Dynamic study for performance improvements of a thermo-mechanically bistable heat engine

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Abstract. This paper focuses on a thermal study of a thermal energy harvester based on the coupling of a bimetallic strip heat engine with a piezoelectric membrane for wasted heat scavenging. Such a harvester is dedicated to power autonomous systems such as wireless sensor nodes. For a better understanding of the working principle of the system, it is compulsory to have a good understanding of the thermal specificities and phenomenon taking place inside the harvester. Attention is consequently focused on the thermal modeling of the harvester in static mode using the equivalence between the electrical and thermal quantities. This first modeling step allowed the improvement of the thermal properties inside the system by increasing the thermal gradient across it. However, the bimetal being the active part of the system has not been taken into account in this model and shadow zones persisted regarding the bimetal operation windows as a function of its snapping temperatures and hysteresis. To overcome this, a dynamic model is proposed in this paper taking into account the bimetal as a switched capacitance alternatively in contact with the hot source and the cold surface. This last model completed the static one by predicting the bimetal’s operation windows in function of its intrinsic properties and the operation range evolution in function of the snapping temperature first and then in function of the bimetal thermal hysteresis. Moreover, experimental measurements enable to validate the proposed model and to point out the most powerful bimetals for scavenging higher amounts of power.

1. Introduction

Energy harvesting technologies have known a significant expansion during the last decades and researchers are still focusing on this area as being a clean and promising technology field. This increased development has been allowed by the need for wireless sensors. Internet of things, smart buildings, industrial and health monitoring these are some domains where sensor networks are widely used. However, the impractical aspect of wired systems and the problems related to the power supply by short-lifetime batteries are raised for those applications. This brought attention on ambient energy harvesters and explains the great interest in energy harvesting devices over the last years. This paper presents a study conducted on a thermal energy harvester previously presented in [1,2,3] and based on a two-step conversion mechanism. At first a thermo-mechanical conversion insured by a
A bimetallic strip occurs and it is then coupled to an electromechanical transduction ensured by a piezoelectric membrane. The thermal energy harvester is presented in Fig. 1.a. The bimetallic strip used in this harvester is characterized by two equilibrium positions as shown in Fig. 1.b. This makes it keeps on oscillating between the cold and the hot reservoirs. For an efficient energy harvesting, the bimetal should be set in a significant thermal gradient to ensure its thermal instability and to increase its cycling frequency. To ensure a good functioning of the bimetal, a static and a dynamic models are established.

![Fig. 1. a. Image of the thermal energy harvester, b. scheme of the harvester when the bimetal is at its upper position then at its lower one.](image)

2. Bimetals experimental characterization

The heat engine presented in this work uses a shell-like bimetal made of two materials with a mismatch in their coefficients of thermal expansion. This mismatch makes them bend when subject to temperature variations. It is made of Invar (Fe-Ni 36%) acting as the low coefficient of thermal expansion coefficient (CTE) layer and of NC4 (Fe-Ni 22%-Cr 3%) acting as the high CTE layer. To point out the most powerful heat engines, bimetals of different thermal hysteresis from 3K to 15K are characterized. First a force sensor is needed to measure its delivered force to the piezoelectric transducer then a vibrometer is used to estimate its snapping velocity and thus its available mechanical power. When the bimetal snaps, these parameters are measured thanks to the experimental setup described in Fig. 2.b and Fig. 2.c.

![Fig. 2. a. Bimetals in the inside air cavity in Fig. 1.a, Experimental setup for the bimetals characterization: b. force captor, c. vibrometer](image)

The results are shown in Fig.3. These graphs show that high bimetal hysteresis improves the force and the mechanical power, in comparison with lower hystereses [4,5].

![Fig. 3. a. Bimetals average force in function of their thermal hysteresis, b. Bimetals instantaneous mechanical power when snapping up as a function of the bimetal thermal hysteresis](image)
3. **Thermal modelling of the harvester in static mode without bimetal**

The key point of this harvester is its ability to maintain an important thermal gradient across it. At first and before any thermal improvements, the thermal specificities of the device were not sufficient to allow bimetals with hystereses higher than 3K oscillate between the hot and the cold sources. A thermal model in static mode was then developed in [6] for the device in Fig. 4.a taking into account all the processes by which heat is transferred inside the structure. This model provided the main guidelines for the optimization step. A new design was then proposed and allowed to increase the temperature difference across the harvester by at least a factor 2. The comparison of the thermal properties of the initial harvester with the optimized one is shown in Fig. 4.b. Experimental data show good agreements with the analytical one confirming this model’s validity.

![Schematic representation of the harvester with the different heat transfer process occurring through it](image)

**Fig. 4. a.** Schematic representation of the harvester with the different heat transfer process occurring through it, **b.** Thermal properties of the harvester before and after the thermal management improvement

4. **Bimetal impact on the device thermal behaviour**

The thermal model in static mode allowed thermal optimization of the structure. However, this model did not take into account the oscillating bimetal. What made the dynamic study become compulsory was the shift observed experimentally between the operation window of a bimetal when it is directly put onto a hot plate to oscillate freely and the one when it is mounted in a harvester. In Fig. 5, this shift is clearly illustrated for a bimetal having a snapping temperature of 70°C and a snapping back one of 67°C. Once mounted in the harvester, it only starts oscillating between the cold and hot source at 84°C and stops at 102°C. To close this gap, a dynamic model taking into account the bimetal became necessary.

![Range of hot source functioning temperatures for a 3°C hysteresis bimetal (67°C-70°C)](image)

**Fig. 5.** Range of hot source functioning temperatures for a 3°C hysteresis bimetal (67°C-70°C)

5. **Dynamic model of the harvester taking into account the bimetal**

To estimate the bimetal snapping frequency, the amount of harvested energy and the bimetals operation windows in function of their hystereses and their snapping up and down temperatures, a dynamic model of the harvester is
proposed in Fig.6. The bimetal is represented by a switched capacitance \([4][7]\) with two switches to model its contact with the hot source (Fig. 6.a) and with the cold surface (Fig. 6.b).

**Fig. 6.** a. Equivalent circuit of the harvester in a dynamic mode when the bimetal is at its lower state, b. Equivalent circuit of the harvester in a dynamic mode when the bimetal is at its upper state

Using these thermo-electrical circuits, one can consequently obtain the expressions of the time spent by the harvester in the lower and upper positions. This leads to the calculation of the hot source operation window by means of the calculation of the minimal hot source temperature for the bimetal to start oscillating \(T_{\text{hot}}^{\text{min}}\) and the maximal hot source temperature for the bimetal to be stuck in its upper position \(T_{\text{hot}}^{\text{max}}\).

\[
T_{\text{hot}}^{\text{min}} = \frac{2. T_s^2 - 2. T_{sb}^2 - T_s - T_{sb}. T_{amb} + T_{sb}. T_{amb}}{3. (T_s - T_{sb})}
\]

(1)

\[
T_{\text{hot}}^{\text{max}} \geq 2. T_{sb} - T_{amb}
\]

(2)

Hot source operation window = \(T_{\text{hot}}^{\text{max}} - T_{\text{hot}}^{\text{min}}\)

(3)

Where \(T_{amb}\) is the ambient air temperature, \(T_s\) and \(T_{sb}\) respectively the snapping and snapping back temperatures.

Simulations of the hot source operation windows are performed and compared with the experimental data for the same bimetals in Fig. 7.a allowing the validation of the dynamic model. Simulations of the hot source operation windows as a function of the bimetals hysteresis are presented in Fig. 7.b revealing that lowering the hysteresis allows to widen the operation window of the harvester.

**Fig. 7.** a. Comparison of the experimental operation windows with the analytical one (bimetals hysteresis=3K), b. Effect of the bimetal hysteresis on the operation window (\(T_s=70^\circ\text{C}\) for all the bimetals)

To complete our study, we simulated the snapping frequency of various bimetals. This study is led in two cases: first for bimetals having the same snapping temperature with different thermal hystereses (Fig. 8.a), then for bimetals having the same thermal hysteresis and different snapping temperatures (Fig. 8.b). Fig. 8.a presents the evolution of the cycling frequency as a function of hot source temperature for bimetallic membranes having the same snapping temperature. This figure shows that bimetals with low hysteresis can work on wider hot source
temperature windows. Fig. 8.b presents the evolution of the cycling frequency as a function of hot source temperature for bimetallic membranes having different snapping temperatures and the same thermal hysteresis. It reveals that it is more interesting to work on high hot source temperatures as for a fixed thermal hysteresis, bimetals snapping up on 100°C have wider operation windows than bimetals snapping at 70°C. This work completes the mechanical characterization of bimetals and gives the main guidelines for a bimetal choice depending on the use case: if one needs more power, it is interesting to choose bimetals with high hysteresis but the hot source operation window will be lower. Contrary, if one needs a bimetal that is able to oscillate on a wide hot source temperatures, it is more interesting to choose bimetals with the lowest hystereses.

**Fig. 8. a.** Frequency evolution in function of the hot source temperature (Ts=70°C for all the bimetals) **b.** Frequency evolution in function of the hot source temperature (ΔT=3K for all the bimetals)

6. **Conclusion**
This paper presents the thermal optimization of a thermal energy harvester based on bistable bimetallic strips and piezoelectric materials and a dynamic model taking into account the bimetal. This allows predicting the temperature operation ranges and their relations to the bimetals hystereses and snapping temperatures. This gives the main guidelines for the bimetal choice depending on the requirement specifications of the application. The established models are then validated using experimental measurements that fit well with the simulation results.

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8. **References**
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