Performance evaluation of a thermoelectric energy harvesting device using various phase change materials

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Abstract. This paper compares the performance of a group of organic and inorganic phase change materials for a heat storage thermoelectric energy harvesting device. The device consists of thermoelectric generators and a closed container filled with a phase change material. One side of the generators is mounted on the aircraft fuselage and the other to the thermal mass. The group of inorganic and organic phase change materials was tested across two temperature ranges. These ranges are defined as “positive” and “negative”, with the former being a sweep from +35°C to -5°C and the latter being a sweep from +5°C to -35°C. The performance in terms of electrical energy output and power produced is examined in detail for each group of materials.

1. Introduction

In an effort to reduce the maintenance cost of an aircraft over its lifetime, wireless health monitoring sensors (WHMS) have been under consideration. The sensors may vary in function, from crack-wires, to multi-axial strain gauges, to acousto-ultrasonic, which usually require different amounts of energy. The energy that such sensors require traditionally is provided by either cables or rechargeable batteries. However, neither of these two solutions is really optimal, because on the one hand cables introduce design complexity, weight and installation cost and on the other hand batteries require regular recharging and/or replacement during the lifetime of an aircraft (≈30 years).

A way to create a truly autonomous WHMS is to convert energy from an otherwise unused, localised source and convert it to useable electrical energy. This concept is known as energy harvesting and a study of different possible harvesting methods for aircraft applications has been reported in [1]. Thermoelectric energy harvesting has been shown to be a promising solution for powering completely autonomous WHMS in aircraft [2].

A possible realization of a thermoelectric energy harvesting device uses an aircraft’s fuselage as a heat source or sink and phase change materials (PCMs) as a dynamic thermal mass in order to increase the temperature difference across a thermoelectric generator (TEG). PCMs, while undergoing a phase change, absorb or release energy additional to their specific heat, known as latent heat, without changing their temperature. This effect enhances the temperature difference across the TEG, effectively increasing its energy conversion potential. In general, the latent heat is the most important
physical property of a PCM in terms of thermal energy storage capabilities, while the phase change temperature determines the effective operating temperature range of the device.

The performance of such devices has been studied during a flight test campaign, demonstrating average electrical energy output densities as high as 2.4 J/g of PCM [2], and can be theoretically as high as 10 J/g [3]. The scope of this paper is to investigate the performance of two different PCM groups, one consisting of organic and one of inorganic materials, in terms of power and total electrical energy output.

2. Design Aspects
The harvester described in this paper consists of a closed aluminium container, a polyurethane insulating sheath, two TEGs (Marlow TG 12-2.5L [4]) electrically connected in series, and a 10 Ω resistor as a matched load. A photograph of the prototype device is shown in Figure 1.

For each test, the container was filled with 23 ml of PCM, which is 7 ml less than the internal volume of the container to allow material expansion during phase change. Separate experiments were conducted for materials exhibiting positive and negative phase change temperatures. The entire device, which would be exposed to the interior fuselage temperature, is subjected to a 40°C temperature change: +5°C to -35°C for the “negative” group and +30°C to -10°C for the “positive” group.

Previous versions of such devices were tested with distilled water or inorganic solutions as PCMs [5, 6]. Table 1 summarizes the physical properties of all the materials used to determine the performance of the proposed device. Distilled water is included in Table 1 as a reference for comparing the physical properties of the other PCMs.

| Physical properties | Distilled water | Inorganic materials | Organic materials |
|---------------------|----------------|--------------------|-------------------|
|                     |                | E-15               | E-11              | RT10-HCG   | RT10-HC  | RT-9   |
| $T_m$ (°C)          | 0              | -15                | -11.6             | +10 – +9   | +10 – +4 | -9 – -10 |
| $C_p$ (kJ/kgK)      | 4.2            | 3.87               | 3.55              | 2          | 2        |         |
| $\rho$ (kg/m$^3$)   | 1000           | 1060               | 1090              | 770        | 770      | 770    |
| $\Delta H$ (kJ/kg)  | 330            | 303                | 301               | 152        | 195      | 260    |

3. Theoretical Background
The PCMs in this application act as thermal batteries, which are “charged” or “discharged” during ascent and descent respectively. The maximum thermal energy that can theoretically be stored is
\[ Q = \int_{T_h}^{T_f} mC_{P,l}(T) dT + m\Delta H + \int_{T_f}^{T_m} mC_{P,s}(T) dT, \quad (1) \]

where \( C_{P,l} \) and \( C_{P,s} \) are the specific heat capacity in the liquid and solid phase, respectively. The mass \( m \), and the temperature on the hot and cold sides and the phase change temperature are represented by \( T_h, T_c \) and \( T_m \) respectively. \( \Delta H \) signifies a material’s latent heat.

The thermal energy that the PCMs can store also indicates the heat flux that goes through the TEGs. The overall efficiency of the TEGs, can be simplified, due to the relatively small \( \Delta T \) [3], to

\[ \eta_{TEG}(\Delta T) = \frac{\Delta T}{T_h} \frac{ZT_h}{4} \quad (2) \]

where \( Z \) is the figure of merit.

To calculate the maximum TEG efficiency, a \( \Delta T \) of 20°C, occurring during phase change, was used. This \( \Delta T \) was assumed to be a representative average temperature difference, a choice that was backed by the experimental data. The theoretical values for the thermal energy stored in the PCMs as well as the harvested electrical energy output are shown in Table 2.

The open-circuit voltage developed by the TEGs is proportional to the temperature difference across them. It is calculated by the Seebeck equation, \( V_{TEG} = \alpha(T) \Delta T \) where \( \alpha \) is the Seebeck coefficient. Combining this with (2) and assuming an optimal load resistance, \( R_l \), equal to the total internal resistance, \( R_i \), the power output is maximized [3] and given by:

\[ P_{out} = \frac{V_{TEG}^2}{R_l} = \frac{\alpha^2}{4R_i} \Delta T^2. \quad (3) \]

4. Experimental Results
A climate chamber (CTS T-70/200) was used to approximate the fuselage temperature profiles found on an Airbus test aircraft. The fuselage temperature change rate is about 0.050 K/s [7] while the climate chamber can achieve 0.067 K/s, and this rate is used for the experiments.

The “positive” PCM group consists of two materials, which have a phase change temperature of +10°C. The cooling and heating rates used by the climate chamber simulates the ascent and descent phases, which each take approximately 17 min. Assuming that the PCM is in thermal equilibrium with the fuselage temperature at the beginning of the flight, the latent heat is released immediately after the aircraft has reached cruising altitude, as Figure 2a illustrates. During this time, the largest possible temperature difference across the thermoelectric generator is achieved and thus the peak electrical power is achieved as seen in Figure 2b. Thermal equilibrium between the fuselage and the PCM is achieved after 45 min. and thus no more electrical energy can be produced. A similar but reversed behaviour is observed during descent. The electrical power and energy outputs are shown in Figure 2b.

![Figure 2](image-url)

(a) (b)
Figure 2. Temperature, power and energy experimental results of the “positive” group. The total harvested electrical energy is 27.4 J for RT10-HC and 28.6 J for RT10-HCG.
Equation (1), when considered with the PCM properties, suggests that in general most of the thermal energy stored in a PCM comes from its latent heat. The latent heat is usually an order of magnitude greater than the heat capacity over a 40°C temperature change.

Inorganic materials exhibit a significant peak in output electrical power during solidification compared to organic materials. Any material can undergo a phenomenon called supercooling, during which its temperature can be lower than its phase change temperature without any solidification taking place. This phenomenon is generally more prominent in pure materials and weaker in solutions or organic materials [8]. The supercooling effect significantly affects the electrical power output of a device and imposes difficulties in numerical simulations (due to its discontinuous nature and nondeterministic occurrence).

The electrical energy outputs of the PCMs in the negative group correspond to their latent heat. This observation shows that the theoretical predictions correlate well with the experimental results. However, the measured electrical energy output is less than the calculated value because heat loss to the environment is not accounted for. The overall efficiency of the device using the E-15 is 24%. The electrical energy outputs of the “negative” and “positive” groups are summarized in Table 2.

| Calculated values         | “Positive” group | “Negative” group |
|---------------------------|------------------|------------------|
|                           | RT10-HCG         | RT10-HC          | RT-9   | E-11  | E-15   |
| Energy stored, \(Q\) (J)  | 10700            | 12700            | 15600  | 20400 | 21100  |
| Theoretical energy output (J) | 128.1          | 151.8            | 187.7  | 244.5 | 252.7  |
| Experimental energy output (J) | 28.6           | 27.4             | 28.5   | 58.8  | 60.6   |

5. Conclusions and Outlook
The thermoelectric harvesting device described in this paper has shown great potential. For the “negative” temperature range, the inorganic PCMs are capable of generating almost twice the electrical energy output compared to their organic counterparts. This is largely due to their greater latent heat and specific heat values. They are therefore the preferred choice for the relevant temperature profile. Furthermore, inorganic salt-solution and organic paraffin based PCMs are compared in terms of energy performance for heat storage harvesting applications. A total electrical energy output of more than 60 J from 23 ml of a salt-based PCM (E-15) is acquired, close to the...
reference performance of water [7]. However, inorganic PCMs are more corrosive to the container material than organic materials. Consequently, alternative container designs are under consideration, in order to achieve the highest possible efficiency with minimum device deterioration over time. Further geometrical aspects are under investigation as well as the use of multiple PCMs in isolated cavities, in order to extend the operating temperature range of the device [9].

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7. References
[1] T. Becker, M. Kluge, J. Schalk, K. Tiplady, Ch. Paget, U. Hilleringmann and T. Otterpohl, Autonomous sensor nodes for aircraft structural health monitoring, IEEE Sensors Journal, Vol. 9, No. 11, pp. 1589-1595, 2009.
[2] Elefsiniotis, A., Samson, D., Becker, T., and Schmid, U. (2013). Investigation of the performance of thermoelectric energy harvesters under real flight conditions. Journal of Electronic Materials, 42(7), 2301-2305.
[3] Kiziroglou, M. E., Wright, S. W., Toh, T. T., Mitcheson, P. D., Becker, T., & Yeatman, E. M. (2013). Design and fabrication of heat storage thermoelectric harvesting devices. IEEE Transactions on Industrial Electronics, 61(1), DOI: 10.1109/TIE.2013.2257140
[4] Marlow Industries, Technical datasheet, Thermoelectric Generator TG12-2.5, DOC #102-0341REV H
[5] Samson, D., Kluge, M., Becker, T., and Schmid, U. (2011). Wireless sensor node powered by aircraft specific thermoelectric energy harvesting. Sensors and Actuators A: Physical, 172(1), 240-244.
[6] Elefsiniotis, A., Kokorakis, N., Becker, T., and Schmid, U. (2013, May). Design and material aspects for thermoelectric energy harvesting devices in aircrafts. In SPIE Microtechnologies (pp. 87631N-87631N). International Society for Optics and Photonics.
[7] D. Samson, T. Otterpohl, M. Kluge, U. Schmid and T. Becker, Aircraft-Specific Thermoelectric Generator Module, Journal of Electronic Materials, Vol. 39, No. 9, pp. 2092-2095, 2010.
[8] Feltham, D. L., & Worster, M. G. (2000). Similarity solutions describing the melting of a mushy layer. Journal of Crystal Growth, 208(1), 746-756.
[9] A. Elefsiniotis, N. Kokorakis, Th. Becker, and U. Schmid, Performance of a low temperature energy harvesting device for powering wireless sensor nodes in aircrafts applications, Proc. of the 17th Intern. Conf. on Solid State Sensors and Actuators, Transducers2013, pp. 2276-2279, Barcelona, 2013.