermoelectric generators, and tailor them to suit size and power requirements of different applications. This customization capability is expected to extend the use of dynamic thermoelectric energy harvesting beyond the aircraft environment, in which prototype systems have been focusing so far. Suitable environments providing temperature fluctuation include industrial equipment with periodic operation, vehicle engines, buildings and infrastructure networks experiencing heating and cooling. For this purpose, suitable PCMs with phase change within the temperature range of the intended environment must be selected. This may be the second energy harvesting technology, after solar cell - based harvesters, to reach the stage of such a simple prototyping and customization ability, with applicability to generally available environmental conditions.

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