Energy-autarkic sensors in aircrafts

Bartholomé, Kilian; Bartel, Markus; Binninger, Roland; Schumacher, Ina
Fraunhofer IPM
Heidenhofstrasse 1, 79110 Freiburg

ABSTRACT

Sensors are the eyes and ears in the service of people - especially in inaccessible areas where regular maintenance or battery replacement is extremely difficult. A solution can be the implementation of self-powered sensor networks that autonomously collect their required energy from their surroundings. After installation of the sensors they collect and transmit their data without any need for further maintenance like battery replacement.

In aeronautics, maintenance of airplanes is one of the major cost factors. To facilitate the future maintenance, sensor systems shall be employed to monitor the aircraft skin for the occurrence of dents or cracks. In order to save on cables and hence on weight, which is a particularly great benefit in aircraft construction, sensors are affixed to the inside of the aircraft fuselage in the form of a »smart patch«. This sensor patch is capable of collecting the required energy for powering the sensors and transmitting the data to a central unit from the temperature difference between ambient air temperature (minus 50°C – minus 20°C) and passenger cabin (20°C) using thermoelectric generators. Besides the quality of the thermoelectric generator, the optimization of the thermal integration into the aircraft body has a crucial influence on the efficiency of the system: target parameters are electrical outputs of greater than 10 mW at temperature differences of 25 °C. Furthermore, the integration concept has to ensure the encapsulation of the thermoelectric generator for protection against corrosion and vibrations. In this paper an optimized concept for the integration of thermoelectric generators into the airplane skin is introduced, maximizing the generated power output under the given boundary conditions.

INTRODUCTION

Thermoelectric energy converters use heat to directly generate electrical energy. It experienced its first heyday at the beginning of the space age in the 1960s. During the Apollo mission, these thermoelectric converters were responsible for the electricity supply and even today they are still the first choice for space missions at the edge of our solar system. They are used wherever the intensity of the sun's radiation is too weak or inconsistent to generate electricity with the aid of photovoltaics. For instance, the Cassini probe destined for Saturn and its moons launched in 1997 draws electricity from silicon-germanium (SiGe) thermogenerators, which use the decay heat of some 30 kilograms of plutonium 238 as a long-lasting energy source, and the USA's next mission to Mars will have lead telluride (PbTe)-based thermogenerators on board.

The fact that the energy-autarkic operation of products is possible for the public and in everyday use was demonstrated impressively by a radio developed around 1990 in Japan which obtained its electricity from the waste heat of a kerosene lamp. As long ago as 1954, Chrysler was using thermoelectricity for air-conditioning the interior of cars. Largely unnoticed, emission-free, thermoelectric refrigerators perform their work a million times over in devices such as camping chillers, which compared with compressor-driven refrigerators and air-conditioning units, however, are still niche applications. Conversely, a wristwatch by Citizen exploits the small temperature difference between ambient air and body heat as a source of energy.

Another field of application for thermoelectric components that has increasingly shifted to the center of attention in recent years is energy-autarkic sensor technology. Here, with the aid of thermoelectric generators (TEG) a temperature gradient is used to supply a sensor incorporating a radio transmission unit with electricity. The sensor is thus able to generate the energy it needs independently from the environment, measure data and transmit them by radio to a central communication unit. Using energy-autarkic sensor technology therefore means there is no need for wires and the required servicing, such as would be required if battery-operated radio sensors were used.

THERMOELECTRIC GENERATORS

All types of thermoelectric modules have a thermocouple consisting of a p-conducting and an n-conducting material as the central component (Figure 1). The two arms of the thermocouple are connected so that a temperature gradient can be accommodated from the upper and lower cover plate, which then results in the creation of a voltage. Commercial thermoelectric components are constructed by connecting a large number of thermocouples in series. The effect of converting a temperature difference into a voltage difference in a structure of this kind was discovered in 1821 by Thomas Seebeck (1; 2; 3). In 1834, Jean C. A. Peltier was also able to show – conversely – that applying a current to two connected different metallic conductors results in the creation of a temperature difference between the two ends. The maximal possible yield of thermoelectric energy conversion is given in physical terms by the Carnot efficiency, η, as $\eta = 1-(T_c/T_h)$. Here T_c is the cold side temperature of the temperature gradient and T_h its high temperature. The usual measure for qualifying the materials and hence indirectly for describing the efficiency of conversion has, since the definition by Altenkirch in 1909 (4), been the dimensionless figure of merit, ZT, which is given as

Equation 1

$$ZT = \frac{S^2\sigma}{\lambda}T,$$

where S is the Seebeck coefficient, σ the electrical conductivity, λ the thermal conductivity and T the temperature in Kelvin. The material parameters contained in the figure of merit primarily depend on the charge carrier concentration of the respective material, with the highest ZT values being achieved – at room temperature – for semiconductors with narrow band gaps of ~ 0.2 eV. Important factors in determining the quality of the material, in addition to the highest possible Seebeck coefficient, are high electrical conductivity combined with low thermal conductivity. Here, however, physics has set limits because these properties cannot be easily attained simultaneously; the Weidemann-Franz law links the electrical and thermal conductivity in metals. Consequently, optimization of the thermoelectric figure of merit can always be understood as optimization of the entire set of parameters and cannot be achieved by maximizing or minimizing only one of the variables contained.

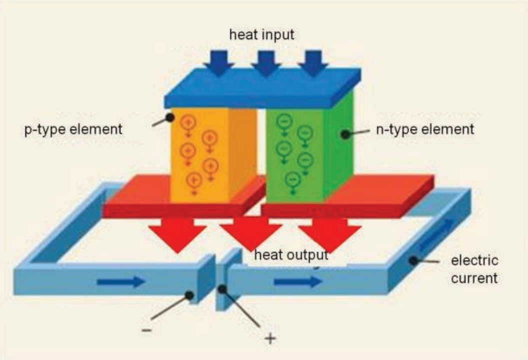

Figure 1

Principle of a thermocouple. At the top, the electrons flow from the p-type to the n-type element. During this process, heat is absorbed as the electrons are raised from a low to a higher energy level. At the bottom, the electrons flow from the n-type to the p-type element. Heat is released as electrons are moved down from a higher to a lower energy level.

Conventional thermoelectric generators (TEG) have a base area of some square centimetres and consist of a series of small blocks a few millimetres in size, which are connected in series and soldered onto a substrate. In addition to conventional thermoelectric generators, for some years it has been possible to produce miniaturized modules on the basis of MEMS (5). This technology was developed at Fraunhofer Institute for Physical Measurement Techniques IPM in a project sponsored by Infineon. Through this technique, several hundred pairs of arms can be connected in series on a base area of only a few square millimetres. The advantage of these miniaturized generators is the high integration density and high attainable current densities. The former enables a large number of arms connected in series to be constructed on a small space. With a minimal size of construction, even at temperature gradients of a few Kelvin it is thus possible to achieve output potentials in the volt range as well as power figures in the milliwatt range (Figure 2). The use of such microgenerators thus enables energy-autarkic sensors to be produced with minute dimensions and minimal weight for a wide variety of applications.

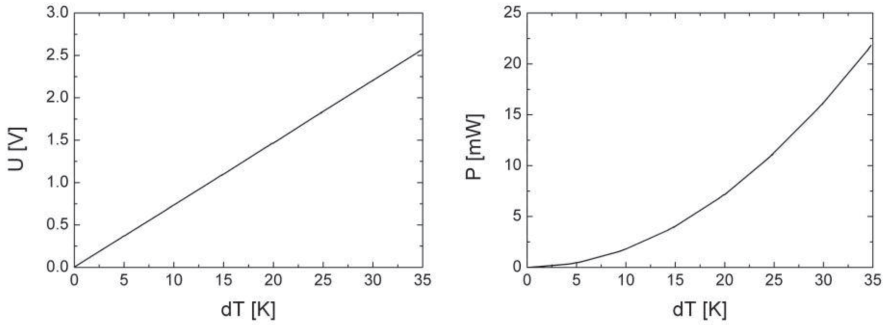

Figure 2

Output data for a thermoelectric generator from Micropelt calculated with the software tool 'MyPelt' (6). Left: the voltage from the thermoelectric generator plotted against the applied temperature gradient. Right: the power produced by the thermoelectric generator plotted against the applied temperature gradient.

ENERGY-AUTARKIC SENSOR TECHNOLOGY IN AIRCRAFT

Aircraft have to be serviced at regular intervals, with one of the reasons being to inspect the fuselage for any possible damage. These inspections are labour-intensive and time-consuming and therefore very expensive. In order to extend the service intervals and thus reduce costs, several sensors affixed to the aircraft fuselage are intended to continuously monitor the skin of the aircraft. As any unnecessary weight in the aircraft is to be avoided and installation of the sensors has to be as simple as possible, the sensors cannot be wired in this application. Battery-operated sensors prove to be similarly impracticable because the aim is to mount the sensors in inaccessible sites, which would make a regular changing of the batteries similarly cost-intensive.

This case presents an opportunity for the use of energy-autarkic sensor technology. The temperature difference between the environment at some minus 20 to minus 50 degrees Celsius and the passenger cabin with some plus 20 degrees Celsius can be converted directly into electrical energy by means of thermoelectric generators (TEG) in order to supply a sensor and a radio transmitter unit.

One key task in developing an energy-autarkic sensor system is to bring the available temperature gradients between fuselage and interior cabin directly to the TEG, in other words to minimize the losses at the thermal resistances so that maximum power can be produced with the thermogenerator, see Figure 3. To provide a sufficient supply of energy for the sensors, the thermoelectric generators have to achieve a power output of 10 mW during flight operations. In order to meet the required power-to-weight ratio of 1 W/kg, the generators may weigh no more than 10 g including the complete thermal coupling.

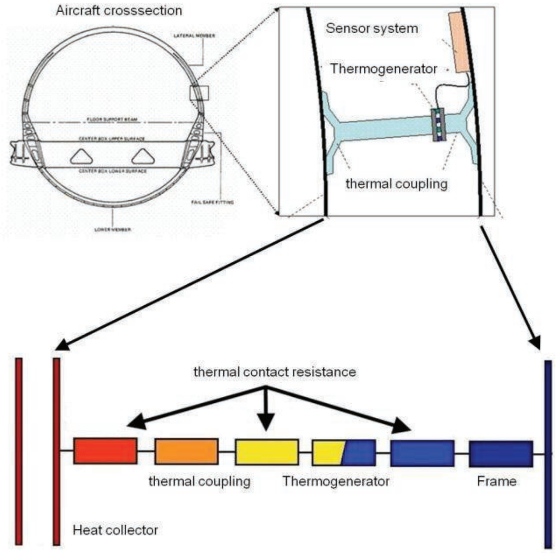

Figure 3

Schematic representation of the thermal coupling of the thermoelectric generator in the aircraft skin. A decisive factor for maximum power yield on the thermoelectric generator involves minimization of the thermal resistances of the heat supply lines.

Integration of the thermogenerator

In order to maximise the electrical power output of the thermoelectric generator, the total thermal resistances K_z in the system (thermal coupling and thermal contact resistances) have to be minimized. Furthermore, the thermal resistance of the thermoelectric generator has to match the total thermal resistance K_z of the entire system. This 'thermal impedance matching' is analogous to the electric impedance matching for a conventional electrical power source: In order to maximize the power output of an electric power source, the load resistance R_{load} has to match the internal resistance R_i of the power source. For thermoelectric generators there is an analogous behaviour, i.e. the electric load resistance R_{load} has to be adapted to the internal resistance R_i of the thermoelectric generator and at the same time the thermal resistance of the generator K_{TEG} has to be matched to the thermal resistance of the system K_Z, see Figure 4.

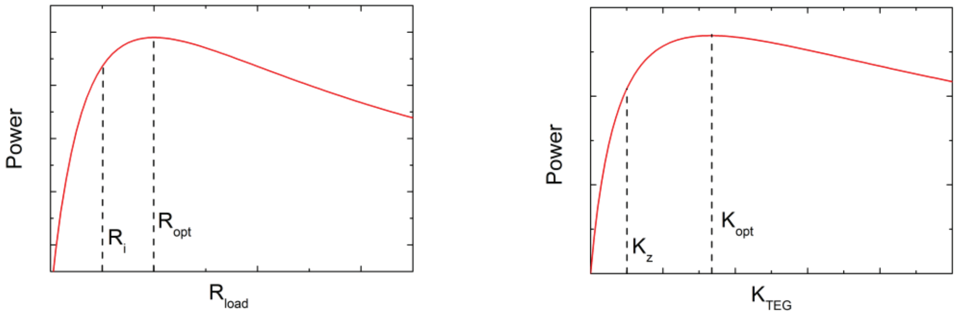

Figure 4
Electrical and thermal impedance matching of a thermoelectric generator.

Thereby, the optimal electric load resistance is given by

Equation 2 $$R_{opt} \approx R_i\sqrt{1+ZT}$$

and the optimal thermal resistance of the thermoelectric generator by (7)

Equation 3 $$K_{opt} \approx K_z\sqrt{1+ZT},$$

where ZT is the figure of merit of the generator (Equation 1).

Thermal contact material

The minimisation of the thermal resistance of the direct thermal coupling of the generator is a crucial factor in obtaining the maximum possible output from the generator. At every contact surface for two materials, surface roughness means there is a reduction in the actual contact area as well as trapped air between the materials and hence a thermal resistance. In order to minimize this resistance and thus maximize the generator output, heat-conducting materials are employed in order to compensate for this surface roughness. An experiment was conducted to investigate various heat-conducting materials under the temperature conditions that prevail in the aircraft and thus find the material best suited for these purposes (8).

The heat-conducting materials measured are two different heat-conducting pastes, indium and silver conductive adhesive. With the simulation software MyPelt [6] by Micropelt one can determine the actual temperature gradient across the thermogenerator, ΔT_{TEG}, as well as the temperature drop along the contacts, ΔT_{loss} and the total heat flux through the thermoelectric generator, Q_{TEG} for each contact material investigated. From this the thermal contact resistances in the system could be determined, see Table 1.

The silver adhesive exhibits the lowest thermal resistance with a value of R_{th} = 0.03 K/W, closely followed by indium with R_{th} = 0.6 K/W and heat-conducting paste A with R_{th} = 0.7 K/W. Heat-conducting paste B has a value of R_{th} = 1.8 K/W. For comparison: the thermal contact resistance without the use of a heat-conducting material was R_{th} =3.3 K/W.

Table 1
Results of the measurement of the thermal resistances of various heat conducting materials.

Thermal contact material	Thermal contact resistance
Silver adhesive	0.03 K/W
Indium	0.6 K/W
heat-conducting paste A	0.7 K/W
heat-conducting paste B	1.8 K/W
without heat-conducting material	3.3 K/W

Design

To guarantee long-lasting and trouble-free functioning of the thermogenerator, a design has to be developed to integrate the thermogenerator so as to protect it against corrosion, the ingression of moisture and damage due to vibration. The plan for the thermal coupling includes connection of a thermogenerator to a frame by means of a perspex block, see Figure 7. Here the perspex block acts both as a stable holder for the heat collector and conductor and also as an encapsulation for the thermogenerator. The perspex block has a broad foot with which it is cemented to the frame. An aluminium rod is integrated into the perspex block so as to remain mobile. Fastened at the end of the rod is the thermogenerator. The aluminium rod has a broadened foot. Resting on this is a spring via which a controlled force can be exerted on the thermogenerator. The other side presses against the upper end of the perspex block. Affixed to the upper end of the aluminium rod is the heat collector.
The design thus selected offers the following advantages:

- Encapsulation of the thermogenerator as protection against humidity and corrosion
- Constant compressive force by the spring
- Due to the low weight of the design, the forces exerted on the thermogenerator as a result of the maximum shock load are 2 N at maximum.
- A suitable choice of materials (aluminium with a thermal conductivity of λ = 167 W/mK, perspex with a thermal conductivity of λ = 0.2 W/mK) and geometry (minimized contact surfaces between aluminium rod and perspex) ensures that greater than 95% of the heat absorbed by the collection plates flows through the TEG and not through the plastic block.
- Guiding the aluminium rod in the perspex block ensures that the power through the aluminium rod acts in a plane-parallel configuration on the thermogenerator and that no damage of the TG occurs due to shear forces.

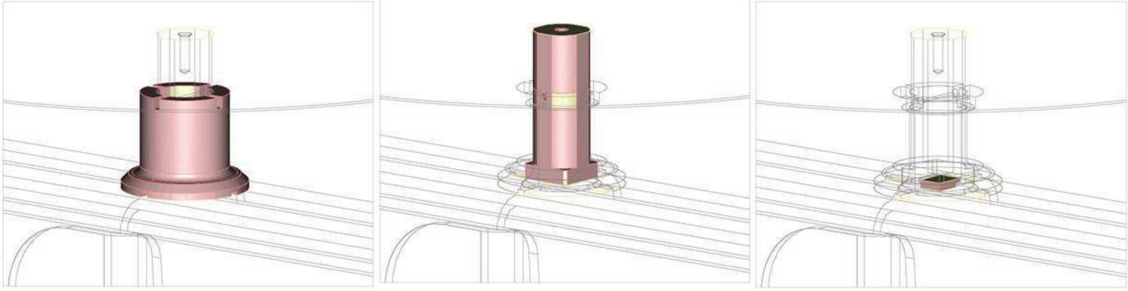

Figure 5
Schematic representation of the thermal coupling.
left: perspex block. middle: aluminum rod. right: thermoelectric generator.

In order to test the new design, the performance data were measured in a climate-chamber experiment. In this experiment the temperature conditions are imposed on a model of the aircraft fuselage.
To achieve this, a heat sink in the climate chamber is cooled down to the desired outside temperature of roughly –40 °C. An aluminium plate is fastened to the heat sink as a model of the frame.
Fastened to the aluminium plate is the construction comprising the perspex block, aluminium rod, thermogenerator and heat collector described above, with the heat collector being located outside of the climate chamber and at room temperature. This experimental setup enables the temperature conditions on the aircraft fuselage to be simulated so that the construction developed for connecting the thermogenerators can undergo functional testing.

RESULTS

Optimizing the structure enables the output data of the thermogenerator to be increased from the initial 2 mW to the present 7.5 mW. FEM simulations of the structure predict a maximum power yield of 8 mW with a weight of 10 g, see Figure 8. In order to raise the output to 10 mW, it is necessary to use a larger heat collector so that the entire construction will weigh roughly 17 g. Experiments to confirm these simulations are in progress.

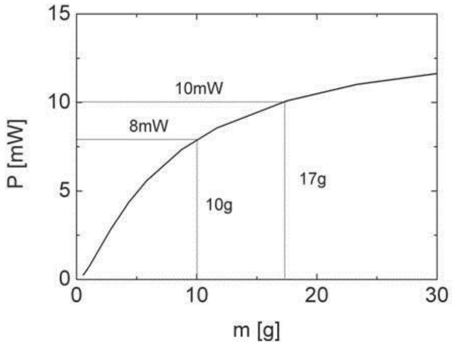

Figure 6

Power produced by the thermoelectric generator as a function of the total mass of the thermal coupling.

CONCLUSION

This study presents the use of thermogenerators for supplying energy-autarkic sensors in aviation. One essential aspect in focus was the need for an optimized thermal coupling for the generators in order to be able to achieve a sufficient output for the thermogenerators. The results illustrate the maturity of the technology and additionally show the potential of thermoelectrically operated energy-autarkic sensors for applications with sufficient temperature gradients (e.g. frictional heat in bearings, temperature change due to the day/night cycle, etc.).

ACKNOWLEDGMENT

The results presented here were generated as part of the project »Ametyst« (9), which was funded by the German Federal Ministry for Education and Research under the identification code 16SV3363. The authors express their gratitude to all the participating research institutes and enterprises for the good working relationship.

REFERENCES

1. **Rowe, D.M. (ed.).** *Thermoelectrics handbook: Macro to nano-structured materials.* s.l. : Taylor & Francis Boca Raton, 2006.
2. **Pelster, R., Hüttl, I., Pieper, R.** Thermospannungen – viel genutzt und fast immer falsch erklärt. *Phydid.* 2005, Vol. 1, 4, pp. 10-20.
3. **Müller, M, Freunek, M.,Ungan, T., Reindl, L.** Wandler für energieautarke Mikrosysteme. *TM-Technisches Messen.* 76, 2009, pp. 532-539.
4. **Altenkirch, E.** Über den Nutzeffekt der Thermosäule. *Physikalische Zeitschrift.* 10, 1909, Vol. 560.
5. **Böttner, H., et al., et al.** New thermoelectric components using microsystem technologies. *Journal of microelectromechenical systems.* 13, 2004, Vol. 3, pp. 414-420.
6. MyPelt. [Online] 6 14, 2010. http://www.micropelt.com/products/mypelt.php.
7. **Freunek, Michael.** *Untersuchung der Thermoelektirk zur Energieversorgung autarker Systeme.* Freiburg : Dissertation, 2010.
8. **Bartholomé, K., et al., et al.** Energieautarke Sensorik im Flugzeug. *TM-Technisches Messen.* 77, 2010, pp. 445-451.
9. Ametyst Projekt. [Online] 6 14, 2010. http://www.ametyst-projekt.de/.