Experimental and computational thermoelectric generator for waste heat recovery for aeronautic application

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Abstract

This study focuses on the evaluation and validation of the InComEss thermoelectric generator (TEG) for aeronautical applications. The thermal conditions representative of aircraft flight stages and the properties of small-scale polymer nanocomposite based TEG prototypes are discussed. Laboratory measurements of the TEG performance are conducted. A computational model is validated by comparing it with experimental data. Overall, the findings show promise in developing polymer based TEGs for aeronautical applications, but further improvements are necessary for effective integration and long-term performance.

1. Introduction

Due to increasing energy demand, environmental concerns such as air pollution and global warming, and the depletion of fossil fuels as the main energy source, attention has shifted towards alternative options referred to as renewable energy resources [1]. However, energy conversion systems encounter significant energy losses due to technical constraints and diverse heat transfer methods [2][3]. To enhance the efficiency of these energy systems, it is possible to harness a portion of this wasted heat energy and convert it into a usable form of energy [4]. Thermoelectric generators (TEGs) hold great potential [5] for aeronautical applications, offering a means to harness temperature differentials and convert thermal energy into electricity [6]. The InComEss project develops a novel environmentally friendly and economically viable approach for high-efficiency energy harvesting by integrating new intelligent advanced polymer-based composite materials and structures into a single/multi-source concept to harvest electrical energy from mechanical energy and/or waste heat ambient sources [7].

This paper focuses on the evaluation and validation of the InComEss TEG specifically designed for aeronautical use cases. The study explores the thermal conditions representative of aircraft flight stages and discusses the properties of small-scale TEG prototypes. Laboratory measurements are conducted to assess the TEG's performance, and a computational model is validated by comparing it with experimental data.

2. TEG configurations for the aeronautic use case

The aeronautic use case defined in this paper is determined by the temperature limitations of the wing of the aircraft. The envisaged thermal conditions are representative of an aircraft going through clouds during the ascending and descending flight stages, with potential ice accretion around the wing leading edge. The resulting temperature difference between the aerodynamic surface (heated on demand to avoid ice build-up) and the outside environment (usually at temperature below the freezing level) is more relevant along the chord-wise direction and such to be exploited to activate the TEG (located within the wing leading edge). Figure 1(a) shows a wing leading edge cross-section profile with a coloured map indicating the expected temperature variations along the wing surface. The greatest temperature difference is attained on the nose tip in correspondence of the anti-icing protection system, which is continuously operating during the ascending and descending stages. Figure 1(b) shows the intended location of the TEG patch to grip on the temperature gradient along the skin of the wing leading edge.

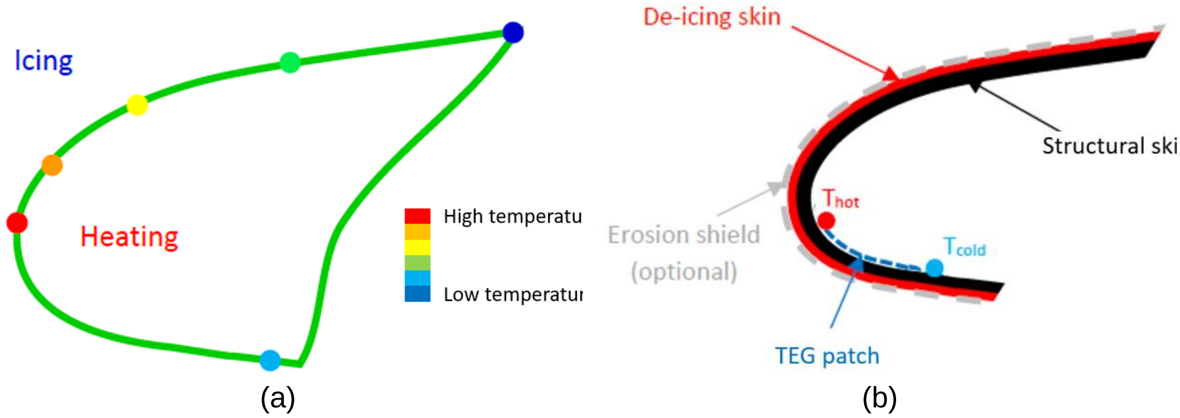


Figure 1 (a) Temperature distribution along the wing leading edge cross-section and (b) preferred TEG location.

For this investigation, a TEG module which was divided into 4 sections, each has 9 p-n pairs was employed. Each TEG leg has dimensions of 50*1*0.3mm (leg length x leg width x leg thickness). The definition of a feasible temperature range to be replicated in the test scenario for validating the TEG performance depends on the maximum attainable outside temperature. Past experimental temperature measurements demonstrated that the outside temperature could drop down to -15°C, while the anti-icing system could operate up to 55°C. This narrows the temperature range of interest, with a maximum 70°C temperature difference. Table 1 indicates the selected temperature gradients within a range of 40-70 °C applied across four test trials to assess the TEG performance. The lower temperature is representative of the atmospheric conditions, whilst the upper temperature is representative of the wing leading edge skin conditions heated up by a heater mat.

Table 1 Selected temperature ranges to assess the TEG performance.

Trial #	Lower temperature (°C)	Upper temperature (°C)	Temperature delta (°C)
1	-15	55	70
2	-10	50	60
3	0	50	50
4	5	45	40

Based on polycarbonate (PC), the polymer selected for this application, with different CNT types, formulations were developed by melt-mixing on small scale in discontinuous production and their thermoelectric properties were investigated. These results were already published [8][9]. Optimized formulations were produced in larger quantities on a continuous extruder HAAKE PolyLab QC - Rheomex QC. In the course of upscaling, the formulations were adapted so that the highest possible Seebeck coefficients and high electrical conductivities were achieved. For the production of the p-type composite, the polymer granulate was first pre-mixed with the singlewalled carbon nanotubes (SWCNTs) selected in a turbula. for the production of the n-type composite, the SWCNTs and the switching additive polyethylene glycol (PEG) were pre-mixed in a turbula and after this the PC was added to the pre-mix of SWCNT/(PEG), before introducing in the melt-mixing equipment. The extruded material was compression molded and from the sheets strips of the needed dimensions were cut and assembled.

3. TEG measurements in the laboratory

The InComEss TEG performance has been assessed in the defined temperature range, the TEG patch consisting of the combination of p- and n-type PC nanocomposite strips is bonded with a room temperature curing epoxy adhesive on the surface of a representative composite laminate (600 × 340 × 4 mm), whilst the self-adhesive silicone rubber heater mat (250 × 50.8 mm) is bonded on the opposite side across the laminate longitudinal axis. As shown in Figure 2, the configuration is such that the TEG hot line (i.e. series of white marked squares) must fall in correspondence of the heater mat for generating a local through-the-thickness thermal gradient to activate the patch itself. Figure 3 shows the laminate as instrumented before testing, with the TEG on the Inner Mould Line (IML) side and the heater mat (HM) on the Outer Mould Line (OML) side.

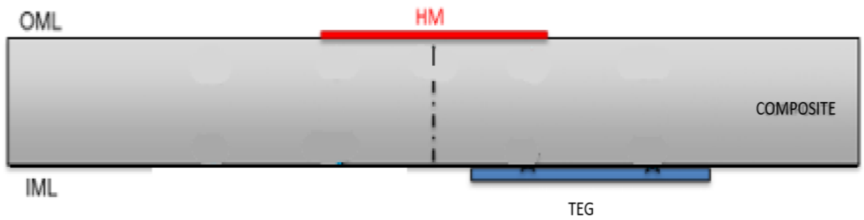
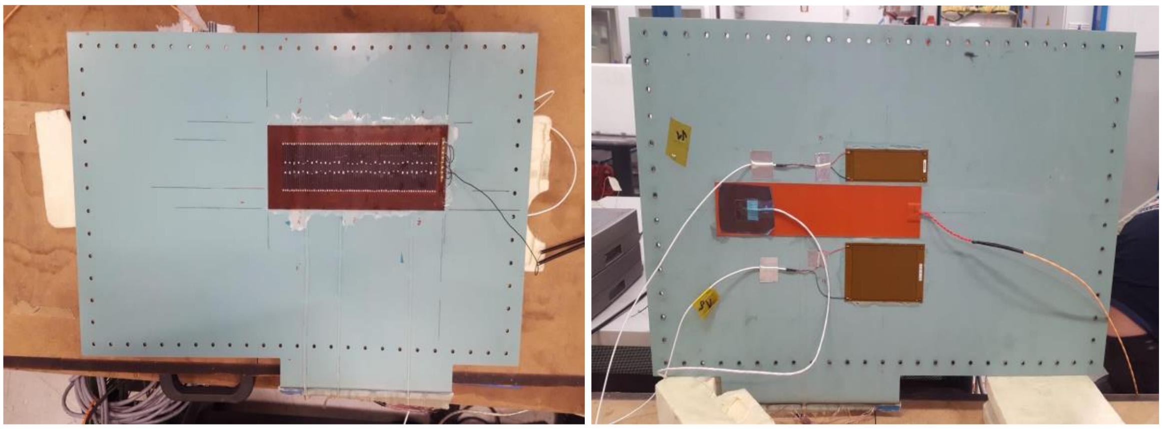


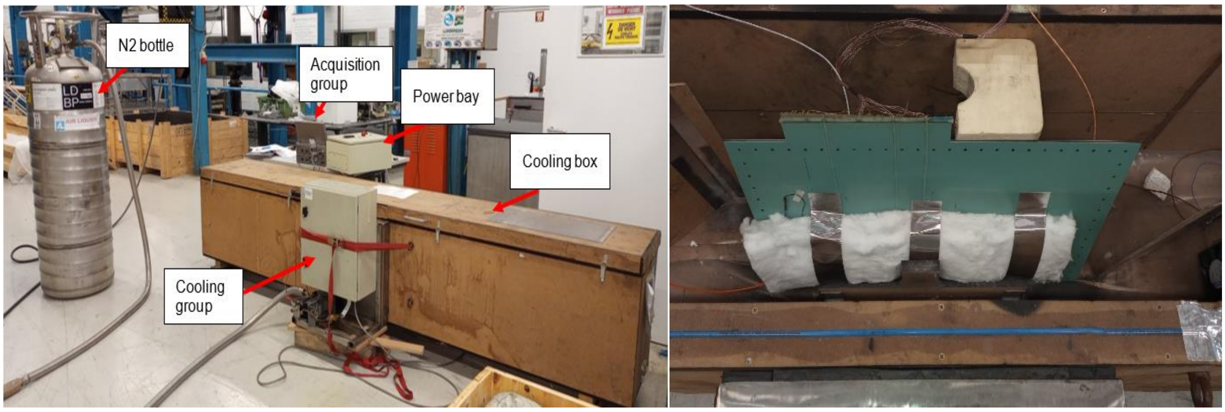
Figure 2. Schematic of the composite laminate with InComEss TEG and heater mat integration.



(a) (b)

Figure 3. Instrumented composite laminate for InComEss TEG performance assessment: (a) patch and (b) heater mat side.

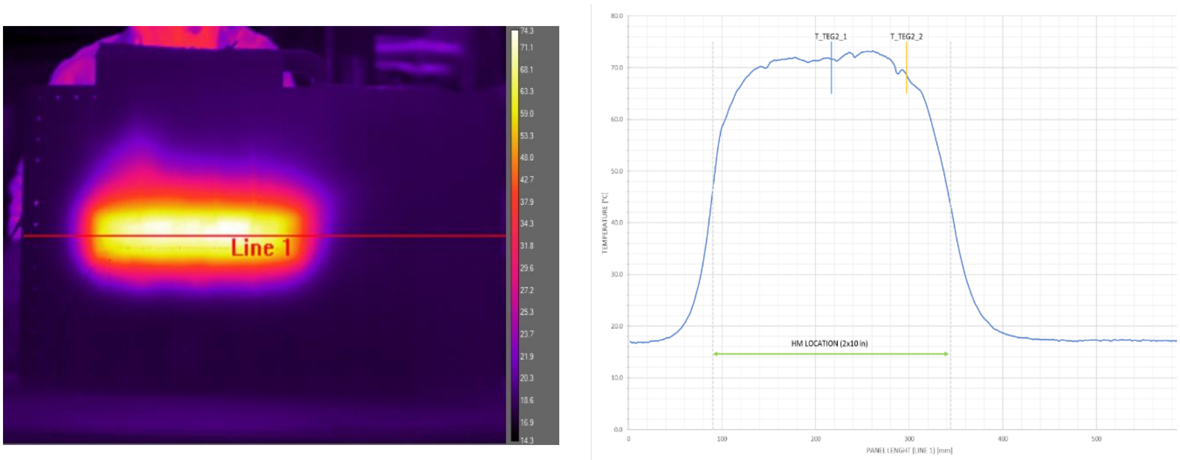
As shown in Figure 4(a), the whole assembly is introduced in a thermally insulated climatic chamber with liquid nitrogen blowing in to achieve temperature values compatible with in-flight conditions. The test setup is completed with (a) a cooling unit to ensure the target temperature is within the limit by regulating the nitrogen flow, (b) a power unit to feed the heater mat and (c) an acquisition unit to measure the InComEss TEG generated output voltage through the application of a 1 MΩ input impedance. As shown in Figure 4(b), the InComEss TEG patch has been covered with insulating material to avoid heat loss between the co-planar hot and cold points of the patch itself. The laminate has also been instrumented with standard T-type thermocouples in critical locations to monitor the temperature distribution during the thermal test.



(a) **(b)**

Figure 4. Test setup configuration: (a) general view and (b) detail on the test demo assembly.

A series of inspections (i.e. visual/NDT, dimensional, thermographic and electric) have been completed prior to testing, with evidence of no technical issues both in terms of composite laminate integrity and TEG functioning. As matter of example, Figure 5 shows the results of a thermographic observation to control the (a) heating capability of the heater mat and (b) the temperature consistency along the heating line on the skin upper side. The temperature distribution is homogeneous in correspondence of the heater mat zone, as evidenced by the thermocouples monitoring the TEG patch and the thermocouple monitoring the heater mat.



(a) **(b)**

Figure 5. Thermographic inspection: (a) thermal scan and (b) temperature distribution profile.

Following the achievement of a stable temperature difference (as indicated in Table 2) between the conditioning environment and the InComEss TEG-side laminate skin, the InComEss TEG behaviour has been monitored for at least 5 min in each test trial. Table 2 correlates the experimental lower and upper temperature values to the InComEss TEG output voltage measured during each harvesting test scenario, with values ranging between 67 – 116 mV. The higher the temperature gradient, the higher the voltage; however, these values are deemed insufficient to continuously power up downstream monitoring sensors.

Table 2. InComEss TEG measured output voltages.

Trial #	Lower temperature (°C)	Upper temperature (°C)	Temperature delta (°C)	Output voltage (mV)
1	-14	63	77	116
2	-10	50	60	90
3	0	50	50	85
4	1	41	40	67

The InComEss TEG element is reactive to the application of an external driving force resulting in the conversion of thermal energy into electricity. However, further development is needed to increase the efficiency and/or the design of polymer-based thermo-electric generator for their integration into aerospace structures for monitoring icing condition risks, whilst guaranteeing a sustainable operation.

4. Model Validation

Model validation compares the COMSOL simulation model results to the results obtained in the laboratory, to quantify the computational model correctness and predictive ability. Figure 5 indicates the results from the COMSOL simulation in comparison to the experimental data. As can be seen from the Figure 5, that in trials 1 and 2, the simulation results indicated a slightly higher output voltage than the experimental results, however, in trials 3 and 4, the results from the lab measurements were higher than the results acquired from COMSOL. It should be mentioned that material properties such as electrical conductivity, thermal conductivity and the Seebeck coefficient of the used PC based materials are temperature dependent and these have been taken as constant values for this simulation. Therefore, that could have caused the slight difference in the computational model and the experimental results. Overall, the results indicate that the findings obtained from the computational analysis are in good agreement with the results obtained experimentally and therefore, the computational model is validated.

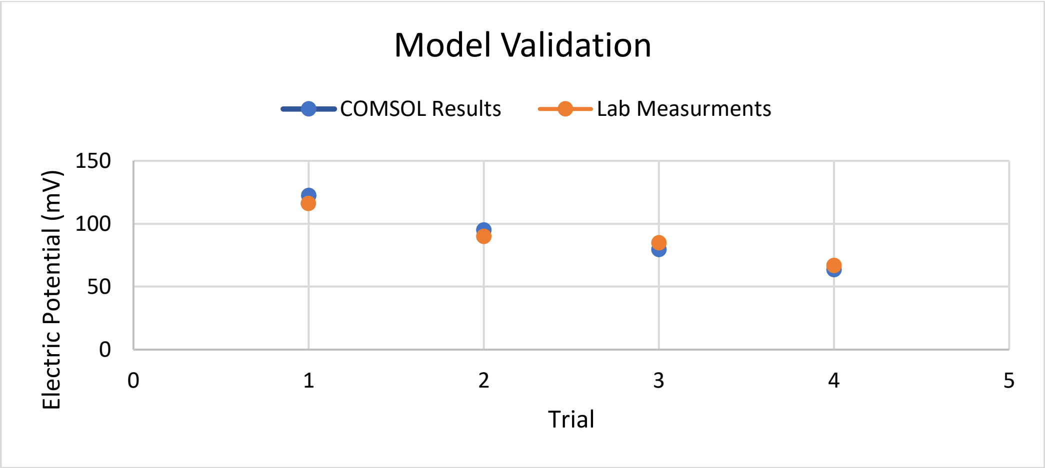


Figure 5. InComEss TEG output voltages, computational analysis vs. the experimental results.

5. Conclusion

In the paper the effectiveness of a polymer nanocomposite based TEG developed within the EU project InComEss was evaluated on a typical composite laminate in a controlled temperature environment. To create a thermal gradient, the TEG patch was attached to the laminate and a heating pad was inserted on the other side. During test runs with varied temperature gradients, the temperature distribution and voltage output of the InComEss TEG were monitored. The TEG produced output voltages varying from 67 mV to 116 mV depending on the temperature gradient. To confirm its accuracy and prediction capacity, the COMSOL simulation model was compared to the experimental findings. The simulation findings and experimental measurements of the InComEss TEG output voltages agreed well, showing that the computational model was validated.

In conclusion, these findings show that progress is being made in the development and testing of polymer based TEGs for aeronautical applications. However, further progress is required to increase the efficiency and to prepare polymer-based thermoelectric generators capable of effectively powering monitoring sensors in aeronautical structures, assuring long-term performance. Overall, this study contributes to the ongoing development of TEG technology for aeronautical applications, emphasizing the need for continued progress and innovation in this field.

Furthermore, it must be mentioned that more details regarding the modelling and COMSOL simulation will be published separately. The additional publication will provide a comprehensive overview of the computational model used, including the simulation setup, boundary conditions, and validation process. This will allow for a deeper understanding of the simulation's accuracy and its correlation with the experimental results.

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