

Numerical Analysis of Potential Energy Recovery via a Thermoelectric Generator (TEG) for the Next-Generation Hybrid-Electric Regional Aircraft [†]

Safa Sabet ¹, Werner Gumprich ², Michael Moeller ², Andrés Felgueroso ³, Iván González Nieves ³, Miguel Díaz ³ and Simone Mancin ^{1,*}

¹ Department of Management and Engineering, Università degli Studi di Padova, 35122 Vicenza, Italy; safa.sabet@unipd.it

² Nord-Micro GmbH & Co. OHG, 60388 Frankfurt, Germany; werner.gumprich@collins.com (W.G.); michael.moeller@collins.com (M.M.)

³ Airbus Defence and Space, 28906 Getafe, Madrid, Spain; andres.felgueroso@airbus.com (A.F.); ivan.gonzalez.nieves@airbus.com (I.G.N.); miguel.diaz.barja@airbus.com (M.D.)

* Correspondence: simone.mancin@unipd.it

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Abstract: The thermal management of next-generation hybrid electric regional aircrafts poses critical challenges due to extreme heat loads, which could reach more than 2 MW and must be dissipated. This rejected heat can be used in a passive system such as Thermoelectric Generators (TEGs), which can directly convert thermal energy into electrical energy. This work is carried out in the framework of the EU Clean Aviation-funded project TheMa4HERA and it numerically explores the possibility of integrating thermoelectric (TE) technology in the next generation of regional aircrafts. Two case studies are considered: energy recovery from the outflow valve originally used to control the pressure of the cabin and the integration of TEG modules in skin heat exchangers used to partially dissipate heat coming from the fuel cells and/or from the power electronics. The results will permit us to understand the feasibility of implementing TEG technology into these specific conditions in terms of overall power generation. The findings indicate that while TEG integration in the outflow valve offers limited power density, the skin heat exchanger shows significantly higher potential for effective energy recovery.

Keywords: numerical methods; TEG; skin heat exchanger; outflow valve; hybrid electric regional aircraft



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1. Introduction

Reducing the environmental impact of the aviation industry requires innovative approaches and technologies. The successful implementation of hybrid engines in the automotive industry has inspired a similar approach in aviation. In this case, the HERA [1,2] and TheMa4HERA [3] projects, introduced under the scope of Clean Aviation [4], aims to develop hybrid electric regional aircrafts that combine a classical internal combustion engine with an electric one.

In the context of future hybrid electric aircraft, thermal loads are estimated to reach substantial values, ranging from 2 to 4 MW. This poses huge challenges, but it also presents a significant opportunity to recover some of this heat and convert it into another form of useful energy. Thermoelectric generators (TEGs) offer a promising solution for this task, as

they are capable of converting heat directly into electricity. By integrating TEG systems into specific aircraft components, it is possible to enhance overall energy efficiency, thereby reducing fuel consumption and emissions.

Thermoelectric generators operate on the principle of the Seebeck effect, where a temperature gradient between two different materials generates electricity. The thermoelectric modules contain pairs of p-type and n-type semiconductor materials that are thermally connected in parallel and electrically in series, as illustrated in Figure 1 [5]. When heat is applied to one side of the TEG, and the other side remains cold, the temperature difference triggers charge carriers (i.e., electrons) to move, creating an electric current. This process allows TEGs to convert heat directly into electrical energy without the need for moving parts, making them reliable technology with minimal maintenance costs.

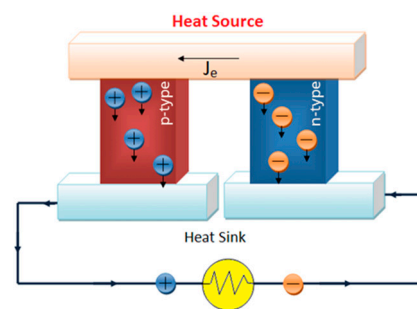


Figure 1. Basic TEG technology.

Currently, TEG technology is widely used in various industries, including automotive, industrial processes, and space missions [6–8]. In aviation, TEGs have been considered for energy recovery applications, such as capturing heat from engine exhaust or cabin air. The performance of a TEG depends heavily on the materials used in its construction. Effective TEG materials need a high Seebeck coefficient, low thermal conductivity, and good electrical conductivity to efficiently convert heat into electricity. However, TEGs generally suffer from low efficiency, often ranging from 2% to 10%, depending on the material and operating conditions. Table 1 summarizes the most common materials used at different temperatures for specific industrial uses. Among these materials, bismuth telluride appears to be a suitable solution for low-temperature applications such as aviation.

Table 1. List of most popular TE modules and their properties [9–11].

Material	Operating Temperature Range (°C)	Max Temperature (°C)	Power Output (W)	Efficiency (%)	Application
Bi_2Te_3	20–300	300	20	5–10	Low-temperature applications; electronics cooling
PbTe	300–600	600	15	7–8	Automotive waste heat recovery
Calcium Manganese Oxide	400–600	600	12	5–6	Industrial waste heat recovery; small-scale power generation
Organic TEG	<130	130	1–5	2–4	Flexible, low-power applications; wearable electronics

The aim of this study is to investigate the feasibility of implementing TEG systems in hybrid electric aircrafts through two specific applications: integration with the warm airflow leaving the aircraft via the outflow valve (OFV) and combination into the skin heat exchanger (SHX). These components have been identified as potential candidates due to the availability of a high amount of heat sources that could be utilized by TEGs. Ultimately, this study aims to evaluate the efficiency of energy recovery via TEG technology and to propose the development of innovative technologies for a more sustainable aviation future.

2. Theoretical Background

In general, the efficiency of a thermoelectric (TE) device is well defined by the capability of converting waste heat into electrical energy and vice versa using a combination of an array of individual p- and n-type semiconducting materials. The heat-to-electricity conversion efficiency (η) is the product of Carnot efficiency (η_C) and the function of a material's interdependent parameter or dimensionless constant, called the figure of merit of a material, zT . The η value for power generation is given by the following equation:

$$\eta = \eta_C \left[\frac{\sqrt{1 + zT_m} - 1}{\sqrt{1 + zT_m} - \frac{T_c}{T_h}} \right] = \frac{T_h - T_c}{T_h} \cdot \left[\frac{\sqrt{1 + zT_m} - 1}{\sqrt{1 + zT_m} - \frac{T_c}{T_h}} \right] \quad (1)$$

Equation (1) allows us to estimate the heat transfer conversion efficiency, as a function of the dimensionless figure of merit and of the hot and cold temperature. Figure 2 reports the Carnot efficiency plotted versus the cold-end temperature and the ends' temperature difference as a function of the hot-end temperature. As is shown, the theoretical maximum efficiency decreases as the hot-end temperature decreases and as the temperature difference decreases.

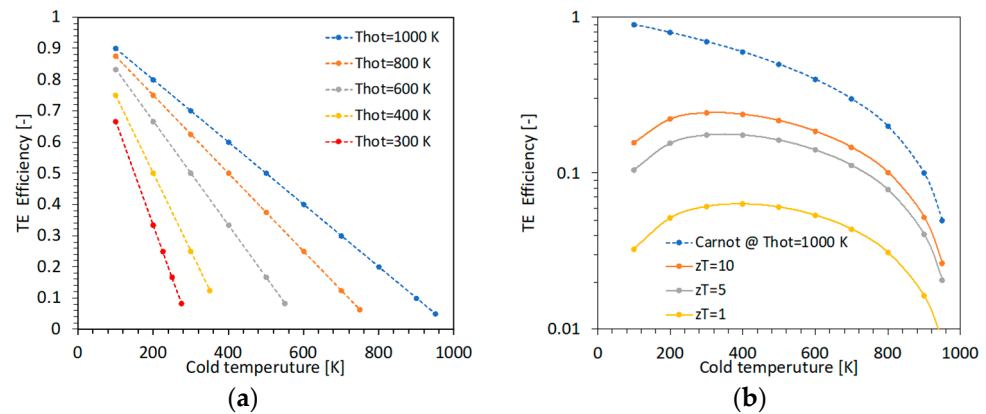


Figure 2. TE efficiency plotted versus the cold-end temperature as a function of (a) the Carnot efficiency of the hot-end temperature. (b) Figure of merit z .

In order to estimate the potential TE energy recovery, knowledge of the behavior of the TE material at low temperature is fundamental. The present calculations are based on the results published by Karabetoğlu et al. [12], who investigated the performance of Bi_2Te_3 at low temperature. In their work, the authors experimentally measured the values of Seebeck coefficients and the electrical conductivity of the Bi_2Te_3 in a mean-temperature range from 125 K to 350 K with a temperature difference of 20 K.

The maximum electrical power generated by the module can be estimated using the following equation:

$$P_{\max}(\bar{T}, \Delta T) = \frac{V_{OC}^2}{4R_i} = \frac{\left[N_{pn} \int_{\bar{T} - \frac{\Delta T}{2}}^{\bar{T} + \frac{\Delta T}{2}} \alpha(T) dT \right]^2}{4 \frac{N_{pn}}{A} \frac{\delta_{pn}}{\Delta T} \int_{\bar{T} - \frac{\Delta T}{2}}^{\bar{T} + \frac{\Delta T}{2}} \frac{1}{\sigma_{pn}(T)} dT} \quad (2)$$

where $\alpha(T)$ and $\sigma_{pn}(T)$ are the Seebeck coefficient and the electrical conductivity, respectively, at the mean module temperature. A is the area of the p-n junction and δ_{pn} is its thick-

ness. The following equations can be used to estimate the values of the non-dimensional Seebeck coefficient and the electrical conductivity:

$$\tilde{\alpha}(T) = \frac{\alpha_{np}(T)}{\alpha_{np}(T = 300K)} \quad (3)$$

$$\tilde{\sigma}(T) = \frac{\sigma_{np}(T)}{\sigma_{np}(T = 300K)} \quad (4)$$

where the measured reference values at $T = 300K$ are $\alpha(300K) = 345 \text{ mV/K}$ and $\sigma_{pn}(300K) = 28,103 \text{ W m}$, respectively. Finally, Equations (5) and (6) are regressed from the experimental database collected by Karabetoğlu et al. [12] to estimate the dimensionless Seebeck coefficient and dimensionless electrical conductivity, respectively.

$$\tilde{\alpha}(T) = -1.132 \cdot 10^{-5} \cdot T^2 + 8.640 \cdot 10^{-3} \cdot T - 0.5820 \quad (5)$$

$$\tilde{\sigma}(T) = 6.127 \cdot 10^{-5} \cdot T^2 - 4.381 \cdot 10^{-2} \cdot T + 8.629 \quad (6)$$

The module studied here is supposed to generate 14.1 W of electrical power for hot- and cold-side temperatures of 250 °C and 50 °C, respectively. The overall sizes are 56 mm width, 56 mm length, and 4.3 mm height (or thickness). The number of p–n semiconductor couples is $N_{pn} = 241$. For both p-type and n-type single semiconductors, base sizes are 1.7 mm × 1.7 mm, and its thickness is $d_{pn} = 1.1 \text{ mm}$. The cross-sectional view is illustrated in Figure 3. The open circuit voltage and short circuit current are 8.4 V and 6.7 A, respectively, for $T_{cold} = 50 \text{ °C}$ and $T_{Hot} = 250 \text{ °C}$.



Figure 3. Schematic cross-sectional view of TEG module (Karabetoğlu et al. [12]).

3. Results and Discussion

In this section, we will provide the results of TEG power generation from the outflow valve and skin heat exchanger configurations. These findings show the power output and temperature profiles for both applications, providing insights into the feasibility and performance of TEG integration for energy recovery in hybrid electric aircraft.

3.1. Outflow Valve

The outflow valve (OFV) is a component of the Cabin Pressure Control System (CPCS) of an aircraft, which controls the exhaust of air flow and the pressure in the cabin [13]. In aircraft, air is constantly flowing in and out of the cabin to provide fresh air for passengers and crew and for cooling the avionics.

The higher the temperature gradient at the TEG, the bigger the energy to be generated. Thus, placement of the TEG close to the A/C skin is considered a reasonable approach as the outside temperature of the A/C will be significantly lower than the inside cabin temperature during flight. Therefore, a duct/channel shall be implemented that allows air to be discharged outside the A/C to flow alongside the TEG. Figure 4 shows the schematic of how warm air is ducted alongside the TEG before it leaves the aircraft at a lower temperature via the OFV. In addition, the numerical calculations were performed based on the input variables given in Table 2.

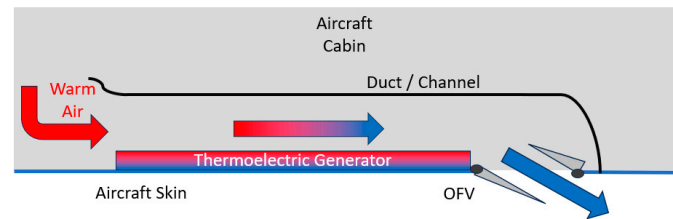


Figure 4. Air guidance principle in the TEG approach.

Table 2. Operating conditions for outflow valve.

Altitude	25,000 ft
Cruise velocity	300 ktas
TEG area	10 m ²
Cabin air temperature	20 °C
Ambient air temperature	−35 °C (238.15 K)
Outflow rate	0.35 kg/s
Heat transfer coefficient	100 Wm ^{−2} K ^{−1}
Surface enhancement factor	5

The number of TEG modules can be calculated by subdividing the length into n strips, with n being equal to the integer part of $L/\text{width}_{\text{TEG}}$. Each strip contains $W/\text{width}_{\text{TEG}}$. This means that the HERA area contains 2975 TEG modules.

Figure 5 shows the profiles of electrical power generation and the temperature at both the cold and hot ends, illustrating the effects of surface temperature variation along the system. As warm cabin air flows through the TEG toward the outflow valve, the temperature on the hot side decreases, leading to an overall reduction in the temperature difference between the two ends. This results in a significant drop in power generation, particularly for the TE modules located at the end of the duct. To simplify estimations, and given the level of accuracy required, it can be assumed that the overall TEG efficiency at this low temperature difference does not exceed 5%. Under these conditions, total power generation was estimated to be around 588 W with a recovered heat flow rate equal to 11,760 W.

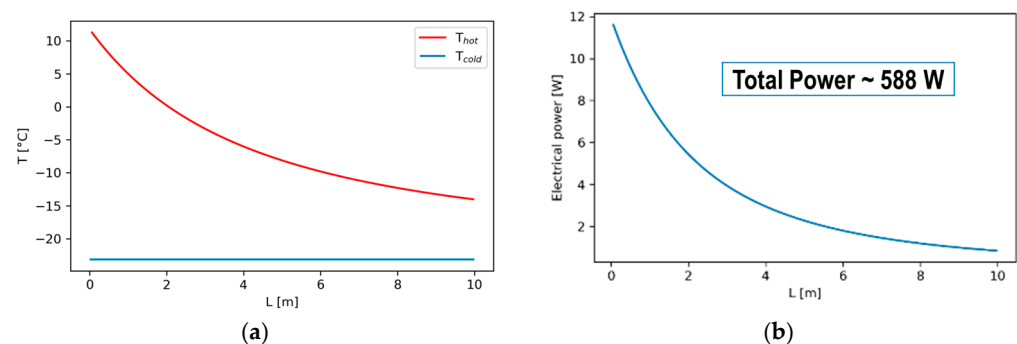


Figure 5. (a) Hot and cold temperature variation along TEG; (b) TEG's total electrical power generated profiles.

Finally, the power density per unit area was calculated to be 0.0588 kW/m² based on the dimensions of the HERA project. The results indicate that, for the time being, this technology does not offer sufficient energy savings to be beneficial in this application.

3.2. Skin Heat Exchanger

The skin heat exchanger (SHX) is a component in the aircraft's thermal management system that dissipates heat through the aircraft's outer skin. This design utilizes the aircraft's surface area for efficient heat rejection and enhancing thermal management. The technology tackled here is the integration of TEG models with a skin heat exchanger that acts as a condenser in vapor cycle systems. The coolant entering the SHX typically has a high temperature, around 70 °C, providing a favorable condition for using the TEG technology. Such integration could be a promising area for further research and development in hybrid electric aircraft.

The proposed design and integration of the TEG within the skin heat exchanger are illustrated in Figure 6 [14]. The operating conditions and model inputs used for the numerical evaluation of TEG performance are summarized in Table 3. Based on these parameters, the effectiveness of the TEG in converting heat to electrical power within the SHX is estimated and shown in Figure 7.

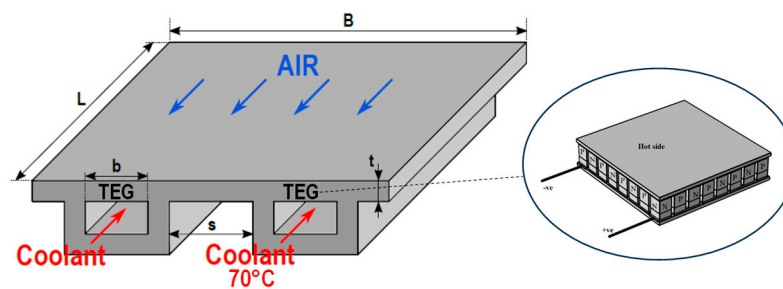


Figure 6. Schematic of TEG integrated into skin heat exchanger.

Table 3. Operating conditions for skin heat exchanger.

Altitude	25,000 ft
Cruise velocity	300 ktas
TEG area	0.55 m ²
Coolant inlet temperature	70 °C
Ambient air temperature	−35 °C (238.15 K)
Coolant flow rate	0.035 kg/s
Average heat transfer coefficient	3000 Wm ^{−2} K ^{−1}

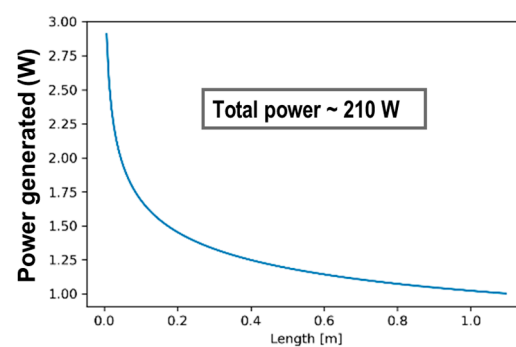


Figure 7. Electrical power generated by the TEG modules inserted inside the 1.1 m long and 0.5 m wide SHX coolant channels.

Figure 7 illustrates the electrical power generated by TEG modules integrated within the coolant channels of a skin heat exchanger that is 1.1 m long and 0.5 m wide. The

power generation decreases along the length of the SHX, with the highest power output at the channel entrance. As the coolant flows along the length, the surface temperature increases, resulting in a reduced temperature difference across the TEGs, which cuts the power output. The total power generated by the TEG modules across the entire SHX length is approximately 210 W. The power density per unit area is 0.382 kW/m^2 , which, in this case, is considerably high for TEGs to recover energy from waste heat.

4. Conclusions

In conclusion, this study investigates the use of thermoelectric generators (TEGs) for energy recovery in hybrid electric regional aircraft. TEGs were integrated into the outflow valve (OFV) and the skin heat exchanger (SHX) to understand their ability to convert waste heat into electrical power. The results show that EG integration with the OFV yields some energy recovery; the power density remains relatively low. In contrast, the integration of TEGs with the SHX shows significant promise, achieving a power density an order of magnitude higher than that estimated for the OFV. This suggests that the SHX is a more suitable location for TEG integration. Future work should focus on improving TEG performance at lower temperatures and exploring new materials to increase the efficiency of TEG technology.

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