Electro-jet engine: a jet engine without turbine - Part 2. Electric power generation

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Abstract: *This part studies theoretically and experimentally the conversion of thermal energy directly into electrical energy. The experimental part was based on the recovery of a part of the heat lost to the cold source, i.e. to the atmosphere, through the walls of hot part of a turboshaft jet engine. For the experimental part I used a small turboshaft jet engine installed on an ultralight helicopter. The recovery was done with a Seebeck bridge currently produced. These Seebeck bridges are manufactured in mass production, have a low maximum operating temperature compared to the temperature inside the jet engine and have a very low efficiency compared to current systems used in space technology.*

Key Words: *electro-jet engine, Coanda-type jet engine, turbine-less, Seebeck bridge thermal-electric converters, thermal-electric energy recovery.*

1. INTRODUCTION: TYPES OF THERMO-ELECTRIC GENERATORS THAT COULD BE USED FOR ELECTRO-JET ENGINE

Next, I will present, without limiting myself to these, several types of thermoelectric generators that could be used to convert thermal energy in the form of heat directly into electrical energy, according to [1].

1.1 Thermo-electronic generator

A thermo-electronic generator is based on the emission of electrons from a cathode heated to a sufficiently high temperature to set the conduction electrons in motion. Such a generator is based on Richardson's theory of electron emission (Figure 1).
The Richardson formula is:

$$j = BT^2 \exp^{-\frac{\varphi}{kT}}$$

where:

j → current density in A/cm^2;
B → a constant = 120 $A/(cm^2K^2)$;
T → absolute temperature in K;

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φ → work of extraction of the electron in eV;
k → Boltzmann constant = $8{,}62 \cdot 10^{-5}$ eV/K.

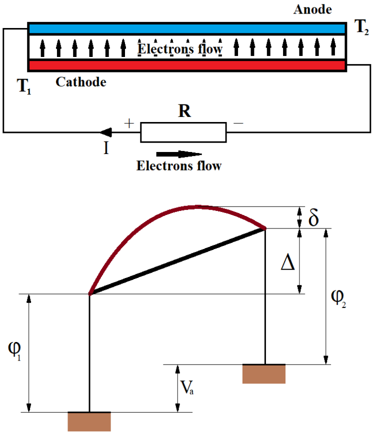

Fig. 1 - Thermo-electronic generator layout and energy levels of the generator

The thermo-electronic generator could be used in the combustion chamber area, when using materials that can withstand high temperatures, such as tungsten (or wolfram). The technical condition that determines the use of this method is the very small gap between the anode and cathode, the electrodes generating electro-motor voltage, of the order of tenths or hundredths of a millimeter, but also maintaining the vacuum between the anode and cathode that is a technical difficulty.

1.2 Magneto-hydro-dynamic (MHD) generator

The Magneto-hydro-dynamic generator is based on the Lorentz theory, in such a sense that in a magnetic field ***B***, in which an ionized gas moves with a velocity ***v***, an electromotive force (E.M.F.) ***E*** is generated between two plates connected to a load resistance R_{load} (Figure 2).

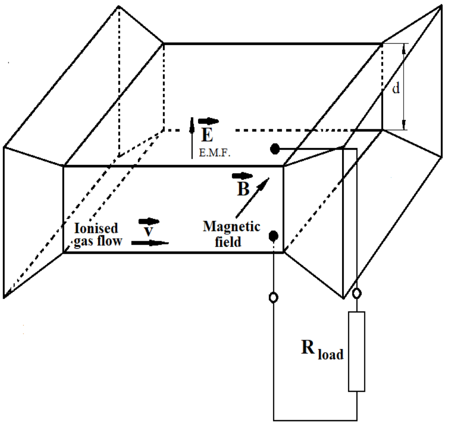

Fig. 2 - Magneto-hydro-dynamic generator layout

According to Lorentz's theory, the force generated by the electric charge q moving with a velocity ***v*** in the magnetic field of intensity ***B*** is:

$$\boldsymbol{F}_{Lorentz} = q(\boldsymbol{v} \mathrm{x} \boldsymbol{B})$$

In this first case, the Lorentz force is

$$\boldsymbol{F} = q(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B})$$

where $\boldsymbol{E}$ is the electric field existing in the working gas flow area (Figure 3).

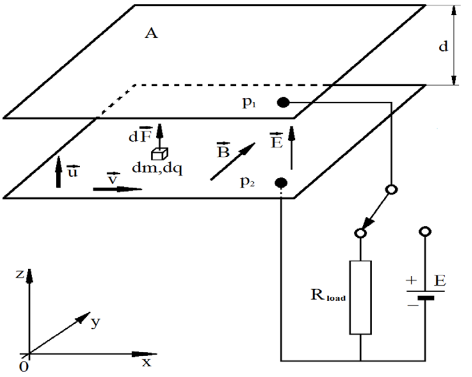

Fig. 3 - Magneto-hydro-dynamic generator equilibrium

But because of the electric field $\boldsymbol{E}$ generated by the electric potential difference U between plates p_1 and p_2, an electromagnetic force appears that causes the ionized working gas particle move at speed $\boldsymbol{u}$, from p_2 to p_1. So, finally, the force $\boldsymbol{F}$ acting on the ionized working gas particle, moving in the generation zone (between plates p_1 and p_2) is:

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} + \boldsymbol{u}\times\boldsymbol{B})$$

where $\boldsymbol{u}$ is the velocity of movement of the particle from plate p_2 to plate p_1, and: $E=\frac{U}{d}$, where U is the potential difference between plates p_1 and p_2 and d is the distance between them.
In this case:

$$U_{total} = U + B\cdot v$$

where $B\cdot v=U_0$ is the open-circuit e.m.f. (considering also that vectors $\boldsymbol{v}$ and $\boldsymbol{u}$ are perpendicular to vector $\boldsymbol{B}$).
The magneto-hydro-dynamic generator would be suitable for use, but due to the need to use a strong magnetic field (which can be generated by powerful electromagnets, which are heavy and require high electrical power) and the need to ionize the exhaust gases, which is done by spraying ionizing elements (such as potassium or cesium powder) which would be a polluting and very expensive material, it is not feasible for use in aviation for this type of jet engine.

1.3 Seebeck Thermo-Electric Generator (TEG)

The Seebeck thermoelectric generator is based on the appearance of a potential difference between two conductors of different materials welded together. This phenomenon is called the thermoelectric effect or Seebeck effect.
The generator is composed of two welds between two such materials, one of the welds being placed in the hot source and the other being placed in the cold source (figure 4).
The Seebeck electromotive force, as a potential difference is: $\Delta E=\alpha\Delta T / \cdot d \Rightarrow dE=\alpha dT$, $\{E_1-E_2=\alpha(T_1-T_2)\}$
The coefficient α, in some books is called the thermal force and is measured in [V/K].
The energy transformed from the form of heat is: $Q=\Phi\cdot I\cdot t$, where Φ is called the Peltier coefficient, $\Phi=\alpha T \Rightarrow Q=\alpha TIt$, where:
Received heat : $Q_1^{rec.}=\alpha T_1It$: from hot source;
Disposed heat : $Q_2^{dis.}=\alpha T_2It$: from cold source;
And work is : $L=\alpha(T_1-T_2)It=Q_1^{rec.} - Q_2^{dis.}$.

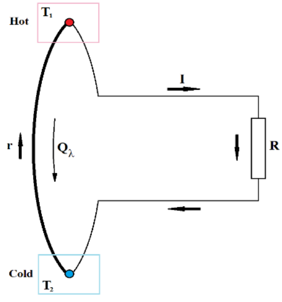

Fig. 4 - Seebeck generator layout

In this case the work *L* is:

$$L=Q_{Joule}+L_{cycle}=\alpha(T_1-T_2)It \Rightarrow L_{cycle}=\alpha(T_1-T_2)It-Q_{Joule}=I^2Rt$$

and the generated power is:

$$P=I^2R=\alpha(T_1-T_2)I$$

If $Q_\lambda^{conduction}$ is the heat exchanged by conduction between the hot source and the cold source, and Q_{Joule} is the heat released by the thermo-electric Joule effect, produced by the electric current circulating through the conductors, it is considered that this is divided into equal amounts for each source, that is, for each section of conductor.

So, in total, have:

$Q_1=Q_1^{rec.}+Q_\lambda^{conduction}-1/2Q_{Joule}$: from the hot source;

$Q_2=Q_2^{dis.}+Q_\lambda^{conduction}+1/2Q_{Joule}$: from the cold source;

and the efficiency of the TEG is:

$$\eta_t=\frac{L_{cycle}}{Q_1}=\frac{I^2Rt}{Q_1^{rec.}+Q_\lambda^{conduction}-\frac{1}{2}Q_{Joule}}$$

and if $Q_\lambda^{conduction}=0$ and $Q_{Joule}=0$ then $L_{cycle}=\alpha(T_1-T_2)It$, $Q_1=\alpha T_1It$ and then:

$$\eta_t=\frac{L_{cycle}}{Q_1}=\frac{\alpha(T1-T2)It}{\alpha T1It}=\frac{T1-T2}{T1}=1-\frac{T2}{T1}$$

therefor that is the efficiency of a Carnot cycle, where T_2 is the temperature of the cold source and T_1 is the temperature of the hot source.

This is the ideal situation in which the heat conduction and heat losses as Joule effect through the conductors are not taken into account.

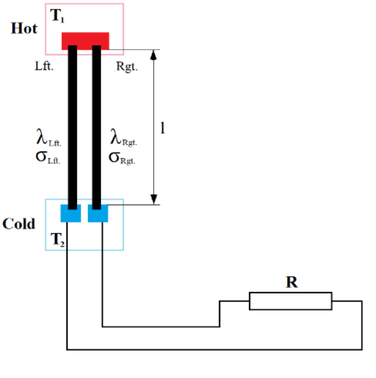

Fig. 5 - Seebeck element layout

If I take account of these losses, I will have:

$$P_\lambda^{conduction}t=Q_\lambda^{conduction}=\frac{\lambda_{lft.}\sigma_{lft.}-\lambda_{rgt.}\sigma_{rgt.}}{l}(T_1-T_2)t=\Psi(T_1-T_2)t$$

where $P_\lambda^{conduction}$, is the power transmitted through conduction, $\Psi=\frac{\lambda_{lft.}\sigma_{lft.}-\lambda_{rgt.}\sigma_{rgt.}}{l}$, and σ is the cross-section of the left and right side conductors and λ is the thermal conductivity of the left and right side conductors (figure 5).

$$P_{Joule}t=Q_{Joule}=I^2rt$$

where $r=\left(\frac{\rho_{lft.}}{\sigma_{lft.}}+\frac{\rho_{rgt.}}{\sigma_{rgt.}}\right)l$, and P_{Joule} is the power lost as Joule effect, and ρ is the resistivity of the conductors on the left and right side. If $\gamma=\frac{R}{r}$, I will have:

$$I=\frac{\alpha(T_1-T_2)}{r+R}=\frac{\alpha(T_1-T_2)}{r(1+\gamma)}\ ;\ Q_1^{rec.}=\frac{\alpha^2T_1(T_1-T_2)}{r(1+\gamma)}\ ;\ L_{cycle}=\frac{\alpha^2(T_1-T_2)^2\gamma}{r(1+\gamma)^2}\ ;\ Q_{Joule}=\frac{\alpha^2(T_1-T_2)^2}{r(1+\gamma)^2}$$

and then,

$$=\frac{\frac{\alpha^2(T_1-T_2)^2\gamma}{r(1+\gamma)^2}}{\frac{\alpha^2T_1(T_1-T_2)}{r(1+\gamma)}+\Psi L(T_1-T_2)-\frac{1}{2}\frac{\alpha^2(T_1-T_2)^2}{r(1+\gamma)^2}}=\frac{T_1-T_2}{T_1}\frac{1}{1+\frac{\Psi r}{\alpha^2}\frac{(1+\gamma)^2}{T_1\gamma}+\frac{1}{2}\frac{T_1+T_2}{T_1\gamma}}=$$

$$\eta_t^{Carnot}\frac{1}{1+\frac{\Psi r}{\alpha^2}\frac{(1+\gamma)^2}{T_1\gamma}+\frac{1}{2}\frac{T_1+T_2}{T_1\gamma}}$$

where: $z=\frac{\alpha^2}{\Psi r}$ is A.F. Ioffe coefficient $z=\frac{\alpha^2}{\lambda_{lft.}\rho_{lft.}+\lambda_{rgt.}\rho_{rgt.}\frac{\sigma_{rgt.}}{\sigma_{lft.}}+\lambda_{lft.}\rho_{rgt.}\frac{\sigma_{lft.}}{\sigma_{rgt.}}+\lambda_{rgt.}\rho_{rgt.}}$, and:

η_t is maximum when z is maximum (or 1/z → is minimum) but z depends on α, $\lambda_{lft./rgt.}$ which are the thermal conductivity coefficients and $\rho_{lft./rgt.}$ the resistivity of the conductors but also on $\left(\frac{\sigma_{lft.}}{\sigma_{rgt.}}\right)$ the ratio of the conductor sections, that is:

$$z'\left(\frac{\sigma_{lft.}}{\sigma_{rgt.}}\right)=0 \text{ when } \left(\frac{\sigma_{lft.}}{\sigma_{rgt.}}\right)_{(when\ z=max.)}=\sqrt{\lambda_{rgt.}\frac{\lambda_{rgt.}\rho_{lft.}}{\lambda_{lft.}\rho_{rgt.}}}\ and\ z_{max.}=\left(\frac{\alpha}{\sqrt{\lambda_{lft.}\rho_{rgt.}}+\sqrt{\lambda_{lft.}\rho_{rgt.}}}\right)^2$$

and for $\lambda_{rgt.}=\lambda_{lft.}=\lambda$ and $\rho_{rgt.}=\rho_{lft.}=\rho$ thus $z_{max.}=\frac{\alpha^2}{4\lambda\rho}$ (1)

Similar for η_t=maximum with respect to γ, denoted by $\gamma_{max.}$, where:

$$\gamma_{max.}=\sqrt{z\frac{T_1+T_2}{2}+1}\,, \tag{2}$$

and $\eta_t=\eta_t^{Carnot}\frac{1}{1+\frac{2(1+\gamma_{max.})}{zT_1}}$ or for z according to $\gamma_{max.}$ will have:

$$\eta_t=\eta_t^{Carnot}\frac{\gamma_{max.}-1}{\gamma_{max.}+\frac{T_2}{T_1}} \tag{3}$$

{and for $Q_{Joule}\approx 0$ I will have $\eta_t=\eta_t^{Carnot}\frac{\gamma'_{max.}-1}{\gamma'_{max.}+1}$ where $\gamma'_{max.}=\sqrt{1+z_{max.}T_1}$ }

If I make a comparative analysis of the three systems for converting thermal energy directly into electrical energy presented above, the conclusion drawn is that a Seebeck-type bridge thermoelectric converter is the best option, both from the point of view of costs and from the point of view of its applicability in aviation. Thus, bridges with low operating temperatures, between 200^{0}C and 1000^{0}C, which are currently mass-produced, can be used. Even if these Seebeck bridges have low transfer efficiencies (between 5% and 30%), considering that they are used to recover heat that is lost by conduction through the walls of the jet engine to the outside, they can be used as a cooling and insulating option for these surfaces. For the heat exchange carried out in the gas flow after the combustion chamber, with the role of replacing the gas turbine, materials that allow high operating temperatures, from 1500^0C to 2500^0C, and with higher efficiencies, from 30% to 60% are suitable. For this reason, I will present such materials, respectively, thermocouples material, in the next chapter.

2. SEEBECK MATERIALS [4], [5]

For mass-produced Seebeck bridges, the materials used are semiconductor metals alloyed and doped to form p- or n-type junctions. The semiconductor materials can be used up to maximum temperatures of approximately 250^0C. These can use an alloy of Germanium and Silicon, the first types of such bridges manufactured. Other types of generators can use alloys of Bismuth, Antimony and Tellurium, such as $(BiSb)_2Te_3$ and $Bi_2(TeSe)_3$. Germanium-Tellurium and Lead-Tellurium alloys can also be used. Newer research also uses other alloys, in which metals are used, as follows, but not limited to: Fe, Cs, Ca, Ce, Mn, Sn, Co, Ce, Ag, La, Nd, S, C, all of these alloys greatly improving the performance of these generators. For high temperatures, typical for the gas temperature of jet engines of this type, combinations of Nickel, Chromium, Silicon, Magnesium, Aluminum, Manganese can be used for temperatures up to 1200^0C, Platinum-Rhodium alloys for temperatures between 1500^0C and 1700^0C and Tungsten (Wolfram)-Rhenium for temperatures above 2300^0C [6] basically used for pyrometer technology. These last thermocouples can be used to recover energy from the gas flow after the combustion chamber, for which the calculated recovery efficiency is approximately 60%, but, due to the very high costs, they are currently used only for temperature measurement devices or for space technology. Recent research has used oxide-based materials for such generators, with operating temperatures comparable to those of high-melting-point metals.

3. CURRENT CASES OF THERMOELECTRIC CONVERTERS USE

Apart from the use in ground heat recovery installations, in thermoelectric power plants or industrial installations that release residual substance at high temperature, in which case magneto-hydro-dynamic generators can be used with good efficiency, I have found such systems, mainly Seebeck-type thermoelectric systems in the automotive sector.
These systems recover between 330W and 1000W on automobile, reaching values of 3000W to 5000W on truck train and vessel engines. The efficiencies of these systems, due to the lower operating temperatures, are between 10% and 30%. (ref.: [3] Automotive Thermoelectric Generators and HVAC, John Fairbanks, US Department of Energy).

4. EXPERIMENT ON TURBO-SHAFT JET ENGINE

I will make a numerical estimation for a Seebeck thermocouple of materials that I will use in the experimental verification presented in the following chapter corresponding to the generator used in the experimental part. For numerical calculation I used formulas (1), (2) and (3) presented in chap. 4.3. I will consider a parameter z between 0 and $5\cdot 10^{-3}K^{-1}$, and the estimated temperature differences will be between 0 and 260^0K, potential differences to be obtained with thermocouples in which materials with operating temperatures above 2300^0C were used, and at external temperatures typical of the stratosphere. I mention these generators that operate at lower temperatures can also be used to recover the heat lost by the engine through the housings of components with lower temperatures, but suitable for energy recovery as heat. With these data, after performing the calculations I present the values in Table 1, represented graphically in Figure 6:

Table 1 - TEG parameters values

z	η_t=	$\Upsilon_{max.}$=	
t2(cold)=	200	t1(hot)=	2600
0.00	0	1	
1.00	0.3118	1.5492	
2.00	0.4325	1.9494	
3.00	0.5014	2.2804	
4.00	0.5474	2.5690	
5.00	0.5809	2.8284	
t2(cold)=	200	t1(hot)=	1100
0.00	0.0000	1.0000	
1.00	0.1588	1.2845	
2.00	0.2489	1.5166	
3.00	0.3091	1.7176	
4.00	0.3531	1.8974	
5.00	0.3872	2.0616	
t2(cold)=	200	t1(hot)=	400
0.00	0.0000	1.0000	
1.00	0.0427	1.1402	
2.00	0.0750	1.2649	
3.00	0.1007	1.3784	
4.00	0.1218	1.4832	
5.00	0.1396	1.5811	

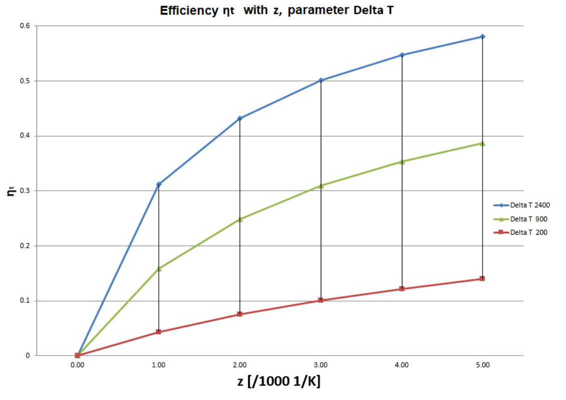

Fig. 6 - Efficiency η_t with z, parameter ΔT

5. EXPERIMENTAL VERIFICATION AND ESTIMATION OF ENERGY GENERATION FROM RESIDUAL HEAT FLOWN ON A TURBO-SHAFT JET ENGINE

To estimate the power lost through the outer walls of a jet engine, I used a Titan Gas Turbine T-62T-32 turbo-shaft jet engine, manufactured by the SOLAR Division of International Harvester Company, San Diego, California, a turbo-shaft jet engine that is used for military technology (APU: Auxiliary Power Unit, for various types of military helicopters) or on ground applications, such as ground generators (GPU: Ground Power Unit, used by the US Navy and USAF). The turbo-axial jet engine on which we conducted the experiment is used to power an ultralight helicopter, according to the identification plate (Figure 9, image on the helicopter). Here are some photos of this turbo-shaft jet engine (Figures 7 and 8, obtained with the support of: “SOLAR Division of International Harvester Company, San Diego, California”):

Fig. 7 - Turbo-shaft jet engine Solar installed on a GPU

Fig. 8 - View of a Solar turbo-shaft jet engine

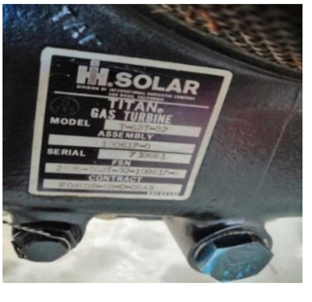

Fig. 9 - Identification plate of Solar turbo-shaft jet engine

Following the measurements, the temperature on the "hot" metal part of the exhaust diffuser was 158^{0}C on the “hot” side at 40% of power, and approximately 50^{0}C on the "cold" side, at the same engine load.

At maximum engine power, on the hot side I measured 222^{0}C on the “hot” side and a temperature of approximately 50^{0}C on the “cold” side.

I mention that the gases in the exhaust flow have a temperature of 362^{0}C at a 40% power load and 567^{0}C at a maximum power of 100%. I also mention that the external temperature at the time of measurement was 26^{0}C and the atmospheric pressure at the runway level was 1011hPa. The engine's thermal load was with stabilized parameters (the helicopter at takeoff parameters).

Below I present some photos (Figures 10 and 11) that confirm the above data:

Fig. 10 - Hot case temperature for 100% power.

Fig. 11 - Hot case temperature for 40% power.

To estimate the power generated I will use Eureca Seebeck thermoelectric generators, manufactured by Messtechnic GmbH, type TEG2-50-50-40/200, which have a maximum power of 40W and a maximum operating temperature of 200^{0}C, have dimensions of 50mm x 50mm x 3.3mm thickness and a weight of 38g. This is manufactured with a Bi_2Te_3-PbTe thermocouple, whose Ioffa coefficient is z=0.5·10-3K-1, according to [7] and the generator's data sheet, the thermoelectric potential (electric force) is 0.0516 V/K, the internal resistance is 0.673Ω, and the thermal conductivity of the plate is γ=1.90W/K. For these values I made the numerical estimation of the electric power generation as presented below.

For the experiment, I simulated the temperature of the turbo-shaft jet engine using an electrical resistance (smooth iron resistance) that I adjusted to heat up to a temperature of approximately 150^{0}C (so as not to destroy the Seebeck generator). I measured the electrical parameters of the generated electrical energy that supplies a consumer (20W/6V light bulb) of 20W, slightly higher than the maximum power generated by the Seebeck generator.

According to the Eureca graph for Seebeck bridge used (courtesy: www.eureca.de) for temperature differences ΔT with values of 200^{0}C, 100^{0}C and 50^{0}C, graphically represented in Figure 12 shown below:

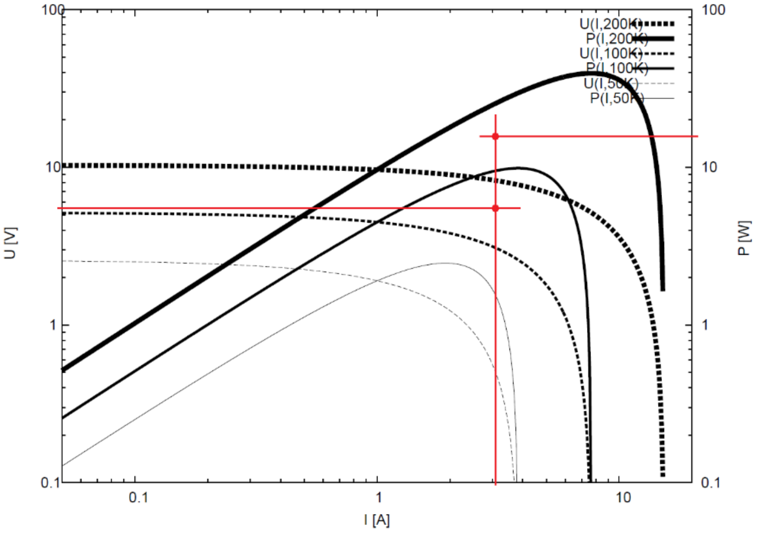

Fig. 12 - Equilibrium points for Eureca Seebeck bridge for Voltage and Power with Current

From Eureca data sheet from [2], the values for the Seebeck generator used are:

α = 0,0516 V/K;

ρ = 0,673 Ω;

λ = 1,90 W/K.

Following the experiment carried out to simulate energy recovery from the hot zone of the turbo-shaft jet engine, the following were measured, at a temperature stabilized at 154.0^{0}C: U=5.33V, I=3.56A for which P=18.98W results, and after approximately 2 minutes from making contact with the electrical resistance of the Seebeck generator, the generated electric current decreased to I=3.01A for which P=16.04W and it was stabilized.

I mention when the parameters are stabilized after a decrease in the generated power of approximately 15.49%. The experiment lasted 10 minutes.

Below are some photos from the experiment (Figures 13, 14, 15 and 16):

Fig. 13 - Simulated temperature

Fig. 14 - TEG voltage

Fig. 15 - Initial current

Fig. 16 - Stabilized current

6. CONCLUSIONS AND INTERPRETATION OF EXPERIMENTAL RESULTS

I have chosen this verification option because it would not have been technically possible to perform the verification on the turbo-shaft engine, first of all because the turbo-shaft is mounted on an ultralight helicopter, and at the maximum speed of the turbo-shaft engine, the Seebeck generator could be destroyed.

Thus, for a ground operating mode of the turbo-shaft engine at 40% of the maximum power, the temperature measured by me on the hot side is 158^0C, and the power is 44.0 kW.

The estimation of the power generated on a diameter of 54.293 cm (according to the technical sheet of the turbo-shaft) will be:

Perimeter: 54.293 x 3.141592 = 170.566 cm, on which 170.566: 5 = 34 pieces Seebeck plates can be mounted.

For the length of the hot side of approximately 50 cm, 340 Seebeck plates could be mounted, which will generate:

340 x 16.04 W = 5.454 kW.

This power represents 5.454: 44.0 = 12.40% of the turbo-shaft engine power at that speed that is a lost power through the walls of the turboshaft jet engine hot side. I cannot recover the energy from exhaust gases which is also a lost energy because I do not have Seebeck bridges suitable for this temperature.

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