THERMOACOUSTIC PROCESS FOR ELECTRICITY GENERATION IN SPACE

FRANCOIS M.-X.
HEKYOM, 3 rue de la Croix Martre – 91120 Palaiseau – France
E-mail of corresponding author: maurice-xavier.francois@hekyom.com

Abstract: To produce electricity dedicated for space applications, the heat source accessibility, the weight, the dimensions and the global efficiency of the proposed solution are of a great importance. One of the conventional solutions is to use the Stirling engine, which have been experimented for many years. However this technology seems to have a limited reliability related in particular to the moving parts. A breakthrough in the conversion processes could be the thermoacoustic (TA) technology where the thermal to acoustic power switch is occurring. In this paper, a brief explanation of the TA process and recent technology development are presented in order to underline the TA competitiveness, its advantages and its weaknesses. Moreover, a conducted experimental investigation on a new acoustic design prototype is presented: the results have shown a relatively high efficiency, however more efforts are needed to enhance the performance of this system. Thus finally, some improvement-keys are proposed to boost the electricity production for space applications.

1. Introduction

For more than 30 years, arousing interests have been dedicated to TA technology. Since no moving parts, no exotic materials and no close tolerance are required, the TA system is a simple, highly reliable and low cost promising solution to generate electricity. Moreover, TA engines can be designed in a way to operate with high heat temperature sources (up to 1000 K). However as any nascent technology, it has been always quite difficult to fund the required research program allowing quick progress in the understanding and the breakdown of technical and theoretical barriers. This may explain the relatively low development of TA process applications.

Stirling process, invented two centuries ago is still considered as one of the best, or the best, thermodynamic cycle and engine for heat driven energy production. But recently, some lack of reliability has appeared for long space mission. On the other hand, for the last twenty years many improvements have been accomplished in the design and construction of TA engine.

Even if most of the barriers are the same for the two technologies as heat supply or acoustic to electrical energy conversion, it is known that TA process may strongly improve the reliability by suppressing nearly all or even all the moving parts.

In this paper, the physical process of TA is described. In the second part, the new acoustic topology proposed by HEKYOM is presented; the results of the experimental investigation conducted on the prototype are given. Finally, key-improvements currently developed in HEKYOM are proposed.

2. Thermoacoustic technology

To perform a thermodynamic cycle supposes a proper phasing of the successive occurring transformations. In the Stirling engine, this phasing is provided by the mechanical component of the systems (e.g. reciprocating pistons, displacers etc...) each intervening at a proper time to build up a thermodynamic cycle. As for the TA systems, this phasing is ensured by the propagation of a wave, who takes in charge the role of the mechanical components in any conventional Stirling engine. Amplitude of the created wave in the resonant cavity of the system must be high enough to replace the piston, the displacer and the expander in the Stirling engines.

As any engine, the performance of the TA technology is firstly revisited based on Carnot's criteria.

2.1. Heat engine and Carnot criteria. A source at high temperature T_h delivers heat Q_h to the engine which will convert part of this heat into energy W (mechanical or acoustic, Fig.1a). The unconverted heat Q_c is withdrawn to the sink at lower temperature T_c. The Carnot factor ($\eta_c = 1 - \frac{T_c}{T_h}$) which limits the real efficiency $\left(\eta_r = \frac{W}{Q_h}\right)$ is presented in (Fig.1b) according to the high heat temperature. The relative real efficiency to Carnot is defined by: $\eta_{rc} = \eta_r/\eta_c$.

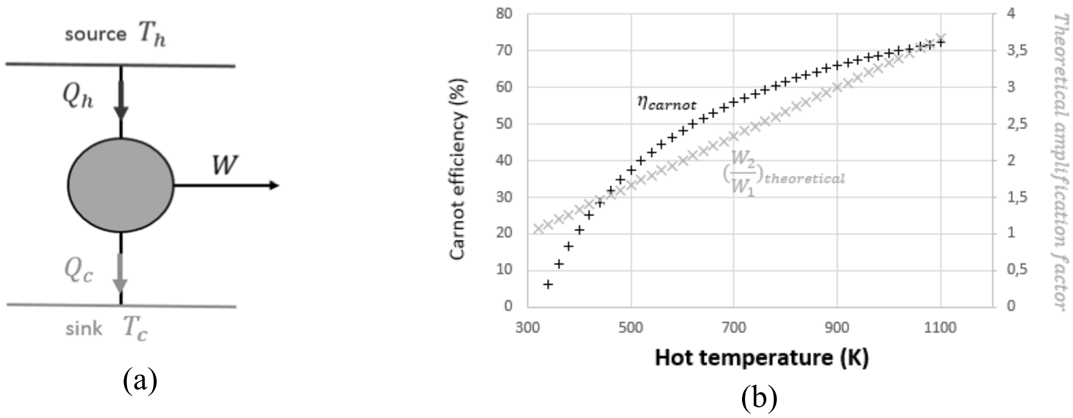


Figure 1: (a) Ideal presentation of an engine (b) Graph showing the variation of the Carnot efficiency and the theoretical amplification factor of a thermoacoustic cell related to the variation of the hot temperature (T_c=300 K)

Then, for a diesel engine, η_{rc} is of the order of 45%, as for many engines except probably gas turbine. Note that it is important to talk about global efficiency including all losses occurring in the process.

2.2. Thermodynamic cycle occurring in a thermoacoustic process (physics at meso scale). In general, TA is the coupling phenomenon of the sound wave propagation described by the motion, pressure and temperature oscillations and the oscillating heat transfer between the compressible fluid (gas in the most of cases) travelling within a small channel and the neighboring solid boundaries. The channel diameter d must be of the order of the interaction scale between an oscillating fluid wetting a solid wall. This scale is known as the thermal boundary layer (δ_κ) which is in practice of the order of 1/10 mm. to get a significative energy interaction, it is thus necessary to associate a maximum of couple boundary layer + wall in the available volume.

In a TA process, the conversion of thermal to acoustic energy takes place in a porous medium (of length L) called regenerator or stack. This device is sandwiched between two heat exchangers (HEXs) to form the heart of the engine called the wave amplifier (Fig.2). Connected to thermal reservoirs, the cold HEX connected to the sink at T_c and the hot HEX connecting to the source at T_h are able to maintain a temperature gradient (ΔT), along the regenerator or stack. Due to this temperature gradient a sound wave is able to be amplified by extracting the heat (Q_h) from the hot source and evacuate the unconverted residual heat (Q_c) to the cold sink. Actually the motion wave of amplitude (2ξ) displaces the parcel of the working fluid in a way that the parcel of gas experiences compression and expansion depending on the oscillation in pressure while it is exchanging heat with the solid boundaries in the porous media. As such, the gas parcel will undertake a thermodynamic cycle and acoustic power is pumped by the wave generator. To be efficient, L must be 5 to 10 times the amplitude of the motion wave (2ξ). It is known that such a device can be used to onset and amplify the wave generation in a resonant cavity as well as to amplify a propagating wave passing through.

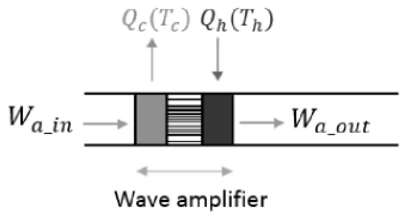


Figure 2: Scheme of a thermoacoustic wave amplifier. Acoustic characteristics are imposed by the resonant or not cavity boundary limits.

In a standing wave heat engine with a stack of plate, the oscillation pressure is about 90° out of phase with the oscillating velocity. In the stack the gas parcel experiences compression or expansion while it is displaced within a peak-to-peak distance (2ξ). Heat transfer occurs when the gas parcel is only tracing the limit of the boundary layer: the distance from the solid surface is approximately equal to (δ_κ). The fluid parcel undergoes a Brayton Cycle which is known to be irreversible in theory.

In a travelling wave heat engine, the oscillating pressure is in phase with the oscillating velocity. In the regenerator an enhanced thermal contact between the gas parcel and the solid surfaces is ensured by the small hydraulic ratios: y<< δ_κ; inevitable viscous losses in the solid matrix of the regenerator make the theoretical perfect thermal heat exchange impossible. The gas parcel travels along the channel within a peak-to-peak distance (2ξ) inside the thermal penetration depth, exchanging heat isothermally in each location of the regenerator. The fluid parcel undergoes a Stirling cycle which is known to be reversible in theory.

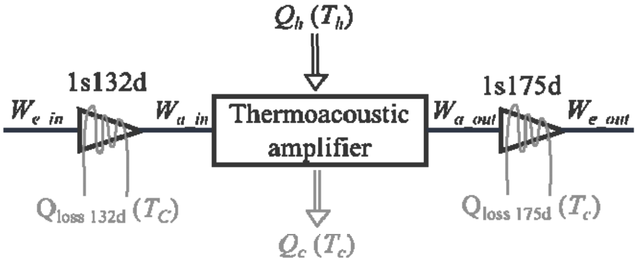
2.3. Acoustic topologies for thermoacoustic engine making. For space application, a great importance is accorded to the compactness which is defined as the ratio of the net output power to the internal system volume. Both, the increase of efficiency of conversion process and the decrease of the machine's dimensions, enhance the compactness of the TA system. On the other hand, it is important to pay attention to the acoustic losses associated with the type of resonator and also to the coupling efficiency to the load which is specific for each configuration. The TA systems developed in the past can be classified in four categories as proposed by K.de Blok in a very clear paper relative to acoustic losses and coupling aspects corresponding to these geometries: a standing-wave resonator, a standing wave resonator with Helmholtz resonator, an acousto-mechanical resonator and a multi-stage travelling wave system [1, 2, 3, 4].

2.4. Thermoacoustic wave amplifier. The following scheme (Fig.3) gives a representation of a TA amplifier, where 'in' and 'out' refer as the input and output electric (W_e) or acoustic (W_a) power.

If ρ_{1s132d} and ρ_{1s175d} are respectively the 1s132d and 1s175d Qdrive efficiencies, it is easily to obtain $W_{e\_in} = W_{a\_in}/\rho_{1s132d}$ and $W_{a\_out} = W_{e\_out}/\rho_{1s175d}$. In Fig.3, α and η_{rc} refer respectively to the imperfect amplification and Carnot efficiency of the amplification.

As seen above the acoustic gain is limited to the ratio of hot T_h and cold T_c heat sources temperature. For a nuclear energy source at T_h =1100 K, this ratio can be of the order of 3 (Fig.1b).

The net maximum acoustic benefit $W_{a\_out} – W_{a\_in}$ is then 2xW_{a_in}. It appears clearly that with two amplifiers supplied by an identical T_h heat source, the net acoustic gain would be 8xW_{a_in} and so on.



$$\frac{W_{a\_out}}{W_{a\_in}} \leq \frac{T_h}{T_c} \qquad \frac{W_{a\_out} - W_{a\_in}}{Q_h} \leq 1 - \frac{T_c}{T_h}$$

$$\frac{W_{a\_out}}{W_{a\_in}} = \alpha \frac{T_h}{T_c} \qquad \frac{W_{a\_out} - W_{a\_in}}{Q_h} = \eta_{rc}\left(1 - \frac{T_c}{T_h}\right)$$

$$\alpha < 1 \qquad \eta_{rc} < 1$$

Figure 3: Scheme of the thermoacoustic wave amplifier developed at HEKYOM [5], where 1s132d and 1s175d are electroacoustic transducers from the manufacturer Qdrive

3. One way to take benefit of thermoacoustic process: the HEKYOM acoustic topology

An acoustic power of the order of 10 kW produced by a standing wave engine requires a low frequency, thus a greater length of the machine and therefore make the standing wave out of scope for space applications. The resonant travelling wave developed by K. de Blok can be considered for space application however compactness must be revisited [4].

A new acoustic topology has been developed in HEKYOM. The prototype funded by AIRBUS has shown a very satisfying result. The one stage TA amplifier shown in Fig. has a relatively high efficiency. Experimental data will be discussed in the subsection 3.2. The final aim is to obtain a compact machine with a higher efficiency compared to photovoltaic power. To prove it, one stage amplifier was considered as a sufficient positive proof.

3.1. Description of the prototype. A wave, generated by an electroacoustic generator Qdrive 1s132d (top of Fig.4a) is propagating through a TA cell which acts as a sound amplifier converting heat into acoustic energy. The amplified wave drives another electroacoustic converter 1s175d (bottom of Fig.4a) working in inverse mode.

The prototype was designed to receive heat at temperature up to 950°C. The TA cell is shown in Fig.4b, with its cold heat exchanger+ regenerator+ hot heat exchanger followed by the buffer tube and the ambient heat exchanger protecting the second Qdrive 1s175d (not shown). The white material is a nanoporous material from PROMAT industry which insulates the system and avoids the heat leaks. In order to insulate correctly the heater (simulated by joule effect), a double tubing was designed, the outer one being filled by nitrogen gas at the same pressure than the inner one where is the TA system. Unfortunately, the heater made in Molybdenum was not perfectly soldered by the manufacturer and the 2 vessels were obliged to be filled with helium gas carrying nearly 20% of heat losses.

3.2. Experimental results. Extensive experimentations were performed using a RC load, the capacitance compensating the Qdrive inertance. One varies as well the input acoustic energy, the frequency, the heat power corresponding to a given hot temperature. Comparisons with our calculation made with our software CRISTA [6] give a pretty good agreement (Fig.5). As an example, data for a run near 700°C are reported in Fig.4c. It can be noticed that for that run:

- ρ_{1s132d} = 74.2% and ρ_{1s175d} = 78.9% which are much lower than the expected values (85% for both) promised by Qdrive. 77.1 W and 122.3 W of heat losses are evacuated by water circuit respectively from the 1s132d and 1s175d;
- α = 80.7% which is a correct value in agreement with our calculation ;
- the heat losses due to the impossibility to surround the helium tube at 30 bars by a nitrogen gas filled tube are important and nearly 200W;
- the real efficiency relative to Carnot is no more than 55.1% because the heat losses;
- as these losses may be considered as easily avoided, the expected efficiency could have been 69.8%;
- the thermal efficiency is given by $(W_{e\_out} - W_{e\_in})/Q_h$ which corresponds to 17.6 % for this hot temperature of 700°C;

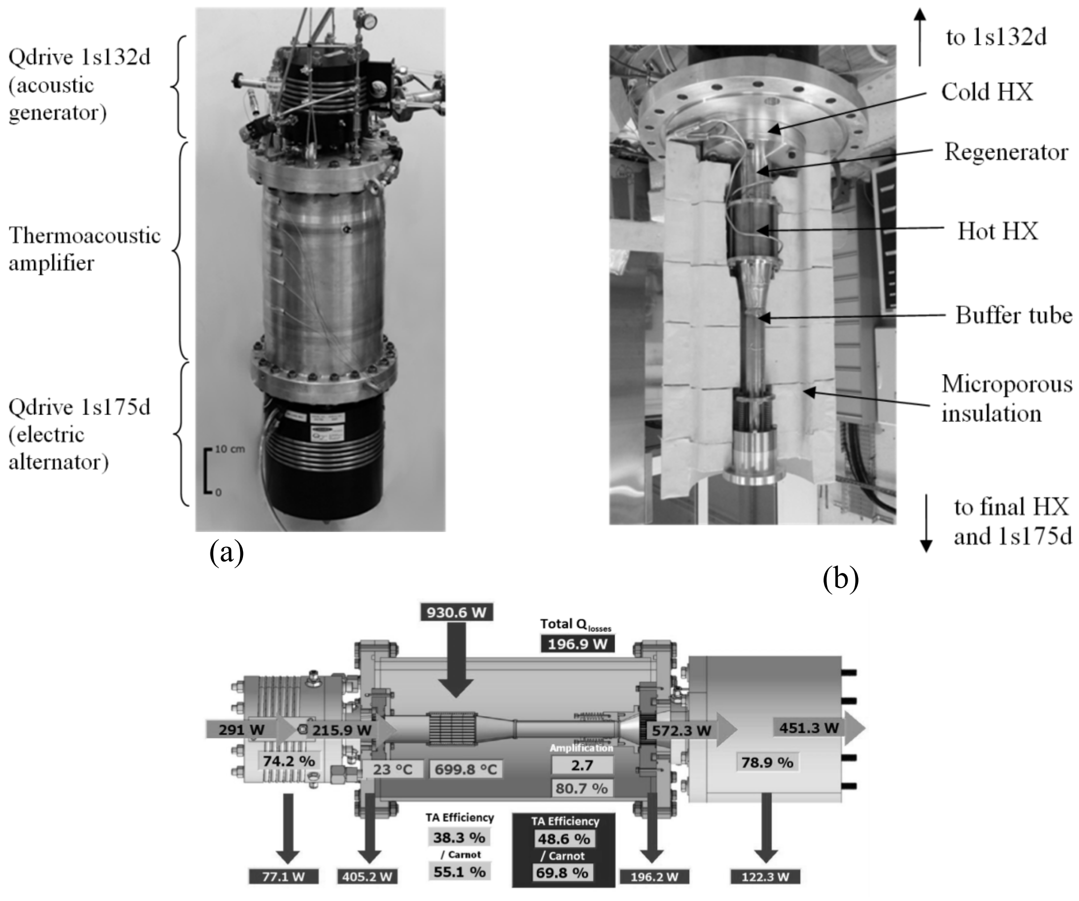


Figure 4: (a) Picture of the thermoacoustic system developed by HEKYOM (b) Internal picture of the thermoacoustic system (c) Scheme of the energetic balance of the system at 700°C.

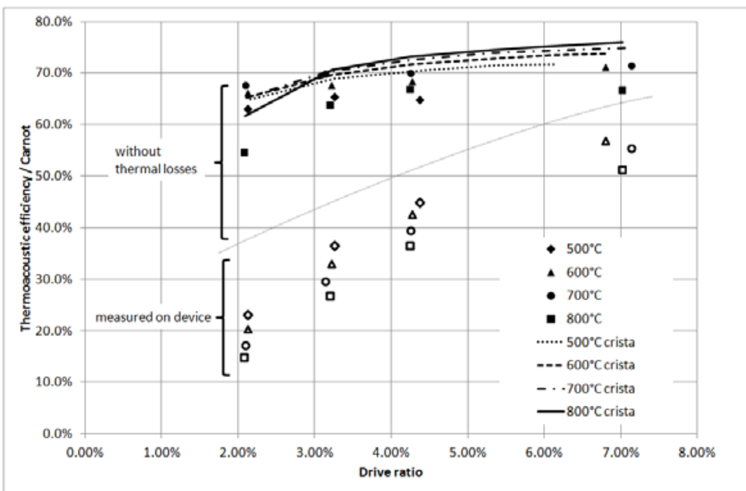


Figure 5: Efficiency of the thermoacoustic amplifier. To compare with the simulation software CRISTA, thermal losses are deduced to the experimental values

- taken in account the expected value of Qdrive efficiency (85%) and suppressing heat losses (not acoustic losses), the thermal efficiency would have been 36%;
- The figure shows the efficiency of the TA part relative to Carnot efficiency versus the drive ratio. Increasing the input acoustic power increases the drive ratio. Due to the limitation in current and stroke for the 1s132d Qdrive, it was not possible to exceed 7%.

In conclusion, the system works very well. It would be possible to improve the Qdrive efficiency, Qdrive manager said. It is reasonable to consider the heat losses as circumstantial. The very good agreement between data and calculation confirms that there is no streaming in such an acoustic configuration.

4. How to improve the thermoacoustic generator

We may propose several available modifications:

1. First of all, it is evident that the efficiency will increase if we used 2 or 3 amplifiers in series. In that case the input acoustic energy could be diminished quite much.
2. The computation has been already done and a prototype is under construction
3. The thermal insulation could be very much improved
4. The buffer length was chosen too large and a 2 stages system will be nearly of the same total length

We may indicate some new technique to be looked at. Some of them will be presented at the conference.

1. The output Qdrive is limited in capacity to 2x15kWe. Another technique converting acoustic energy into electrical energy consists using a bi-directional turbine associated to a rotating alternator. This has been already successfully tested at small acoustic energy of the order of one $kW_{acoustic}$ by K. de Blok [7].
2. The Qdrive technic must be improved and lighter material must be used in the manufacturing. Other approach could be thought for the electrical conversion concept. A system study has been performed by AIRBUS Group with the participation of HEKYOM. Results will be presented at the conference [8].
3. TA system can be used for moving a conductive liquid as Na. Space TRIPS European FP7 project is in progress.

For Space application it is clear that the problem of heat source is not yet solved except using nuclear heating source. Improvements still need to be done in order to be able to catch and transfer solar energy with a light and reliable way. Some interesting new idea will be presented at the conference also by AIRBUS Group.

5. Conclusion

In conclusion, TA process seems likely to be a good partner for electricity generator in space. Even if many improvements have to be done, the concept used by HEKYOM has proved to be efficient.

6. Acknowledgements

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7. References

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