Charging on board batteries through the Seebeck effect

Hot Wing Team

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Abstract

The Seebeck effect has been already used to recover energy from wasted heat both in very high technological projects, like the Cassini space probe, and for commercial purposes, like trucks. This report shows that more economical and eco-friendly flights can be obtained exploiting this physical law in the aviation field. A huge difference of temperature is present between the engine's combustion chamber and the external air. The aim of HERO (Heat to Electricity Recovery On-board) is to connect the hot liner, just outside the combustor, and the covering. This device will produce electricity that can charge on-board batteries, power electrical systems, carry current to electrical buses. Thanks to HERO, the load of the engine is reduced so some fuel is saved. HERO can be adapted for many different needs and situations, however this report analyse several technical aspects like choice of materials, costs, electric circuits and thermal analysis for one of the possible designs.

Contents

1 Introduction

The Seebeck effect was discovered in 1821 by physicist Thomas Johann Seebeck. In particular he observed that, if two different materials are connected to two parts at different temperature, a voltage is produced. Since 1821 several studies on this effect were carried on, although it was early realized that the currents produced were really small to have practical applications. However with the development of technologies and materials that could serve as more efficient thermocouples, this physical property is no longer marginal. Today, indeed, this effect is exploited in many fields and the market of the thermocouples is constantly expanding. The aeronautical field is definitely a prime candidate to exploit this effect since in engines high temperatures are reached. The purpose of HERO is, therefore, to retrieve an important amount of energy through the effect described.

A study of one of the possible designs has been carried on. The data has been calculated considering turbofan with annular combustion chamber in cruise flight. However HERO can be also used in different phases of the flight (and on ground) and in different engines.

2 Description of the device

2.1 Location

HERO is designed to have a minimum impact on the engine's components, so its location has been chosen in order to not obstruct the hot flow inside the combustion chamber: it is placed just above it. As to the upper limitation, it is where the first covering is, in order to not create holes in the parts of the engine.

HERO will be placed all around the combustion chamber but it will not obstruct the flow, necessary to cool the combustion chamber. In fact HERO is made of different parts that are connected to each other, but allows the air to flow between them and to go to the combustion chamber through the holes present in the liner. On the other hand, a very little modification of the position of the holes is mandatory, because the device needs some space.

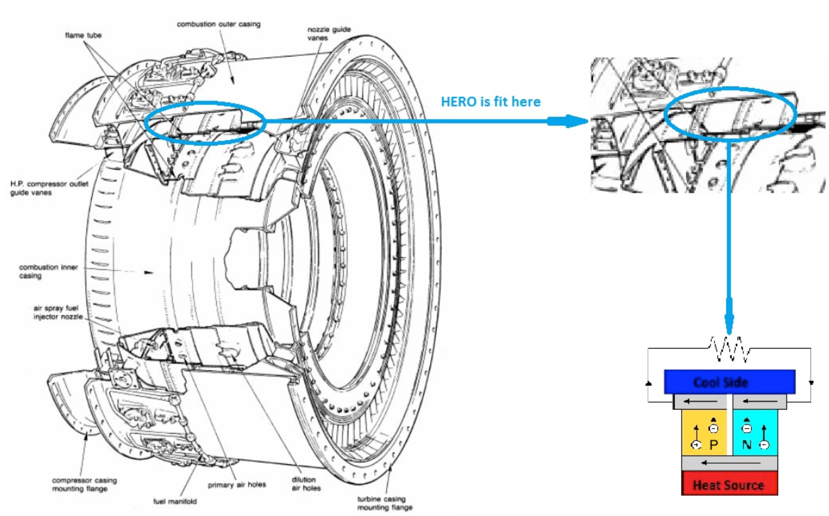

Figure 1: Position of HERO

2.2 Junction

Junctions are HERO's core. Each junction is composed of two pillars, one is made of Constantan, the other is made of Chromel (both Nickel alloys). The pillars are connected to each other either in the hot part (through a copper cable) or in the cold part (through an aluminum cable). This configuration creates an electric series, as it is explained in detail in Chapter 3. Each junction generates a voltage of 58.8 mV.

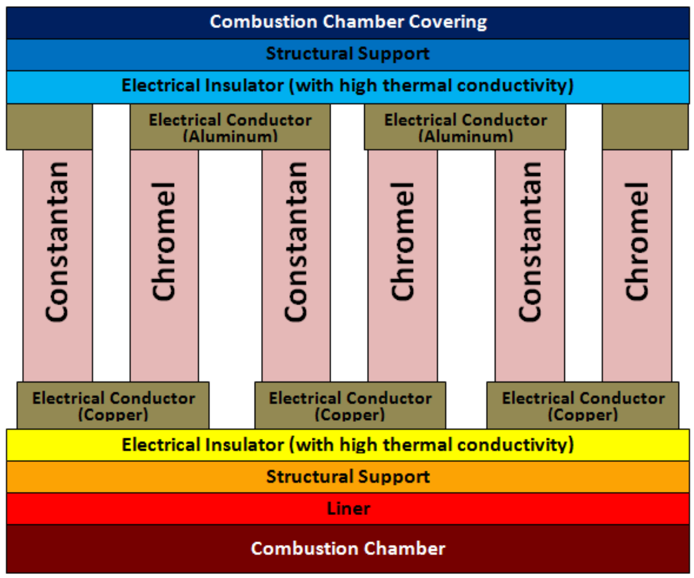

Figure 2: Schematic representation of junctions

The pillars have the shape of a truncated pyramid; their section is a square so they can be produced in easily. This configuration has been proven to be the most performing.

The area of the base of each Chromel pillar is 12.5 mm^2; the Constantan one is 8.65 mm^2. The top side of each Chromel pillar is 4.2 mm^2; the Constantan one is 2.9 mm^2. The empty surface at the bottom between pillars is 0.45 mm^2. Each copper cable that connects pillars in the hot part is 6.6 mm long and has a 0.3 mm^2 cross section. The aluminum cable that connects pillars in the cold part is 6.6 mm long and has a 0.15 mm^2 cross section. The difference of the cross section is due to the difference of electric resistivity between the materials (considering its variation with temperature).

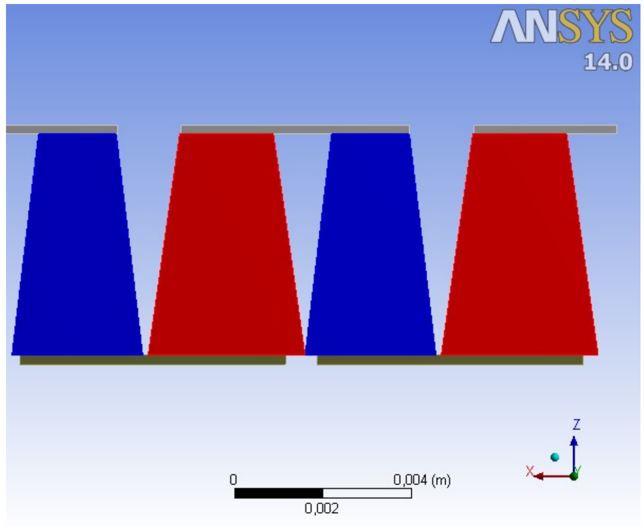

Figure 3: Zoom of a junction (different colors for different pillars) with aluminum (at the top) and copper (at the bottom) cables - side view

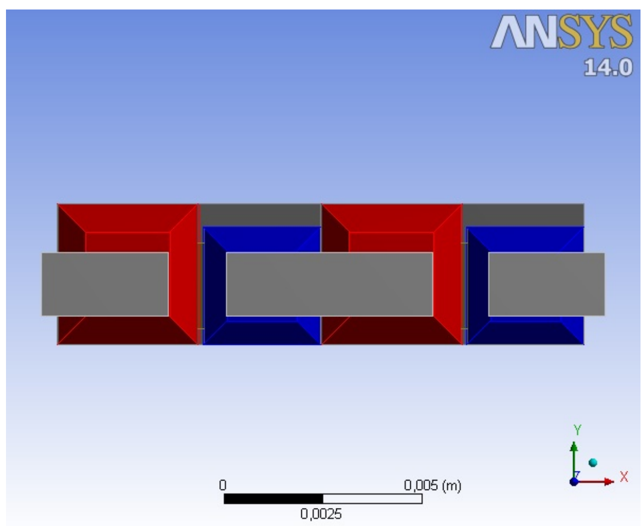

Figure 4: Zoom of a junction (different colors for different pillars) with aluminum (at the top) and copper (at the bottom) cables - top view

There is a small empty cavity between the pillars and the top of the device (not shown in figure) in order to take on account thermal dilatation. Indeed the whole device changes its temperature during its life; it must be both reliable and undamaged when the engine is on (very high temperature) and when the aircraft is not flying. This empty space must be neither too large (if the pillars do not reach the upper part the device does not work) nor too small (thermal stress could break the device)

2.3 Block

In order to reduce the length of the pillars (therefore to reduce their electric resistance as an electic current close in them and also to reduce their weight), it has been designed a block, made of Graphene. The block introduces some negative aspects like its weight and a lower temperature at the bottom of the pillars but some simulations through a Matlab script have shown that it can really improve the HERO performance. Moreover the thermocouple works at lower temperatures so its reliability increases. The dimensions of the block and the expected temperatures are shown in the figure below.

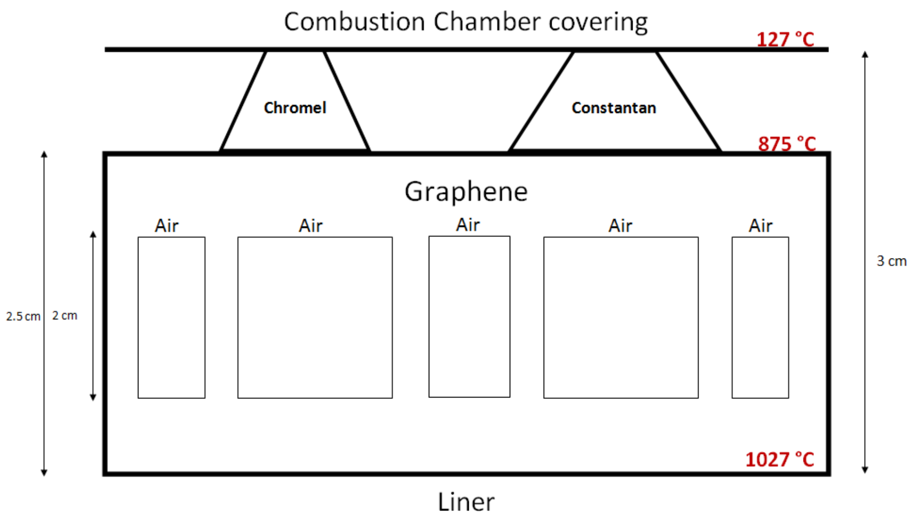

Figure 5: Temperature and dimensions in HERO (the combustion chamber is below the liner; the combustion chamber covering is a more external part)

The section of the pillars is bigger near the block than near the combustion chamber covering, in order to have an electric resistance to length ratio constant.

In order to reduce the weight of the block as much as possible a part of it is perforated. The normal of the holes is perpendicular to the air flow, for thermal reasons. In fact the temperature at the bottom of the pillars is 40 degrees higher than the temperature calculated with the normal of the holes parallel to the air flow (and therefore HERO can produce more power). With respect to the holes, it has been chosen an empty to total ratio of 70%. There is not one hole but several of them for structural reasons (considering the same empty to total ratio).

The optimal length of the block has been studied through an iterative method (using a Matlab script) and an ANSYS analysis. Different size for the perforated part as well as different percentage of empty to total ratio have been also studied.

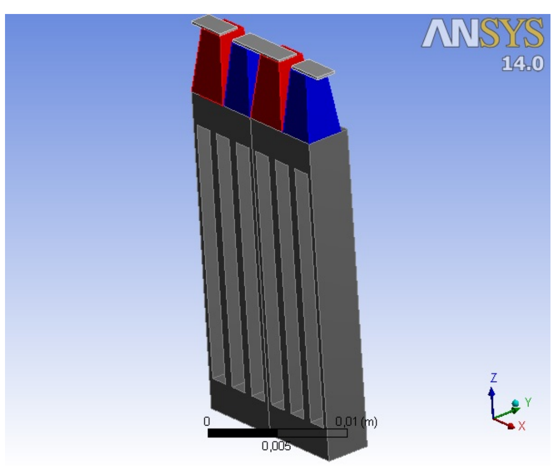

Figure 6: Junction and block

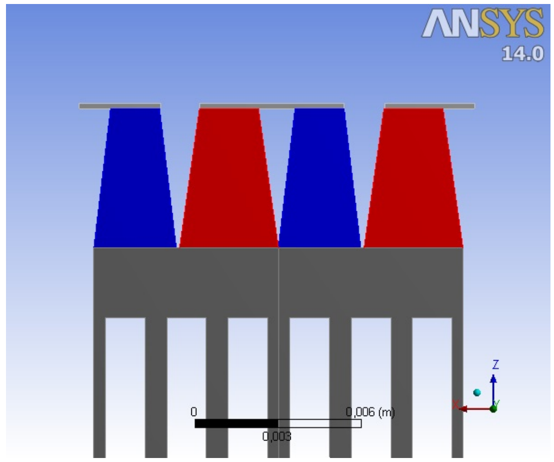

Figure 7: Junction and block

The block can be fastened to the liner through a Zirconia adhesive that can withstand very high temperature without degradation and oxidation. It is actually used for thermocouple protection and, for other purposes, in the Aerospace field. The same adhesive can connect the block to the pillars. An electric insulator between the block and the pillars has also to be put in order to avoid a short circuit. An electric insulator is also needed in the upper part; it can be fastened to the covering through another adhesive.

2.4 Shapes' Concept

It has been considered an available area of about 1.02 m^2. Even if HERO is not outside the engine, there is a slow flow between the liner and the covering (air that goes to the combustion chamber to cool) and HERO's structural problems have to be avoided. In order to reduce the drag due to the aerodynamical interaction between the air and the device, the junctions are covered by a thin shell of Graphene with the shape of a NACA 0012 profile. Each profile has a surface of about 8 cm^2 and contains 37 junctions. There are 1300 profiles, and their junctions are connected to each other. The profiles have small holes to allow the air to flow inside. These profiles are actually placed between the liner and the external part.

It has been chosen a NACA 0012 because it is symmetric (in HERO location the profile generates no lift and no aerodynamical torque) and because it is quite thin (less drag and less flow modification around the profile). With regard to the chord of each profile it is 10 cm (a lower value would create problems because junctions need space; a higher figure would make the thickness too large).

2.5 Materials

All the materials that have been chosen for HERO keep their chemical and physical properties over time in an extreme environment, at very high temperatures. They have been chosen taking into account many requirements such as high melting point, low electrical resistivity, low density and low thermal expansion. The materials chosen for the junction (Chromel and Constantan) can work at temperatures between 0 °C and 1000 °C. The pillars can withstand 5 A current in their environment (difference of temperature between the pillars and the air: about 475 °C).

The graphene has been chosen as it is a good conductor so the temperature at the bottom of the pillars is not too low. Moreover it has very low density because the mass budget of the device has been a guideline along the whole project. However, as it has not good properties against oxidation, a very thin layer of ZrB2-SiC should be put between graphene and the environment.

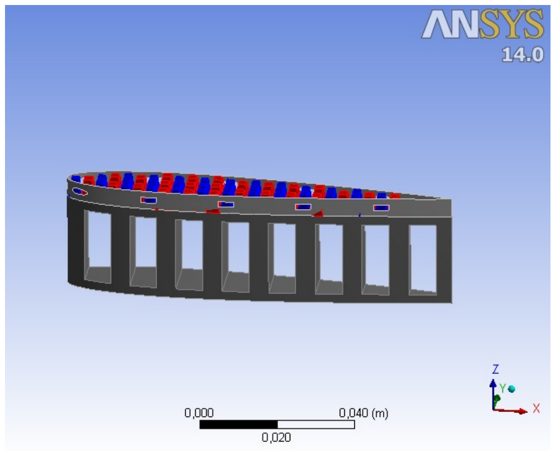

Figure 8: One profile made of 37 junctions

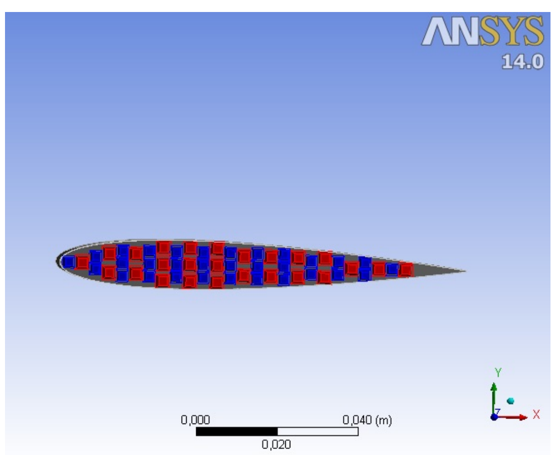

Figure 9: One profile made of 37 junctions

3 HERO design

3.1 Powered Electrical System

Through computational tools, technical data of HERO has been obtained and it has been used to quantify the recovered energy as well as the new fuel consumption of an engine. It has been adopted as a model a Trent XWB which is usually mounted on Airbus A350 XWB. Even if this engine has an annular combustion chamber, it does not mean that HERO cannot be used, with some modifications, in other types of airplanes, both large or small, both four-engine or twin-engine.

In a Trent XWB are present generators that produce current at 28 V or 115 V or 220 V. HERO is designed to be connected to the buses that have a voltage of 28 V. This value has been chosen because, as it is evident from figure 12, there are not earnings using higher voltages. On the other hand, it can be noted that the surface needed from the device increases proportionally to the voltage of the user (figure 15) and therefore, using higher voltages, it would have intolerable dimensions. In fact the surface of the liner is not so large and it cannot be fully used in order to not impede the cooling obtained by the flow. They have also been studied the weight and the power to weight ratio of the device as a function of the current available for the bus. It has been also studied the output current for maximum gain in terms of energy, taking into account the losses due to the resistance of the line. Set the number of parallel, the total current supplied by HERO is equal to the sum of the currents generated by a single parallel, obtaining the value of 250 A (5 A multiplied by 50 parallels).

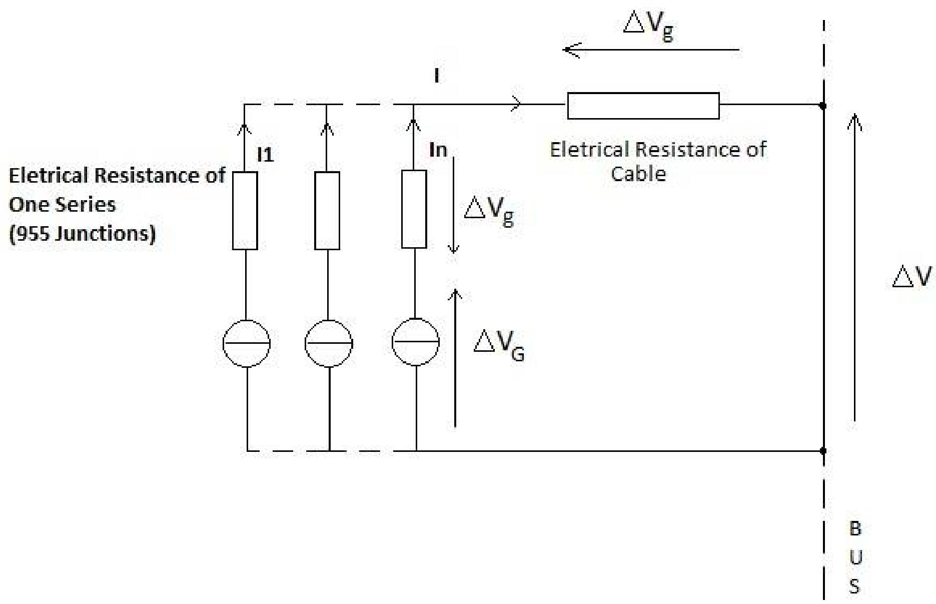

Figure 10: Electric circuit

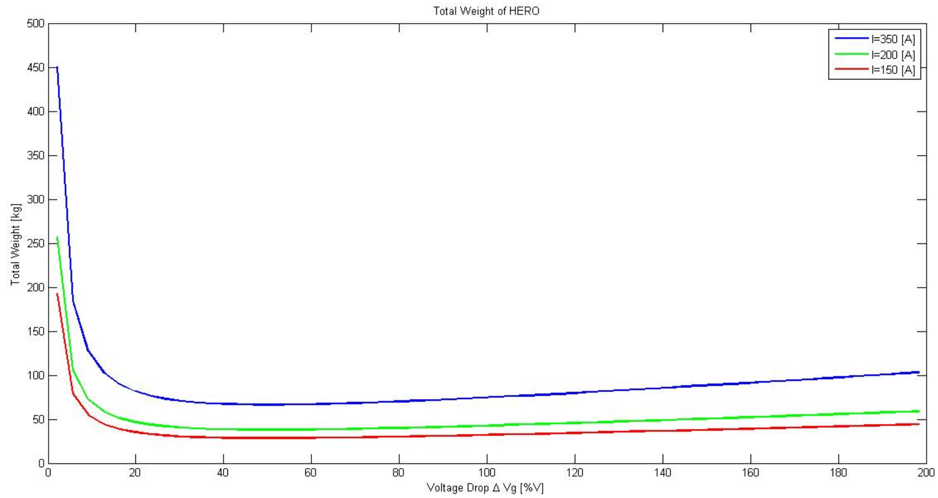

Figure 11: Needed weight as a function of the available current for the bus and the voltage drop between the junctions and the bus (HERO data: Current: 250A; Voltage drop: 50%)

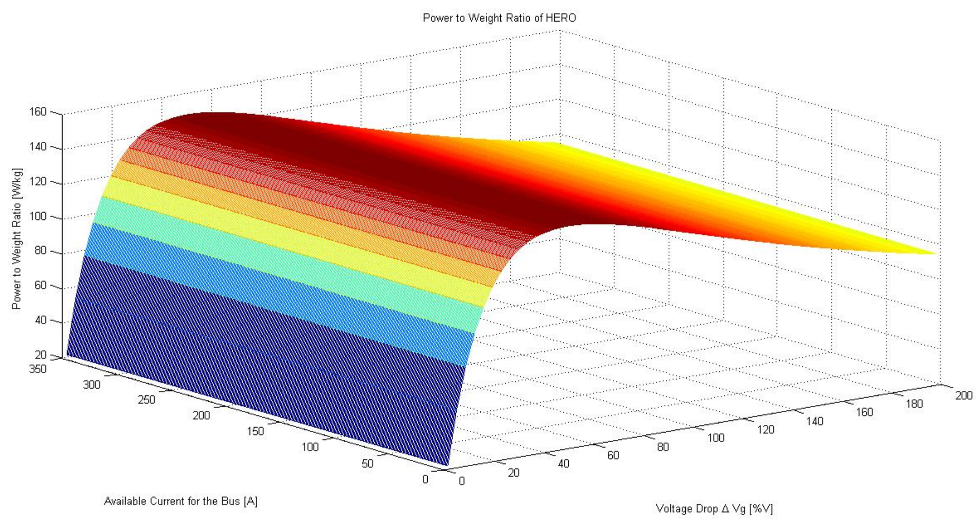

Figure 12: Power to weight ratio as a function of the available current for the bus and the voltage drop between the junctions and the bus (HERO data: Current: 250A; Voltage drop: 50%) - the needed surface follows the same trend

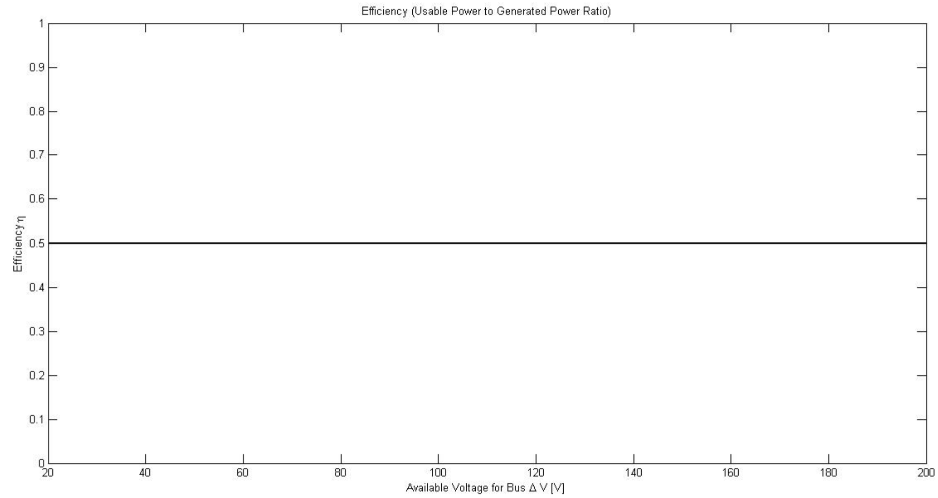

Figure 13: Efficiency of HERO as a function of the available voltage for the bus (HERO voltage for the bus: 28V)

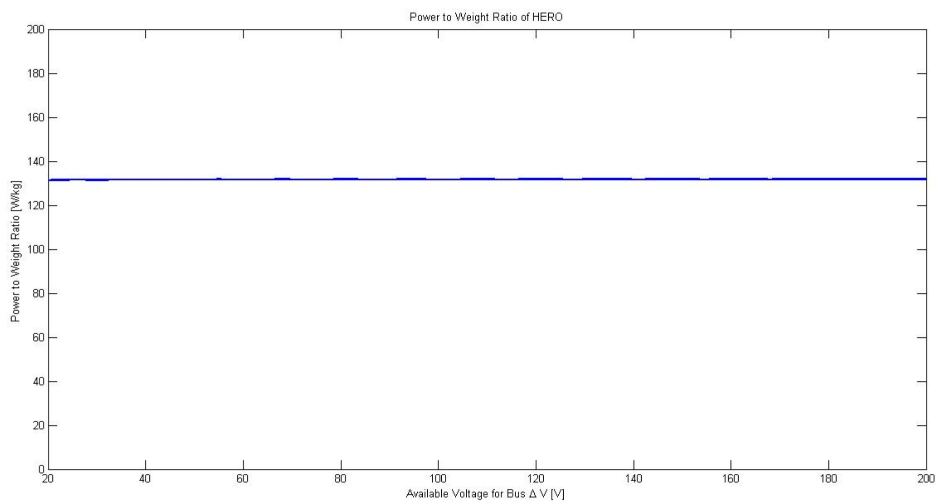

Figure 14: Power to weight ratio as a function of the available voltage for the bus (HERO voltage for the bus: 28V)

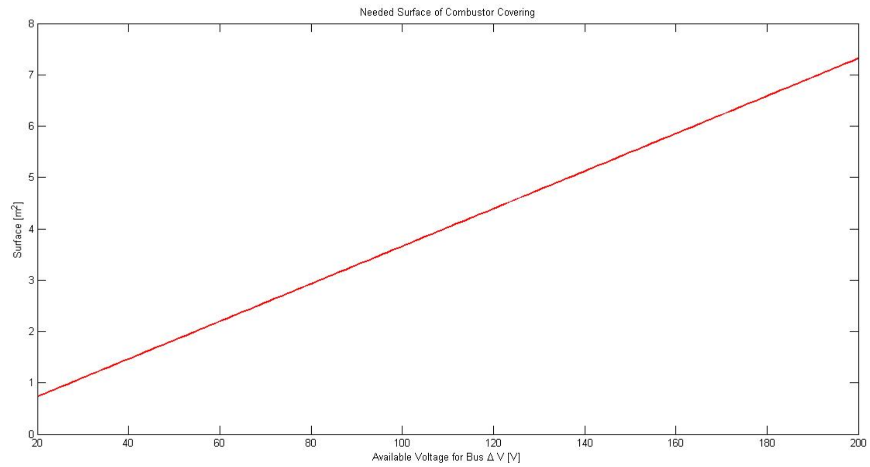

Figure 15: Needed surface as a function of the available voltage for the bus (HERO voltage for the bus: 28V)

3.2 Circuit Design

As far as the circuit design is concerned, 955 junctions are connected in series and all the series are connected in parallel. The number of junction in series has been decided in order to reach 28 V (considering the voltage drop of the whole circuit). As to the number of parallels, HERO efficiency, needed surface and power to weight ratio do not vary with the number of parallels. However the reliability depends on this number: if the number of parallels increases the reliability also increases, in fact when one junction breaks the whole series is lost but all the other parallels continue to work. On the other hand, the more is the number of parallels, the less is the area of a pillar of each junction (it could lead to structural and manufacturing problems). The number of parallels that has been chosen is 50.

A useful parameter $(Efficiency * GeneratedPower)^2/(Weight * Surface))$ has been studied. Its maximum has been found and it corresponds to 50% of voltage drop along the line. This condition is the optimum of the device. The available power is a linear function of the current.

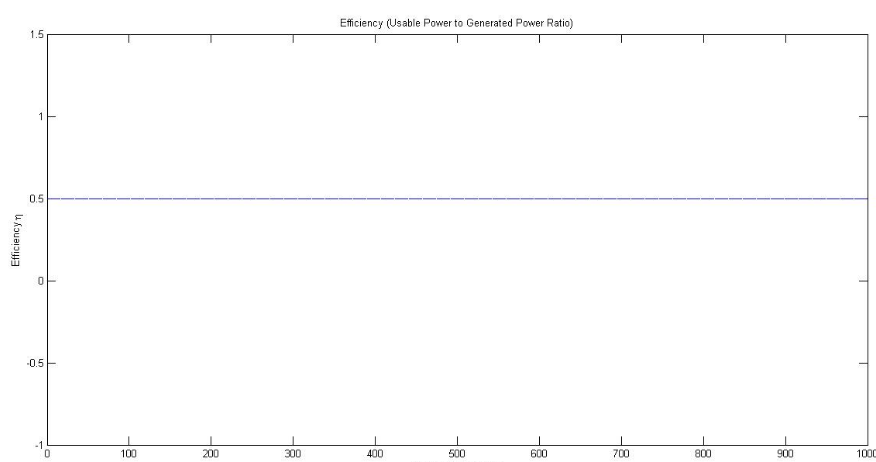

Figure 16: Efficiency as a function of the number of parallels (HERO number of parallels: 50)

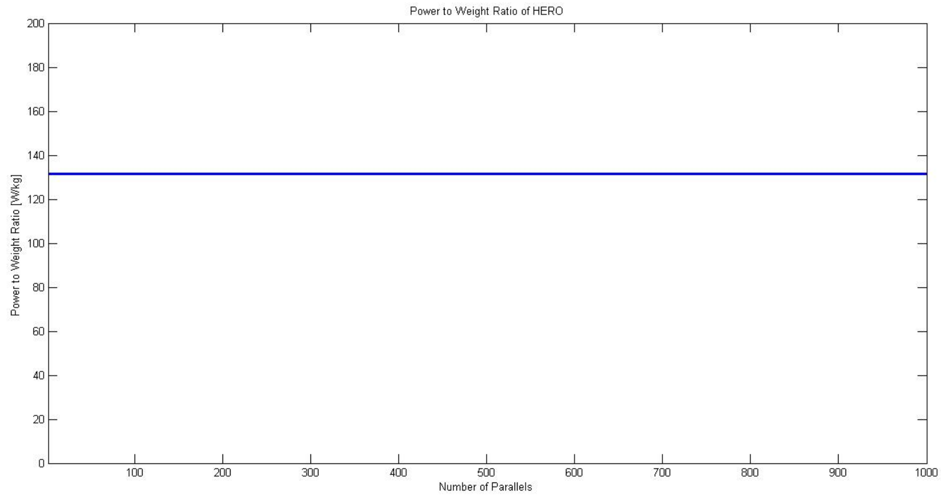

Figure 17: Power to weight ratio as a function of the number of parallels (HERO number of parallels: 50)

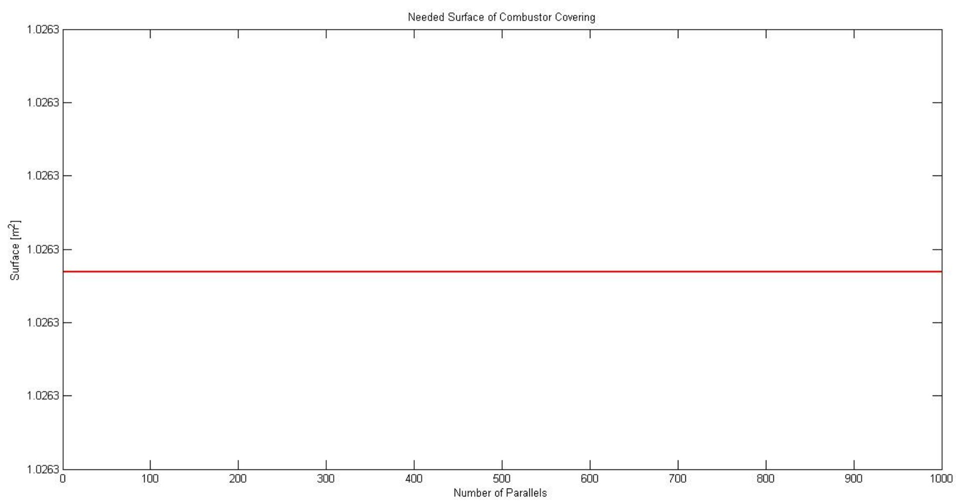

Figure 18: Surface as a function of the number of parallels (HERO number of parallels: 50)

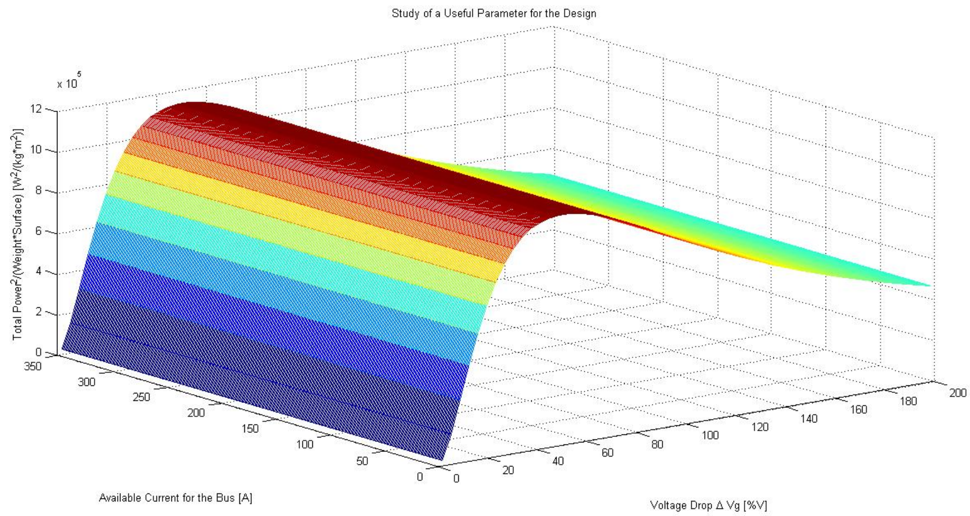

Figure 19: Optimization of HERO (HERO data: Current: 250A; Voltage drop: 50%)

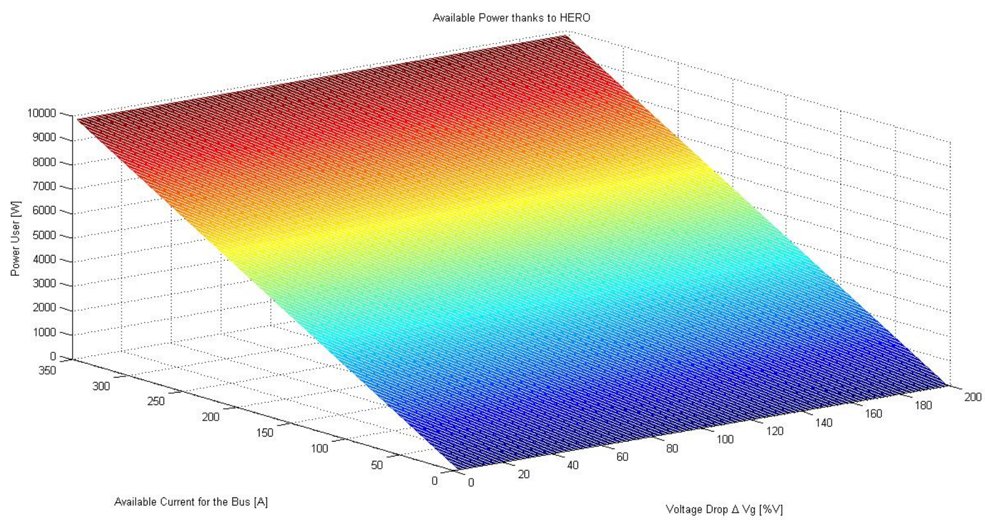

Figure 20: Available power (HERO data: Current: 250A; Voltage drop: 50%)

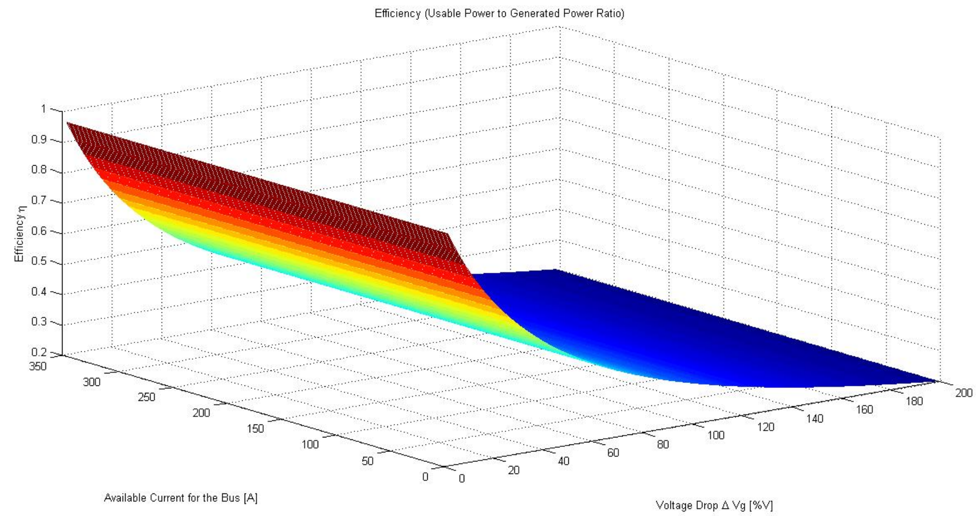

Figure 21: Efficiency (HERO data: Current: 250A; Voltage drop: 50%)

3.3 Cables

The cable that connect HERO with the bus is made of aluminum and has a cross section of $4mm^2$, is 5 meters long (2.5 m to go to the bus and 2.5 m to go back), its weight is 54 g. The thermal and electrical insulation for this cable is made in glass fibers with silicone (about 100g). The cable can ensure the 250 A current with a difference of temperature between the cable and the exterior of 50 °C. The cable can work between 0 °C and 350 °C. It will be put in the coolest place of the device.

It was decided to adopt multiple small sections for cables, rather than having a single cable, to carry the electrical load. This was done primarily because the cables are subject to less thermal and structural stress and secondly because if a cable breaks due to fatigue problems, the device current and voltage are not too penalized. Another reason to use small sections for cables is that, since HERO could be designed to carry three phases current, the skin effect could be avoided. In the case of a single cable, in fact, the current flowing would be mostly on the external layer of the cable, thus making the effective area smaller. With the availability of small cables, instead, these effects are negligible and it would be able to exploit the entire area of the cable.

4 Analyses

4.1 Thermal Analysis

A thermal analysis has been required in order to estimate the voltage of a single junction and to know if the chosen materials can withstand the temperature. A Matlab script has been written using these hypotheses: temperature out of the liner of 1027°C, temperature in the cold part of 127°C, distance between liner and combustion chamber covering of 3 cm, validity of Fourier's law, linear variation of the temperature along the pillars (following different trends in different areas), linear variation of thermal and electric resistivity with the temperature. A validation of the results has been performed thanks to ANSYS.

The process that led us to define the areas of cable and pillars was the thermal verification (guaranteed current flow at that temperature range).

4.2 Fatigue and Reliability

It has also to be considered that if only one junction breaks, HERO does not stop to work but continues to produce 6.86 kW (only one out of fifty parallels stop to carry current). However it has been considered that the reliability of HERO is the reliability of its junction

Structural analyses performed using ANSYS have shown that HERO can withstand the loads and has a very long fatigue life but other possible cases of failure have to be taken into account so the mean time before failure has been increased of ten times (final evaluation: mean life of time per device of 50000 flights) .

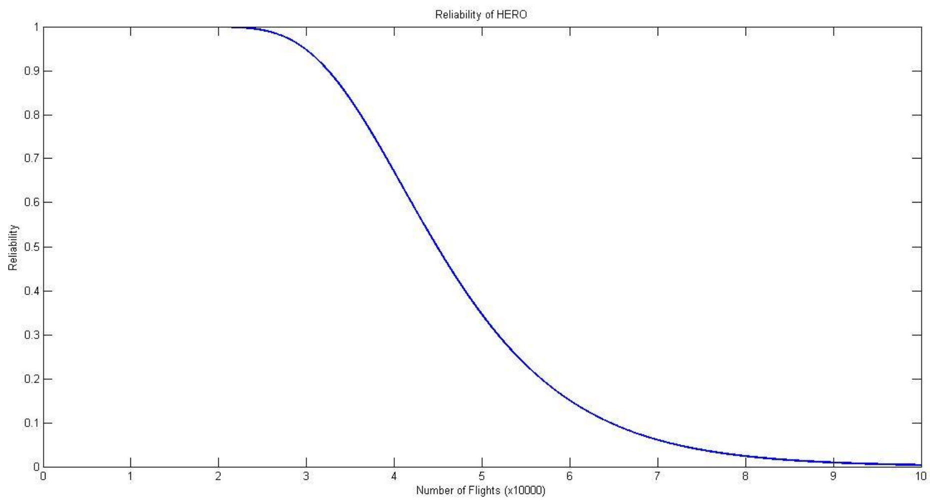

Figure 22: Reliability of HERO

4.3 Cost Estimation

It is quite hard to estimate the cost of the device because a lot of parameters have to be evaluated: materials, manufacturing, validation, certification, maintenance, repairing, as well as the cost of the design so the following values are just a rough estimation. However it seems to be clear that to invest money on HERO can lead to a money saving.

HERO requires a lot of particular materials considering his design and the extreme environment in which it is positioned. The greater cost of the materials comes from the thermocouples. After a market research, it has been evaluated a range of prices between 2000 and 8000 euro . It will be considered a cost of 5000 euro per engine.

As far as the maintenance is concerned, it has been considered that when one junction breaks, the whole device is substituted. However, some methods to save time and cost of maintenance have been studied. For example, if only one junction breaks, it can be found thanks to thermosensitive spray that change color due to temperature. It would allow to substitute only one junction instead of the whole device.

4.4 Interaction between HERO and the Aircraft

A variation of temperature of the combustion chamber would make the voltage of HERO changing. However, since those variation are slow, the device does not generate electromagnetic interference with the antennas of the aircraft.

As far as the combustion chamber is concerned, its cooling is not obstructed as it has not been used the whole available surface. The holes that allow the cold flow to go to the combustion chamber are not closed but moved and HERO itself helps the cooling since it is mostly made of materials with high thermal conductivity.

5 Results

5.1 Effects on Engine Performance

HERO does not affect the combustion chamber so the thrust is not modified. However it reduces the load required to the engine to power on board systems, so the needed fuel is reduced.

Some graphs have been drawn in order to show the increased efficiency of the engine.

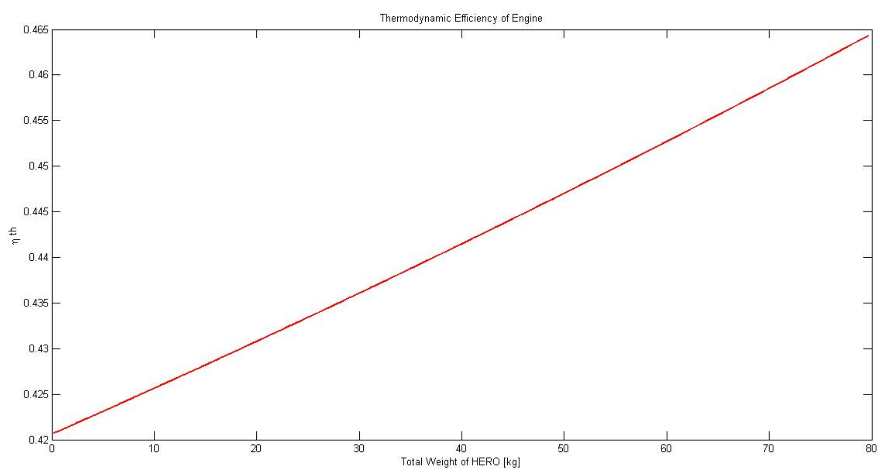

Figure 23: Thermodynamic efficiency of the engine as a function of total weight of HERO (HERO weight: 53 kg) - the needed surface follows the same trend

5.2 Effects on Fuel Consumption and Cost Saving

HERO supplies a current of 250 A and for this value has a power output equal to 7 kW for a single combustion chamber. In twin engine aircrafts there will be a power of 14 kW, in four engine aircrafts there will be a power of 28 kW. The weight of HERO is 53.3 kg per engine. The needed surface is $1.02m^2$. The power to weight ratio is 132 W/kg. The surface and the weight can be raised or decreased and the power would follow the same trend, whereas the power to weight ratio is constant.

Each engine consume about 3l/km. This fuel consumption is needed both for the thrust (80%) and for the electrical power of aircraft (20%). HERO produce 7 kW; since the electrical generator provide about 90 kW, the device reduces 8% of the engine load for powering on board systems. Therefore HERO will allow the engine to save about 1.5% of fuel. However, its weight has a negative effect on fuel saving so it has been estimated a reduction of 0.5% of fuel consumption. This data has been given by the expert. However, using an empiric method that considers the variation of the weight of the aircraft due to the fuel consumption modification, higher values of savings could be obtained (less fuel consumption means less fuel and so lighter tanks and lighter structure).

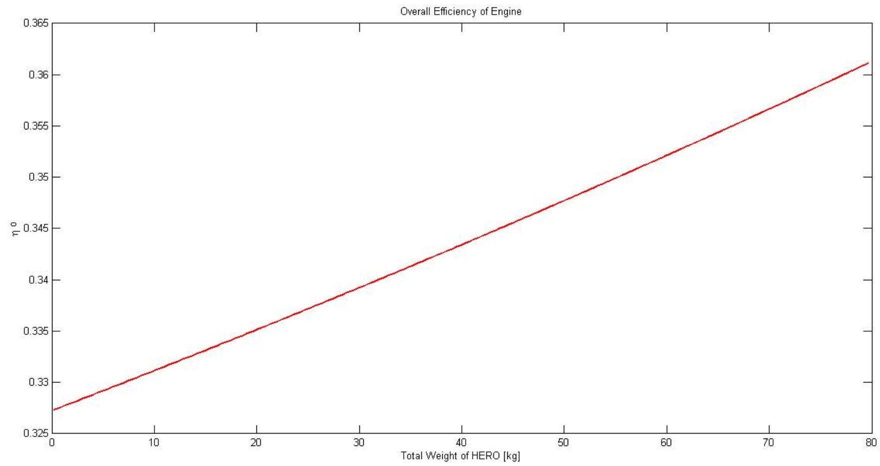

Figure 24: Overall efficiency of the engine as a function of total weight of HERO (HERO weight: 53 kg) - the needed surface follows the same trend

Considering the available power thanks to HERO, 120 kg of fuel can be saved in a 10000 km flight. The figure below shows how much fuel can be saved as a function of the length of the flight compared to the weight of HERO.

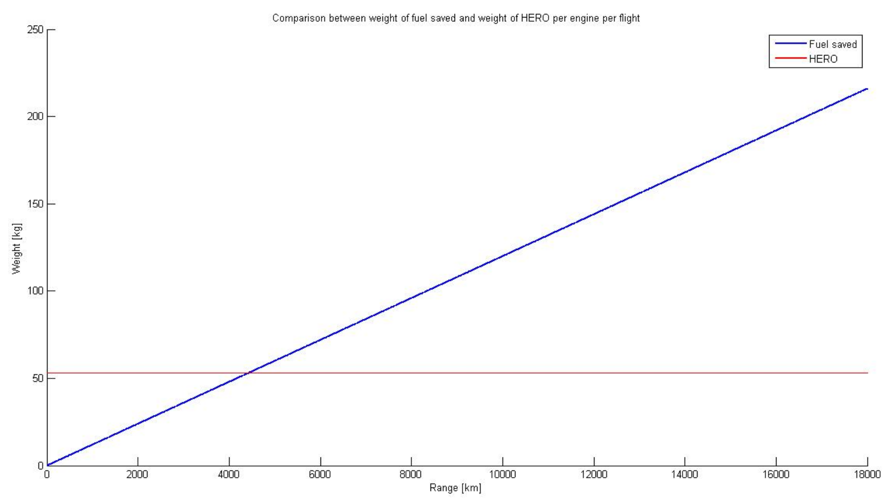

Figure 25: Comparison between weight of HERO and weight of fuel saved per engine per flight as a function of the distance

This graph compares the money spent for HERO (initial cost + maintenance) with the money saved thanks to the reduction of fuel consumption. For example, 132 euro can be saved in a 10000 km flight.

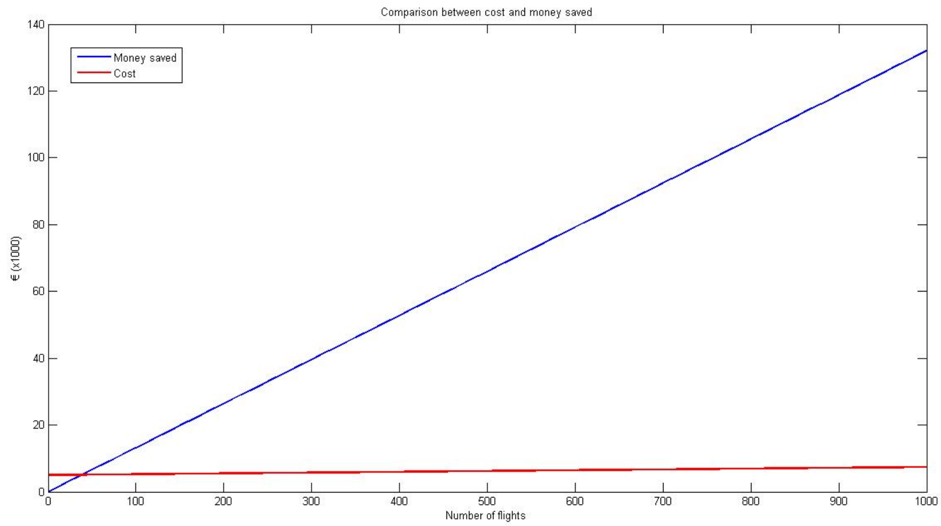

Figure 26: Comparison between money saved and money spent to build and to maintain HERO per engine as a function of the number of flights (considering flights of 10000 km)

Fuel saving means also less exhaust gas in the air and so less pollution. As to the CO2, this graph shows how much CO2 is not produced as a function of the number of flights. For example 380 kg of CO2 can be saved in a 10000 km flight.

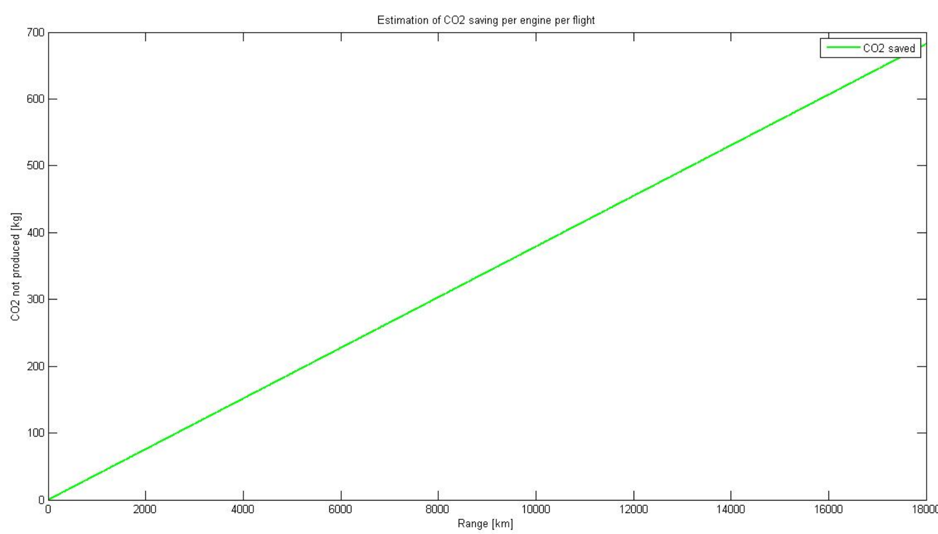

Figure 27: CO2 not produced per engine per flight as a function of the distance

Considering 10000 km flights, this graph shows the amount of CO2 saved as a function of the number of flights.

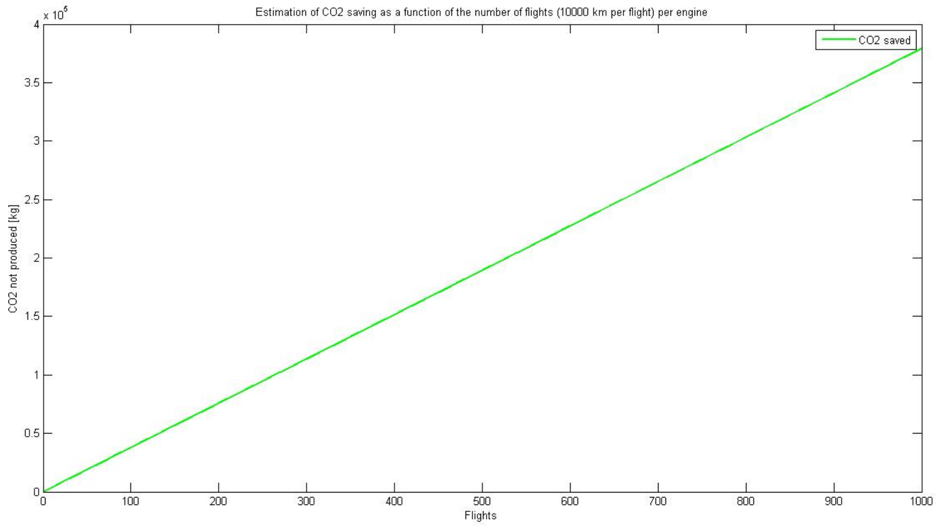

Figure 28: CO2 not produced per engine as a function of the number of flights (considering flights of 10000 km)

5.3 Use as an Emergency Power System

HERO could also be used if the engine has a failure. Indeed, even if the engine switches off, the combustion chamber keep its heat for a long time so the device can continue to provide 7 kW to the on-board systems. When the temperature decreases, HERO continue to work but the power that it can provide decreases as well. It will not increase the reliability of the engine but, even in case of failure, some power can be used for critical systems.

5.4 Use on the Ground

HERO could also be used on the ground, thanks to the high thermal capacity of the internal part of the engine. Often aircrafts do not stay on the ground as much time as it is needed to the combustion chamber to have low temperature, so HERO could be always on, in order to produce energy both in flight and on ground. It would allow to reduce the APU load. It would lead to an important fuel saving for short haul flights, for example for aircrafts that have a turnaround time of 30 minutes with many flights of about 60 minutes. On ground, fuel consumption is not for thrust so the percentage of fuel saving would be much higher.

5.5 Pros and Cons

Thanks to HERO, some fuel can be saved and it means less costs for airlines, less pollution and less CO2 produced. These are the main advantages, but HERO allows also to produce power in case of failure of an engine so it can improve the overall reliability. On the other hand, a disadvantage is that to modify the combustion chamber is always hard and a lot of experimental proofs are needed. The device has been designed in order to make the required engine's modification the least possible. In fact, it keeps clear both the combustion chamber and the external part.

6 Further developments of HERO

6.1 Different Configurations

The project has been developed to place HERO outside the combustion chamber, however different configurations can be designed and it could be also put near the turbine, the avionics or wherever a large difference of temperature is available.

The initial idea was to charge on board batteries but it has been changed in order to reduce losses. The device is optimized to be connected to one of the buses already present in the engine, although a different design would allow to power any other system.

Different materials for the block have also been studied. For example, the graph shown in the figure 29 compares the voltage with the power to weight ratio of a single junction when the block is made of ZrB2-SiC instead of Graphene (performance studied through a Matlab script). A lower temperature would be reached at the bottom parts of the pillars (so the power produced by HERO would be lower) but some advantages can be found (it is already used in the combustion chambers, less degradation due to the environment).

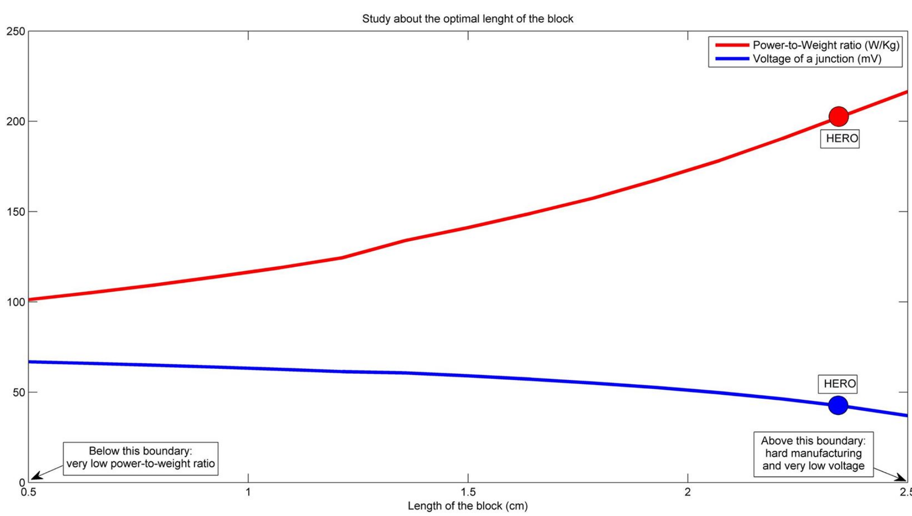

Figure 29: Voltage of a junction and Power to Weight ratio - other version: block fully made of ZrB2-SiC

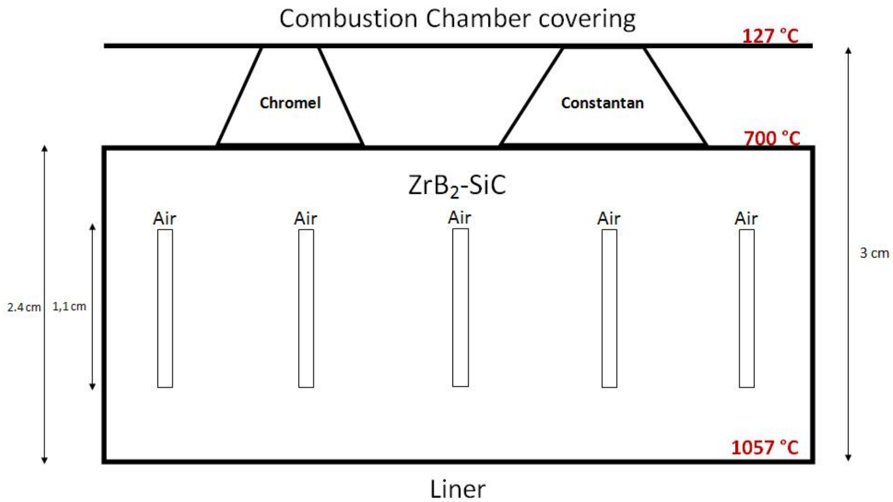

Figure 30: Temperature and dimensions in HERO - other version: block fully made of ZrB2-SiC (the combustion chamber is below the liner; the combustion chamber covering is a more external part)

In some designs of engines, there is a heat exchanger necessary to a regenerative cycle. In particular the cold air coming from the compressor is mixed with the hot air coming from the turbine in order to decrease the fuel consumption. In this configuration of the engine, there are two heat sources at different temperature so HERO could also be placed there.

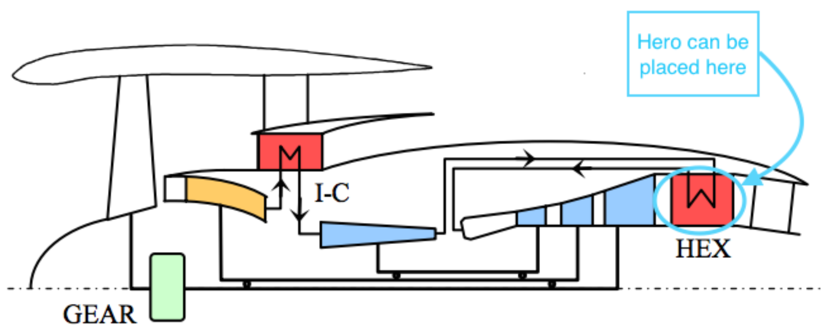

Figure 31: A different configuration for HERO in a heat exchanger

6.2 Looking at the Future

HERO has been designed by Hot Wing Team, using the current technology. In the future, its performance will increase enormously. Indeed, new alloys will be available making HERO more efficient: the cables and the pillars will be lighter and will have more electric conductivity, the junction will be made of new materials that will produce more voltage, the block will be made of lighter and more thermal conductor material. It will increase the produced power and will decrease the weight.

With the innovation of materials and the shrinkage of the components, with the same floor area, there will be more space in which to stay HERO. In this way there would be a substantial increase of the power to weight ratio of the device and a reduction of losses.

In the next years, the combustion chambers will generate higher temperatures so HERO will be able to exploit a larger difference of temperature that will produce more voltage and more power.

Other effects could be used, for example the Seebeck spin effect that could produce voltage when there is a temperature gradient in a ferromagnet. Ferromagnetic materials could be used for HERO, in order to exploit also this effect.

If alloys with higher thermal capacity will be used for the combustion chamber, HERO's performance on ground and in case of failure of the engine will be improved.

A study of how several parameters (temperature in combustion chamber, available materials with high thermal conductivity and low density at high temperature, available materials with high electric conductivity at high temperature) have changed from the beginning of the aviation to nowadays has been carried out. It has been estimated how the power produced from a device like HERO would have increased over the years from 1960 to 2010. An estimation of the amount of power that could be produced by HERO in the future has been done, considering a trend similar to the past. The power to weight ratio that HERO should have in 2025 is 167 W/kg whereas the ratio should be 192 W/kg in 2035. These values have been calculated not considering other possible improvements like materials with high electric conductivity at high temperature for cables and new materials for thermocouples. A graph has also been drawn too.

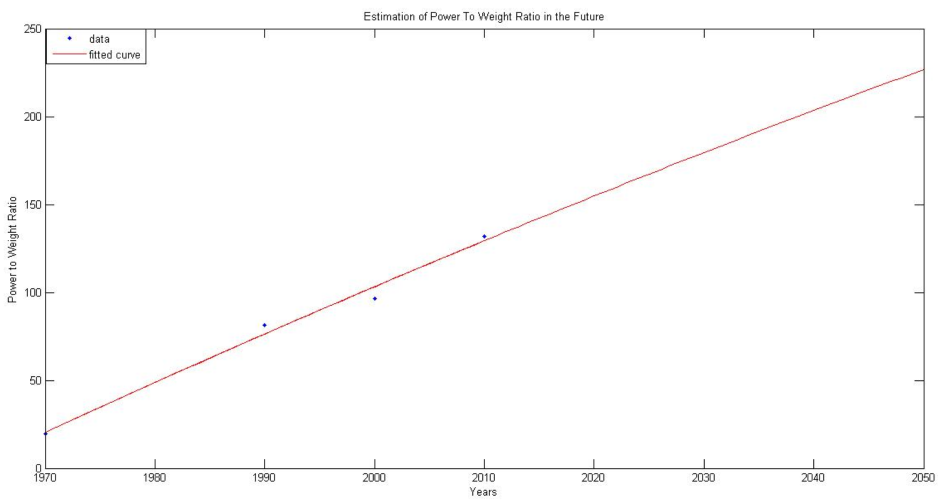

Figure 32: Variation of power to weight ratio of HERO along the years

7 Conclusion

From the results obtained so far it is clear that an investment directed to the development and maintenance of HERO in airplanes would be convenient. This device in fact, in the period of its life, allows to reduce the needed amount of propellant and the CO2 emissions. It means lower cost of tickets for passengers. Moreover the reliability of the engine is increased as it has another generator that can be used also in case of failure. Exploiting the Seebeck effect in aviation, even if in some ways it may seem still not profitable, will produce more and more benefits in the future so HERO will play an essential role. In the coming decades there will definitely be further developments and HERO will ensure a greater recovery of energy.