# The MHD generator - Thermoacoustic engine interface

Kees de BLOK[1], Maurice-Xavier FRANCOIS[2], Armands KRAUZE[3]

[1] Aster Thermoacoustics, Smeestraat 11, 8194LG Veessen, The Netherlands
[2] Hekyom, 3, rue de la Croix Martre, 91120 Palaiseau, France
[3] Institute of Physics, University of LATVIA, Miera str.32, Salaspils, LV-2169, Latvia

e-mail address of corresponding author: c.m.deblok@aster-thermoacoustics.com

**Abstract** :
Driving a MHD generator by a thermoacoustic engine is a promising concept concept without any moving mechanical parts. Because of the density of the conducting fluid in the MHD generator exceed largely the density of the thermoacoustic working gas transferring energy from the acoustic wave towards the moving fluid columns is a real challenge. Transferring a certain amount of acoustic power to such a high impedance requires a high acoustic pressure amplitude. This is not the preferred working condition for thermoacoustic engines which by default operate at less than half the pressure amplitude needed to power the MHD generator. This paper address the design of the acoustic interface between a thermoacoustic engine and a MHD generator.

## 1. Introduction

Thermoacoustics is a key enabling technology for the conversion of heat into acoustic (= mechanical) power. Nowadays, thermoacoustics in itself well understood and has proven to be an generic applicable and efficient conversion technology. This however, is only part of the story. For practical and economic viable applications the interface with the outside world is found to be even more important. Two major issues has to be solved, in a practical and cost effective way, to bring thermoacoustics to successful applications. (1) Heat to be converted need to be supplied at high or medium temperature and rejected at a lower temperature from the process with minimal temperature loss and (2) The generated acoustic (wave) power, which is proportional with input- heat and temperature, has to be converted into electricity in a scalable and efficient way.

Focus of this paper is on the conversion of the acoustic power generated by a thermoacoustic engine into electricity by an MHD generator in which the acoustic driven, periodic movement of a conducting fluid in a magnetic field convert the acoustic wave energy into electricity.
Main issue for this design is that the density of the (moving) conducting fluid in the MHD generator largely exceed the density of the thermoacoustic working gas. In acoustic terms, the high acoustic impedance of the MHD generator need to be matched to the lower impedance of the thermoacoustic engine. Transferring a certain amount of acoustic power to such a high impedance requires a high acoustic pressure amplitude while at the same time the actual fluid displacement and velocity is relatively low.

## 2. Acoustic impedance MHD generator

For this work we will consider the data available for a small scale MHD generator designed for having an electric output power of about 270W. This data is given in Table 1.

*Table 1 Typical data of a 270W high amplitude MHD generator.*

| | | | | | | |
|---|---|---|---|---|---|---|
| Mass | kg | 0.395 | | Melt velocity vz | m/s | 8.88 |
| Frequency | Hz | 50 | | Pressure drop re ($\Delta p$) | kPa | 42 |
| Efficiency MHD | - | 0.75 | | Pressure drop im ($\Delta p$) | kPa | 598 |
| Volume flow rate $U$ | $m^3/s$ | 0.016 | | Pressure drop $\lvert\Delta p\rvert$ | kPa | 600 |

According to Table 1, the acoustic impedance at the MHD generator input is

$$Z_{MHD} = \frac{\Delta P}{U} \qquad \text{N.s.m}^{-5} \quad (1)$$

This highly complex impedance (inertance) is independent of the gas type and mean pressure. Using the data in Table 1 gives for the absolute value of the acoustic impedance of the MHD generator $Z_{MHD} = 6e^5 / 0.016 = 37.5e^6$ N.s.m$^{-5}$.

## 3. Acoustic impedance thermoacoustic engine

The acoustic impedance of a thermoacoustic system is given by

$$Z_a = \frac{\rho . c_0}{A_0} \qquad \text{N.s.m}^{-5} \quad (2)$$

In which ρ is the density of the gas, $c_0$ the propagation velocity and $A_0$ the reference cross-sectional area of the acoustic resonance and feedback circuit of the thermoacoustic engine.

Default working gas for TA systems is helium at 4 MP mean pressure. Regenerator (or reference) diameter for a single stage standing wave resonator thermoacoustic engine able to deliver 330 W acoustic power is about 90 mm. Using these numbers, a typical value for the real acoustic (source) impedance of the TA engine $Z_a$ = 6.47 kg.m-3 *1012 m.s$^{-1}$ / 0.064 m$^2$ = $1.02e^6$ N.s.m$^{-5}$ which is significant lower than the acoustic (load) impedance of the MHD generator. In an acoustic system a step in impedance introduce a partial reflection of the forward propagating wave which means that only part of the wave is absorbed by the load. This reflection coefficient (r) defined as the ratio between reflected and forward wave is given by

$$r = \frac{Z_{MHD} - Z_a}{Z_{MHD} + Z_a} \qquad (3)$$

Which gives for the reflection coefficient a value of r = 0.95. Consumed power by the load is given by

$$P_{ac\_load} = P_{ac\_source} . (1 - |r|^2 \quad (4)$$

Which implies that only 0.1 of the acoustic source power is or can be consumed by the MHD generator for conversion into electricity.

## 4. Working gas

In general, for thermoacoustic systems, helium as chosen as working gas by default. For some applications however it is worth to consider another gas type. Because of the thermodynamic cycle in the traveling wave driven thermoacoustic process is nearly reversible, the efficiency in theory is independent of the working medium. In practice however some irreversibility remains and these irreversible loss terms are dominated by the γ value of the gas. In order to minimize this loss terms the γ value therefore should be high as possible which limit the choice to (inert) gasses or argon having a γ value around 1.6.Due to the higher density of argon the acoustic propagation speed is lower than for helium which means that for the same frequency (50Hz as required by the MHD generator), the length of the acoustic tubing could be made proportional shorter. As compared to helium, for argon the acoustic power density is less, which implies that at the same pressure amplitude or drive ratio the cross-sectional area of feedback loop and regenerator-hex unit need to be increased to get the same acoustic output power. In other words, length will reduce and diameters increase for the same acoustic power, cycle efficiency and oscillation frequency.

## 5. Dual TA engine driven MHD generator

From the data given in Table 1 the required pressure amplitude to drive the MHD generator is about 600 kPa. Driving the MHD generator from one side, assuming no back pressure at the other side, means that at 4 MPa mean pressure the TA engine drive ratio has to be 15%. Such a high drive ratio is hard to reach efficiently with a single stage TA engine because of the high associated acoustic losses [1,2].

Because of the MHD generator is symmetric in nature, an option to solve this limitation, is to drive the MHD generator from each side, both with half the pressure amplitude and opposite phase. Such a configuration could consist of two identical TA engines mutually coupled by the (impedance of) the MHD generator. Problem with this configuration however is that both (independent) TA engines tend to oscillate in phase [3], consequently eliminating the pressure difference across the MHD generator.

In order to force both engines to run in opposite phase they need to be coupled acoustically by sharing (part) the same resonance or feedback circuit. This can be done as follows. *Figure 1* shows a basic traveling wave TA engine consisting of a regenerator clamped between the high and low temperature heat exchanger. In this type of traveling wave engine reduction of gas velocity is obtained by increasing the regenerator-heat exchanger diameter with respect to the acoustic circuit diameter instead of impedance enhancement by interfering waves [4]. Losses of these diameter transitions are more than counterbalanced by the small feedback tube diameters and lower amplitude in traveling waves [5,6]

Input reflection of the section is minimized at 50 Hz by adding an impedance matching network ($L_2$, $L_3$). This is shown in *Figure 1*

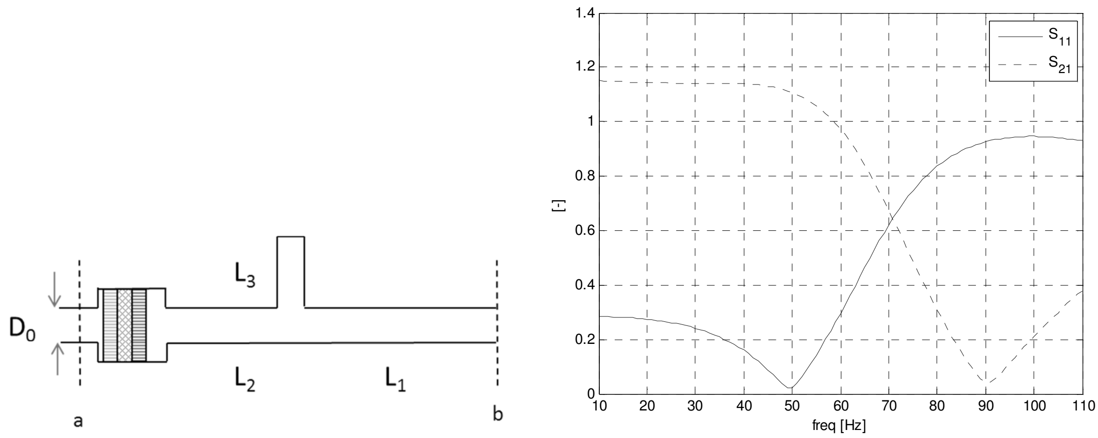


*Figure 1 Traveling wave TA engine with input reflection (s11) at reference plane a, minimized by position ($L_2$) and length ($L_3$) of the acoustic matching stub (compliance)*

*Figure 1* shows that at the operating frequency of 50Hz the reflection ($s_{11}$) at the input (a) is minimized and that forward gain ($s_{21}$) exceeds one, which is an essential condition for oscillation. The length of $L_1$ is chosen such to make the acoustic length between reference planes a and b equal to ½ λ. So when connect b to a by a ½ λ long feedback tube we get a total of 2π radians phase shift and if the temperature is above onset, a (near) traveling wave will be generated and maintained in this loop.

Replace the ½ λ feedback tube by and identical TA section with an equivalent acoustic length of ½ λ then the circuit has the same acoustic feedback lengths but with double thermoacoustic gain. This is depicted schematically in **Fout! Verwijzingsbron niet gevonden.**.

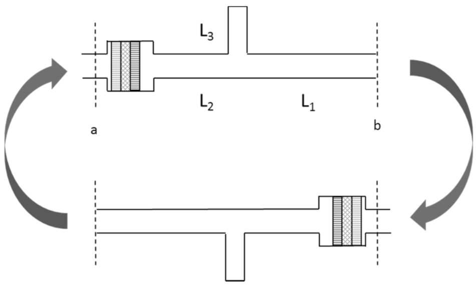


*Figure 2 Two coupled TA engines*

Because of the input reflection of both engines is minimized they acoustically terminate each other with an impedance close to ρ.c, yielding a traveling wave in the feedback loop. Traveling wave feedback has the advantage of transferring maximum acoustic power ate the smallest possible tube diameter and lowest pressure amplitude yielding the lowest acoustic losses [2,6]. Further the phase develops proportional with position along the loop, which means that at "mirrored" positions the pressure amplitude has opposite phase.

Therefore both terminals of the MHD generator will connected to opposite positions along the (traveling wave) acoustic feedback circuit. Because of the pressure amplitude at opposite positions has a mutual 180° phase shift, the pressure amplitude difference across the MHD generator will be twice the pressure amplitude or drive ratio at each individual engine stage.

In principle the high impedance MHD generator can be coupled everywhere in the circuit but an option to eliminate additional T-junctions is to connecting them between the end of the compliant stubs ($L_3$). The final configuration then looks as depicted in *Figure 3*

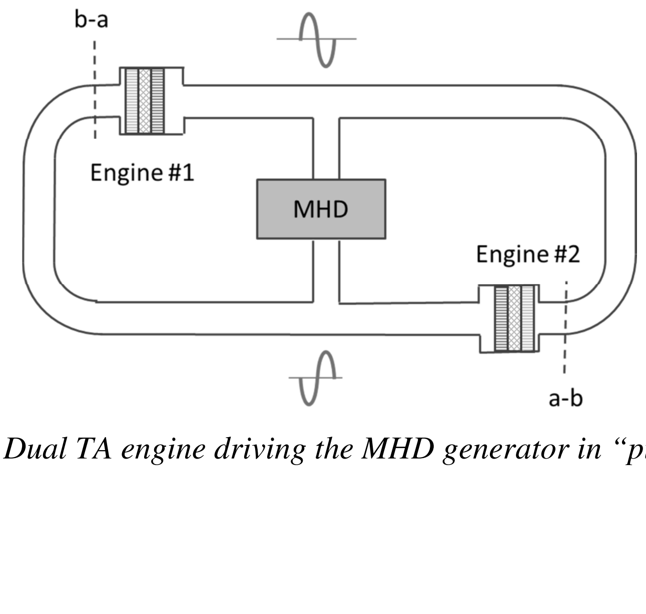


*Figure 3 Dual TA engine driving the MHD generator in "push-pull" mode*

Simulations for the configuration of Figure 3 shows that due to the “transformation function” of the acoustic circuit ≈ 620 kPa is generated across the across the MHD while the cold hex pressure amplitude of the TA engine is ≈ 110 kPa (drive ratio 3.3%). For an input temperature of 995K and a heat rejection temperature of 400K the thermal efficiency (without static heat losses) is calculated to be 35% which corresponds to an exegetic efficiency of 58%. From the simulations it is also observed that efficiency with argon as working gas could be as good as for helium.

## 6. Conclusions

Driving a MHD generator by a thermoacoustic engine yield an attractive concept without any moving mechanical parts. Initially the difference in acoustic impedance between MHD generator and thermoacoustic engine cause that only 10% of the engine output power can be consumed by the MHD generator

In this paper a geometry is proposed which match both impedances both by and alternative geometry using a dual stage thermoacoustic engine and by using a more heavy working gas

In this configuration the MHD generator is driven in “push-pull mode” by two traveling wave thermoacoustic engine stages. This way a high pressure amplitude is generated across the MHD generator while at the same time the thermoacoustic engine operates at a much lower pressure amplitude.

For this application argon instead of helium is considered as working gas and is found to strongly reduce acoustic tube length yielding a more compact device for the same power and efficiency

## 7. References


[1] Backhaus, S. & Swift, G. W. (2000): A thermoacoustic-Stirling heat engine: Detailed study. Journal of the Acoustical Society of America, 107[6], pp. 3148-3166, 2000.

[2] Kees de Blok, Hassan Tijani, Thierry Le Pollès. “Report on minimizing acoustic losses”. THATEA project deliverable D1.2, 2009.

[3] P. S. Spoor and G. W. Swift "The Huygens entrainment phenomenon and thermoacoustic engines,", Journal of the Acoustical Society of America 108, 588-599 (2000).

[4] Blok, C.M. de & Rijt, N.A.H. van: Thermo-acoustic system, 1997, WO 99/20957, US 6,314,740 B1

[5] B.L Smith, G.W. Swift. “Power dissipation and time-averaged pressure in oscillating flow through a sudden area change” J. Acoust. Soc. Am. 113 (5), May 2003. p2455-2463.

[6] C.M. de Blok, “Low operating temperature integral thermo acoustic devices for solar cooling and waste heat recovery”, Acoustics’08, Paris. PA15