Thermoelectric energy harvesting in aircraft with porous phase change materials

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Abstract. We present a model and simulations of harvesting of thermal fluctuations occurring in the fuselage of an aircraft during a flight and their transformation into electricity using the thermoelectric effect. The model couples a Thermoelectric Generator with a Phase Change Material as a heat reservoir to boost the generation of electricity. We show how introducing a metallic foam within the PCM enhance the production of electric power, and how it occurs through shorter and higher sprouts of voltage generation.

1. Introduction
Wireless sensors are employed in a wide range of applications to monitor environmental variables, industrial process, health parameters, etc. Batteries usually power them. However, in applications involving remote locations, extreme conditions or the need of autonomous systems, the requirement of periodic replacement or recharging of batteries makes them impractical. Among the different technologies aimed at power low consume sensors - as solar cells, piezoelectric devices, electrostatic methods, etc.- thermoelectric energy harvesting is one of the best solutions to create autonomous monitoring sensors.

Thermoelectric Generators (TEG) are devices that transform temperature gradients across them into electrical energy using the Seebeck effect. In spite of being an old tested technology, interest in TEGs is witnessing a renewed interest in the last years for their capacity to transform low-grade waste heat in useful power in the very important social and engineering field of sustainable energy resources.

Efficient TEGs require a substantial temperature difference across the device structure. This has restricted their use to applications where a hot metal surface is available. An alternative approach to overcome this limitation is to take advantage of external temperature fluctuations using a heat storage unit, which is filled with a Phase Change Material (PCM), to create a sustained temperature gradient in time. In such a way, time-temperature fluctuations are transformed in spacial temperature gradients.

The PCMs take advantage of the high latent heat of the solid/liquid phase change to store or release a significant amount of energy during melting or solidification, barely changing the temperature [1]. The storage of latent heat provides them a very high thermal energy density and makes them very suitable materials for applications in thermo-regulation and energy storage.

The coupling of TEG with a heat storage unit in the form of PCM has been successfully demonstrated in a wide variety of engineering fields for different purposes, such as space cooling [2,3] or solar energy harvesting [4-6]. We are interested in aircraft applications, where aircraft are subjected to distinctive thermal gradients in a typical flight during the takeoff, cruising, landing, and taxiing.
These thermal gradients have been used in TEG/PCM units to power structural health-monitoring systems, like humidity, temperature, and acoustic-ultrasonic parameters [7-11]. Depending on the intended purpose, different type of PCM has been employed, such as water [7-10], erythritol [11], or E-11 [10]. The micro-harvesters developed in these works allow to remove wires and create robust autonomous micro-harvesters. This decreases the complexity and weight of monitoring systems in aircraft and improves their security by the augmented monitoring options.

In section 2, we present the model equations of the TEG and PCM units, their thermal coupling, and geometry of the harvester. In particular, we describe the model equations briefly for conductive transport in PCMs embedded in a metallic foam. Results for the energy harvesting under thermal conditions characteristics of the fuselage of an aircraft are given in section results 3, and conclusions are provided in section 4.

2. Governing equations and geometry

2.1. Governing equation of a PCM embedded in a porous media

The thermal energy of the PCM comes from the contribution of the sensible heat, due to changes in temperature in the solid and liquid phases of the PCM, and from the latent heat content. Following [12], and assuming the same density in the solid and liquid phases of the PCM, the evolution of the temperature field in a PCM embedded in a porous media is

$$\frac{\partial \bar{c}T}{\partial t} = \nabla (\kappa_{eff} \nabla T) - \varepsilon \rho L \frac{\partial f_l}{\partial t}$$  \hspace{1cm} (1)

where $L$ is the latent heat of the solid/liquid phase change of the PCM, $\kappa_{eff}$ the effective conductivity of the porous media, $\bar{c}$ refers to the mean thermal capacity of the mixture, defined as $\bar{c} = f_l \rho c_l + (1 - f_l) \rho_c c_s + (1 - e) \rho_{m} c_m$. Here $e$ is the porosity of the porous matrix, $c_s (c_l)$ the specific heats of the solid (liquid) phases of the PCM, $\rho_m$ the density of the PCM (porous matrix), and $f_l$ is the liquid fraction of PCM in a given volume control. Notice that a given control volume $V$ contains a volume of PCM $V_{pcm}$ given by the porosity $\bar{V}_{pcm} = eV$, and $V_{pcm}$ contains PCM that can be in liquid and solid phases whose respective proportions are given by the liquid fraction $V_{pcm,l} = f_l V_{pcm}$ and $V_{pcm,s} = (1 - f_l) V_{pcm}$. At $\epsilon \rightarrow 1$ the classical limit of the heat equation for a pure PCM is recovered.

Metallic foams are a type of porous media characterized by a very high contrast in thermal conductivity with respect to the saturating fluid, large surface areas per unit volume and high porosities. Their modeling depends critically on determining the appropriate conductivity for the heat equation. It is usual to use an effective conductivity $\kappa_{eff}$ that lumps the contributions of matrix and fluid around it. Expressions for the conductivity are usually founded on analytical models based on the topology of the pores [13,14], and on empirical data [15,16]. All the models predict a decrease of the effective conductivity with increasing the porosity due to the reduction of volume fraction of the conductive metal. In spite of the broad differences between those models, the predicted dependence of the effective conductivity on the porosity is relatively similar. This is something to be expected since all of them have been calibrated using experimental data.

In this work, we use a recent model proposed by Yang et al [14], which has been validated to a broad set of empirical data at high porosities. They model the open-cell metallic foams with a periodic distribution of unit cells with the form of a tetraakidecahedron. These cells keep a high similarity with real metallic foams, and the resulting equation for the effective conductivity is

$$\frac{\kappa_{eff}}{\kappa_m} = \frac{4\lambda (1 - \delta)}{9 \epsilon (1 - \delta) - 6 \lambda \ln [1 - (1 - \delta)(1 - e)]} \cdot \frac{1}{2 (1 - e) - (1 - \delta)(1 - e)^2 + \lambda e} + \frac{\kappa_{pcm}}{\kappa_m} \epsilon$$  \hspace{1cm} (2)

where $\lambda$, $\delta$ and $e$ are topological parameters of the unit cell, $\kappa_m$ the matrix conductivity, and $\kappa_{pcm} = \kappa_t f_l + \kappa_s (1 - f_l)$ is the conductivity of the PCM averaged by the volume fraction of the liquid ($\kappa_t$)
and solid ($\kappa_s$) phases. This expression has been validated experimentally for aluminum foams air and water saturated, with $\varepsilon=0.3$, $\lambda=1.5$ and $\delta=0.5$.

The latent heat released by a control volume during the solid to liquid phase change depends on the melted PCM given by liquid fraction as $f_l \rho L$. As a consequence, the coupling between the energy and momentum equation is given through the liquid fraction field $f_l$, which in turn depends on the temperature, the master variable of the phase change process. We model the liquid fraction in the mushy zone using a linear relationship between the solidus and liquidus temperatures

$$f_l = \begin{cases} 0, & T \leq T_s \\ 1, & T \geq T_l \\ \frac{T - T_s}{T_l - T_s}, & T_s < T < T_l \end{cases} \quad (3)$$

2.2. Governing equation of the TEG

A basic thermoelectric unit is composed of an n-type and p-type semiconductor joined by metallic junctions. At the range of temperatures of interest in this work, they are generally formed by doped semiconductors of $Bi_{2}Te_{3}$. A high number of these p and n pairs are joined electrically in series and thermally in parallel to form a thermoelectric module. When the hot and cold junctions are at different temperatures, the Seebeck effect originates a difference of potential across the thermocouple. The voltage across a TEG module is $V_T = N(\alpha_p - \alpha_n)(T_{HJ} - T_{CJ}) = \alpha \Delta T_{eff}$; where $\alpha_p - \alpha_n$ is the Seebeck coefficient of a single couple, $N$ is the number of couples, and $\Delta T_{eff} = T_{HJ} - T_{CJ}$ is the difference of temperature between the hot and cold junctions of the module. The commercially available products are modules, and the value of the Seebeck coefficient is usually listed per module as $\alpha = N(\alpha_p - \alpha_n)$.

TEG modules protect the semiconductors with ceramic plates thermally conductive and electrically insulating. Thus the environmental difference of temperature the plates of a module are subjected to is $\Delta T = T_H - T_C$, which is related to $\Delta T_{eff}$ through the relation [17,18]: $\Delta T_{eff} = \frac{K}{K+2K_{in}+\frac{2\alpha^2 T_m}{\alpha^2 + K_{in} R_L}} \Delta T$, where $R_{in}$ is the internal resistance of the TEG, $R_L$ the external load of the circuit the TEG is connected to, $K$ the thermal conductance of the ceramic plates, $K_{in}$ the internal conductance of the module and $T_m = (T_H + T_C)/2$ the mean temperature of the TEG. We choose the TEG module TEG1−9.1−9.9−0.8/200 based on $Bi_{2}O_{3}$ and manufactured by Eureca [19].

We need to model the transient heat transfer along the TEG. For that, we use the heat equation:

$$\rho_{teg} c_{teg} \frac{\partial T}{\partial t} = \kappa_{teg} \nabla T \quad (4)$$

where $\rho_{teg}$, $c_{teg}$, and $\kappa_{teg}$ are the effective density, specific heat, and conductivity of the TEG module. This model enables to neglect the internal heat transfer between the TEG parts, considering it as an isotropic media, taking effective values to collect the averaged contributions of all the parts. Notice that the thermodynamic coefficients of the heat equation are not provided by the manufacturer. To overcome this limitation and be realistic in our predictions, we use the experimental data from Samson et al [7], which report the energy generated as a function of $\Delta T$ for four TEG1−9.1−9.9−0.8/200, to establish an empirical relation between $\Delta T$ and $\Delta T_{eff}$. From that relation, we obtain the value of $K$ that provides the best fit to the experimental data. Furthermore, following [4], we take for $\kappa_{teg}$ of the ceramic layer and estimate the density from the weight and volume of a module (1 gr, 9.1 × 9.9 × 2.3 mm^3 [19]). The effective conductivity is calculated as well after estimating it from the empirical data from [7]. In short, we take $c_{teg} = 840 \ J/kgK$, $\rho_{teg} = 5250 \ kg/m^3$ and $\kappa_{teg} = 1.5 \ W/m\cdot K$, the physical properties of water from Reg. [20], and the thermal and electric properties of module TEG1−9.1−9.9−0.8/200 are provided by the manufacturer in [19].

While the specific values affect the energy output, they are much less important than the effect of...
the metallic foams embedded in the PCM, whose influence is the goal of this work.

2.3. Boundary conditions
All the outer boundaries of the TEG and PCM are adiabatic, then at these boundaries $T_z = 0$. The conductive wall at the bottom of the TEG is subjected to the thermal environmental conditions.

The key boundary condition that couples the TEG and PCM units is the temperature field at the interface between both media. This is a calculated quantity that comes from solving the heat equation in both domains. For conservation of the energy, the flux of heat that leaves the TEG must be equal to the flux of heat that enters into the PCM: $\kappa_{\text{teg}} T_z = \kappa_{\text{pcm}} T_z$. After discretizing this equation, one obtains the temperature at the TEG/PCM interface:

$$T_i = \frac{\kappa_{\text{teg}} \frac{\partial T_{\text{teg}}}{\partial y_{\text{teg}}} + \kappa_{\text{pcm}} \frac{\partial T_{\text{pcm}}}{\partial y_{\text{teg}}}}{\kappa_{\text{teg}} + \kappa_{\text{pcm}}}$$

(5)

where $T_i$ is the temperature at cell $i$ of the TEG/PCM interface, $T_{\text{teg}}$ ($T_{\text{pcm}}$) is the temperature of the nearest centroid to that cell in the TEG (PCM). The determination of $T_i$ allows the conjugate heat transfer and closes the mathematical model. In this way, we can solve equation (1) along equation (5) to obtain the difference of temperature between the TEG plates $\Delta T = T_H - \langle T_i \rangle$. Where $T_H$ is the environmental temperature, and $T_C = \langle T_i \rangle$ is the average temperature at the interface TEG/PCM.

As for the environmental temperature $T_H$, we use the temperature profiles shown in figure 3, labeled as Average, of reference [10]. Takeoff lasts 17 min, and decreases the temperature from 20°C to −20°C. The fuselage temperature is held at the last value during the cruising stage of the flight that lasts 100 min. Landing increases the temperature from −20°C to 20°C and lasts 30 min. The last stage of the flight, the taxiing, begins at the latest temperature and lasts 60 min.

We simulate the conjugate heat transfer problem with a volume finite software. This software has been validated with experiments and numerical works in previous works [1,21-24].

2.4. Geometry
We model the TEG unit as a rectangle of side 1 cm and height 1 mm. A PCM unit of size 1 cm $\times$ 1 cm is superposed to the TEG. The contact between the TEG and PCM units takes place along the bottom side of the PCM and upper side of the TEG, which are in thermal contact.

The bottom side of the TEG is conductive and subjected to the environmental field of temperature. The rest of the outer boundaries of TEG and PCM are adiabatic, and the initial temperature of the PCM reservoir and TEG unit are supposed to be the same for simplicity.

3. Results
The capability of harvesting is mostly effected using a PCM as a heat reservoir. Thus using a liquid like water without phase change generates 0.027 J during the flight, whereas the release/storage of latent heat of water at its phase change temperature generates 0.22 J. This shows how powerful is to couple the TEG with a latent heat unit in the form of PCM, since this coupling allows for higher and longer $\Delta T_{\text{eff}}$, leading to greater transformation efficiency of thermal energy to electric energy.

We have carried out simulations using the base PCM and introducing metallic foams at different porosities to evaluate their impact on the energy harvesting capacity. Figure 1 shows the evolution of the cumulative electric energy (left) and instantaneous voltage (right) during the flight. Vertical guides separate the different flight regimes (takeoff, cruising, landing, and taxiing). The bulk of energy harvesting occurs mainly during the flight regimes that induce a phase change, solidification during takeoff, and melting during landing.

The base PCM has lower conductivity and higher thermal inertia, and there exists as well non-zero voltage and ensuing electric energy generation during the first minutes of the cruising phase. This effect is more pronounced after landing phase finishes, then the influence of melting on $\Delta T_{\text{eff}}$ lasts
longer, and there is still voltage creation during the first half of taxiing. The extension of these inertial effects is limited by the amount of PCM present since they finish when the PCM reaches a uniform temperature equal to the environmental temperature $T_H$. Thus more energy production can be achieved with rectangular geometries that enclose a more substantial amount of PCM in the vertical direction.

![Figure 1](image1.png)

**Figure 1.** (color online) Cumulative electric energy and voltage as a function of the time at different porosities. Vertical lines separate the different phase of the flight (takeoff, cruising, landing, and taxiing).

The introduction of the porous foam has a strong effect on the energy harvesting capacity of the PCM/TEG device. Thus at high porosity $\varepsilon = 0.95$ the total electric output of electricity is augmented 68%, and for a higher amount of metallic foam at $\varepsilon = 0.85$ it is augmented 82%. This increase can be higher, introducing more foam; however, the effect of decreasing the porosity is progressively smaller on the increased electricity creation.

The metallic foam produces a substantial increase of the peaks of the voltage, for instance at the takeoff phase the peak for pure PCM produces 86 mV, whereas it reaches 164 mV for $\varepsilon = 0.85$. Again, the melting phase at landing is not symmetric with respect to the solidification phase during takeoff, thus a peak at 42 mV is generated by base PCM whereas it is more than tripled at 137 mV for $\varepsilon = 0.85$. The slope of the voltage curves exhibits also important differences when the metallic foam is introduced in the PCM. Thus, the progressive decrease of porosity leads to narrower curves with higher maxima. This reflects the effect of the enhanced thermal transfer rate of higher conductivities.

![Figure 2](image2.png)

**Figure 2.** (color online) Total electric energy generated after finishing of the flight (Left) as a function of the porosity. Average power, measured as total electrical energy over the duration of the flight (Right) as a function of the porosity. Both curves are provided for different external loads.

Figure 2 summarizes the total energy and averaged power for different porosities and loads. The monotonous increase of harvested energy when decreasing the porosity is observed together with the decrease of improvements with lower $\varepsilon$. The latter is because while lower porosities lead to an
enhanced thermal transfer, they reduce the amount of PCM and the ensuing thermal storage capacity. The average power, measured as total energy harvested over the entire flight duration, points as well to increased power for lower porosities. The effect is stronger than in the energy harvesting since power more than doubles from pure PCM to $\varepsilon = 0.85$. Interestingly, the average power does not show any indication of saturation at high occupation level of the metallic foam.

It is well known that when external load matches the internal load of the TEG, then the maximum of electric power is generated. Figure 2 shows the effect of different external loads. The relative difference of energy collected and power at all the loads at a fixed to $\varepsilon$ is roughly conserved when decreased $\varepsilon = 0.85$.

4. Conclusions

We have modeled and simulated the harvesting of environmental thermal fluctuations to transform them into electricity using the thermoelectric effect. The thermal changes correspond to a typical temperature profile during a flight occurring at the outer part of the fuselage of a plane. The total duration of the flight is 10200 s; the PCM is water enclosed at a container of size 1 cm × 1 cm; and the TEG is a module manufactured by Eureca [19].

The capability of harvesting is very augmented using a PCM as a heat reservoir. Thus using a liquid like water without phase change generates about on order of magnitude less energy than taking advantage of the latent heat of the solid/liquid transition. The work has focused on further improve the performance of the PCM/TEG harvester. Thus a porous metallic foam has been introduced in the PCM unit to enhance the effective conductivity and increase the heat transfer between the TEG and PCM units. Decreasing the porosity $\varepsilon$ from 1 to 0.85 we increase the conversion of electric energy, from 91 mJ to 162 mJ (respectively). Notice that there is a diminishing return on electric energy generation when the more metallic foam is included.

The introduction of the metallic foam leads to a higher $\Delta T_{\text{eff}}$, which is responsible for the superior electric energy generation with respect to the pure PCM. However, that occurs at the expense of shorter duration of high $\Delta T_{\text{eff}}$. In short, the foam leads to higher and shorter $\Delta T_{\text{eff}}$ with respect to the pure PCM. From the results of the simulations, it is clear that the most dominant factor for enhanced energy harvesting is high $\Delta T_{\text{eff}}$. Thus, future developments where the high $\Delta T_{\text{eff}}$ caused by the metallic foam can be extended to a longer duration are another direction of research to optimize further the TEG/PCM autonomous energy harvesters.

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