Multiphysics Analysis of a Thermo Acoustic MHD Inductive Generator

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Abstract: This paper fits in the multi-physics analysis of an innovative conceptual design of Magneto-Hydrodynamic (MHD) inductive generator, coupled with a Thermo-Acoustic (TA) resonator. The thermo-acoustic effect occurs when an intense gradient of temperature is present along the axial direction of a duct containing a gas. Such effect allows the heat to be statically converted into mechanical energy of vibration. If the gas is ionized and the charges of opposite sign are separated into two clouds, an alternate electric current is associated to the thermo-acoustic vibration. That current, in its turn, can induce an electromotive force into a magnetically coupled coil. In this way, a thermo-electric conversion is performed, without solid moving parts or matter transport. A FEM analysis has been performed to assess the suitability of the complete energy transformation chain. In particular, the possibility that the charge carriers are involved in the vibration motion is investigated. An acoustic analysis has been done, in a glass tube containing a ionized gas, in order to study the velocity profiles within the duct in presence of viscous and thermal effects. Then, a multiphysics simulation has been performed by using the same geometry, by coupling the acoustic module with the electrostatic module, and the particle tracing module, in order to study the behavior of the unbalanced charge carriers when they are subject to a vibration and to an electric force, for a given set of design parameters.

Keywords: MHD, EHD, Induction, Thermo-Acoustic, Particle Tracing, Electric Field.

1. Introduction

The Magneto-Hydrodynamic (MHD) energy conversion have aroused the interest of the Industry all along the second half of the past century, due to the fact that this kind of energy conversion is performed without any mechanical moving parts [1, 2]. In the process, a conducting fluid (plasma) passes through an intense magnetic field, giving rise to an electrical current induced in the plasma, which can be retrieved by means of two electrodes immersed in the fluid, and connected to an electric load.

The main drawbacks of traditional MHD generators are the high temperatures necessary to properly ionize the gas, the high magnetic field (about 5 T), and the rapid deterioration of the electrodes for electric current extraction.

In [4, 6] two different designs of MHD generators are proposed, which avoid the cited limits, both of them combining the thermo-acoustic effect [3] with MHD and magnetic induction. In [6] the thermo-acoustic vibration of the gas is hand over to a liquid metal, through a solid interface. The liquid metal is immersed in a magnetic field generated by a permanent magnet. In fact, the high conductivity of the liquid allows to adopt low values of magnetic field. The vibration of the liquid induces an alternate electric current, which by induction causes an electromotive force into a magnetically coupled coil. The system in [4] (see Fig. 1) represents an evolution of the previous described one. The liquid metal and the permanent magnet are removed, and the primary current is created in the gas itself, by ionizing it with an electrical discharge and separating the two clouds of opposite charges. In order to maintain the two clouds separated, an electrostatic field is applied by means of two plates. In order to confine a sufficient quantity of charges with a reasonable applied voltage, the surface of the plates has to be maximized. The present work aims to develop a model of the behavior of the unbalanced charge carriers when they are subject to a vibration such as that one produced by the thermo-acoustic effect. A multi-physics analysis has been necessary, where the acoustic phenomenon is coupled with the electrostatic analysis and the particles tracing.

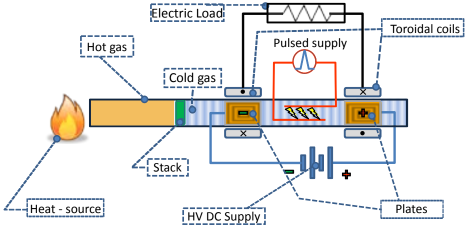

Figure 1. Setup functional scheme.

This paper is organized as follows: in Section 2 the TA-MHD generator functioning and the specific analyzed problem are briefly described, in Section 3 the adopted multi-physics approach is roughed out, in Section 4 the equations governing the handled problem and the corresponding modules of Comsol® used for the analysis are listed, in Section 5 the model of the system is described, in Section 6 the obtained numerical results are reported and, finally, in Section 7 it is explained how the results could help in the dimensioning and simulation of the whole TA-MHD generator.

2. Theory

The TA phenomena occurs when a high gradient of temperature is present in the longitudinal direction of a duct containing gas. This phenomenon is known for centuries, as it was observed by the glass blowers during the shaping process of glass vases. On the other hand, only in the recent years the phenomenon has been explained. In the case of the blown glass preparation, the thermal gradient is due to the fact that in one end the temperature has to be so high to melt the glass, while in the other end the temperature has to be so low to be tolerated by the man. In order to obtain a high gradient of temperature one can put a stack inside the duct with a large surface. The use of this stack gives more degrees of freedom in defining the design parameters of the resonator. The thermo-acoustic effect represent a direct conversion of heat into mechanical work, without solid moving parts. Usually, the mechanical energy associated to the vibration is converted into electrical energy by means of piezoelectric crystals, in this way realizing a totally static thermo-electric conversion. In [4, 6], the second stage of the energy conversion is performed by means of an MHD process. This makes it possible to strongly increase the power level.

In [4] the gas subject to the thermo-acoustic vibration is first ionized and then the charge carriers of opposite sign are segregated. The ionization of the gas is obtained by means of one electrical discharge, which is created at the beginning of the process by means of a pulsed high voltage generator. The charge carriers are then separated by means of a stationary external electric field, which is applied through two plates with a very high ratio surface/volume. Such characteristic derives from the need of high capacitance, so that the DC voltage to apply to confine the charge carriers could be reasonable. Since the stack has to have the same characteristic to prime the thermo-acoustic effect, it is reasonable that the same element plays both the roles of stack and plate. The ions are confined in a first stack and the electrons in a second one. The electric field maintains the charge carriers in a dynamic equilibrium. When the thermo-acoustic vibration occurs, the charges participate to the oscillating motion, giving rise to an alternate electrical current. Such current induces an alternated electromotive force in two coils surrounding the duct, wrapped all around two toroidal ferromagnetic cores. Finally, this coils are connected to the electric load. It is possible to adjust voltage and intensity of the induced current by properly choosing the number of turns of the coils. In Fig. 2 the layout of the generator is shown.

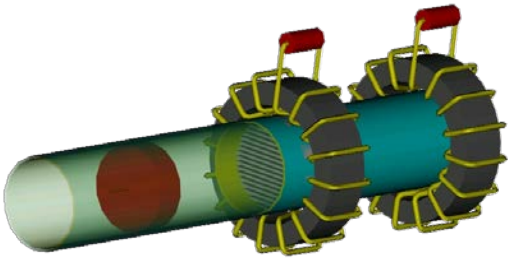

Figure 2. Layout of the generator

In [4] the results of a preliminary analytic study have been reported in order to propose a simplified theory about the performances of the generator and, therefore, to give the design criteria. In particular, in a first approximation the parameters of the generator for a given set of requirements have been stated considering a real case scale, and a demonstrative facility. The order of magnitude of design parameters obtained in that first study has been used in this paper to model and simulate the system.

One of the most critical aspects of the system concerns the mobility of charge carriers during the gas vibration occurrence. In fact, as it is well known [7], the electrostatic field cannot have stationary points of the potential, therefore the charges are attracted towards the wall of the plate, but the velocity of particles vanishes in the vicinity of the wall, therefore also the ionic current should be zero. On the other hand, contrary to what happens in the metals, the charge carriers in a gas cannot stick on a wall, because the mutual repulsive force among them is not compensated by the electrical field provided by a crystal structure. The combination of these two effects causes the charge carriers to be in permanent agitation, and the second effect makes the charge concentration to vanish near to the wall.

The aim of this study is developing a multiphysics model of the gas, which takes into account both the acoustic and electric phenomena, in order to assess if a considerable quantity of charge remains out of the viscous/thermal boundary layer, and then could give rise to an electric current when the thermo-acoustic effect takes place. The velocity profile in the cross-section of a rigid cylinder traversed by a wave is totally determined by the shear wave number [5]. By acting properly on the parameters, the velocity profiles can be modified as needed.

3. Methods

The studied process combines different physical phenomena: thermo-acoustic effect, gas ionization and confinement, electromagnetism, fluid mechanics, and heat transfer. Based on the theoretical study of the device in [4], a FEM analysis has been performed to simulate some aspects of the system functioning. First of all an acoustic analysis has been done in order to study the velocity profiles within the duct. The objective is to confirm the theoretical results from literature, or rather that the axial velocity is null close to the walls due to thermal and viscous losses, and that it shows, for high values of the shear wave number, a profile that is almost completely flat, with small peaks next to the tube wall (Fig. 3).

Hence, by acting properly on the involved parameters, it is possible to modify the velocity profiles as needed. The goal has been to obtain the highest velocity where the charge is thickened, in order to maximize the magnetic induction. In fact, both the velocity and the charge density are non-uniformly distributed along the cross-section, therefore, if most part of charge carriers are concentrated in zones with null velocity, the conversion process cannot take place. Furthermore, a second multiphysics simulation has been performed, which combines the acoustic module (without thermal and viscous losses, to reduce the computational time) with the electrostatic, and the particle tracing modules. A special attention is paid to the phenomena occurring in the volume where the charges are confined, therefore the thermo-acoustic effect is treated here as an external pressure source.

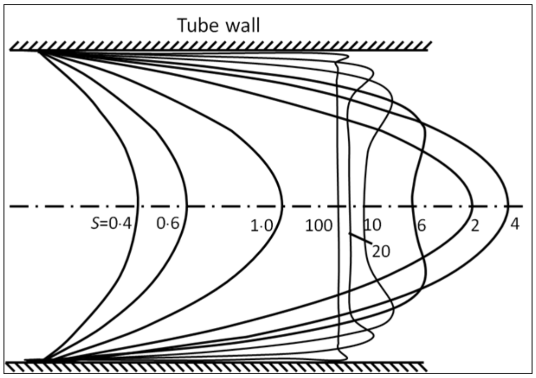

Figure 3. Velocity profiles from literature [5].

4. Governing Equations

The simulations have been done with the following assumptions: homogeneous medium, which means that the wavelength of the acoustic vibration and the radius (R) of the tube must be large compared with the mean free path (this condition breaks down for $f > 10^8$ Hz and $\mathbf{R} < 10^{-5}$ cm); no steady flow; small amplitude, sinusoidal perturbations (no circulation and no turbulence); tube long enough, so that the end effects are negligible. On the one hand, the Acoustic simulation solves a linearized, small parameter expansion of the Navier-Stokes equations, the momentum equation, the continuity equation, and the energy equation.

This model is able to solve simultaneously the equations for the acoustic pressure p, the particle velocity vector $\boldsymbol{u}$, and the temperature T. On the other hand, the Electrostatic Module solves the Poisson’s equation, where the electric potential V represents the dependent variable of the problem. Finally, the Particle Tracing Module, governed by the formulations from classical mechanics (Newtonian, Lagrangian, or Hamiltonian), allows to compute and to visualize the trajectory of the particles in the fluid, under the action of the electric field and of the acoustic force.

5. Numerical Model

Two different models with the same geometry have been considered: the first one for the acoustic analysis and the latter for the multiphysics. The models are both 2D-axisymmetric. The device to be modeled is a glass tube of radius equal to 3.5 cm and length equal to 20 cm (characteristic dimensions of the demonstrative facility [4]) containing Air in which the propagation of the vibration occurs at a temperature equal to 273°K and a background pressure of 1 bar. For the multiphysics analysis, two copper sleeve plates, surrounded by an insulating material, have been positioned at an equal distance from the duct extremities and connected to an HVDC power source (see Fig. 4).

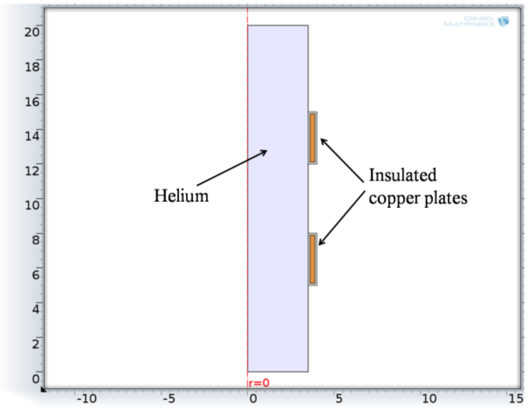

Figure 4. Model used for the FEM analysis.

The boundary conditions considered, in the glass tube for the acoustic study are the “axial symmetry” on the z-axis and the “sound hard boundary (wall)” on the outside, where the normal component of the pressure vanishes. A velocity has been chosen in agreement with the typical values reported in literature [6], and consequently the inlet acoustic pressure has been imposed.

In order to solve the viscous boundary layer, a very fine mesh , with a high number of parallel layers of thickness equal to a fraction of the viscous boundary layer δ_v, has been considered near no-slip boundaries.

$$\delta_v = \sqrt{\frac{\mu}{\pi \cdot f \cdot \rho_0}}$$

where μ is the dynamic viscosity, ρ_0 is the equilibrium density and f is the frequency of the acoustic wave.
In Fig. 5 a detail of this mesh is shown.

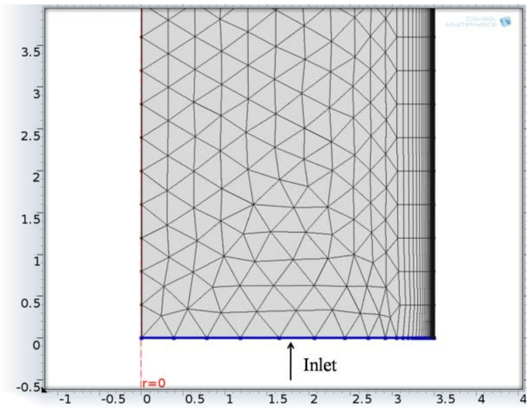

Figure 5. Meshed model for the acoustic analysis with boundary layers next to the tube wall.

As previously mentioned, for the multiphysics Model also two sleeve plates have been included, and it has been assumed that they were connected to a 10kV High voltage DC supply. The insulating material surrounding the plates determines dielectric shielding. This boundary condition describes a thin layer with a thickness and a relative bulk permittivity that shields - out the electric field.

Finally, for the particle tracing analysis an initial distribution of negative charged particles, (based on the density), has been considered. In Fig. 6 the meshed model for the multiphysics analysis is shown.

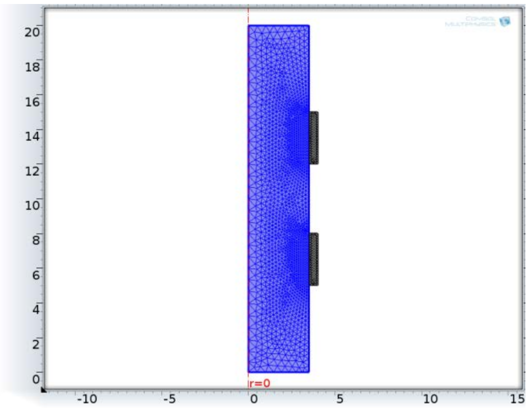

Figure 6. Meshed model for the multiphysics analysis.

6. Numerical Results

Differently than in lossless acoustics, the thermo-acoustic formulation takes into account viscous and thermal dissipative effects, which cannot be neglected in acoustic wave propagation through narrow geometries. A homogeneous fluid, with no steady flow, and sinusoidal perturbations of small amplitude (no circulation and no turbulence), has been considered. Moreover, the tube is long enough to neglect the end effects. From the first acoustic analysis, by using the thermo-acoustic module of Comsol®, different velocity profiles were obtained by varying the frequency of the inlet vibration. The velocity profiles depend on the shear wave number [5] defined as:

$$S = R\sqrt{\frac{\rho \cdot \omega}{\mu}}\,.$$

As can be noted, starting from a fixed radius of the tube R, the shear wave number depends directly on the frequency: as the frequency increases the shear wave number become higher. The numerical results confirm the theoretical ones retrieved from the literature (Fig. 3).

The axial velocity shows a parabolic profile for a low shear wave number; for higher values of the parameter, the velocity becomes smaller in the center and the profile becomes more uniform (Fig. 7).

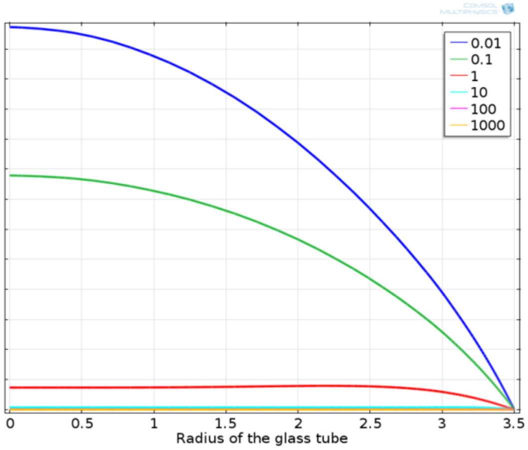

Figure 7. Velocity profiles by varying the frequency from 0.01 to 1000Hz.

For very high values of the shear wave number, the profile is almost completely flat, with small peaks close to the tube wall (Fig. 8).

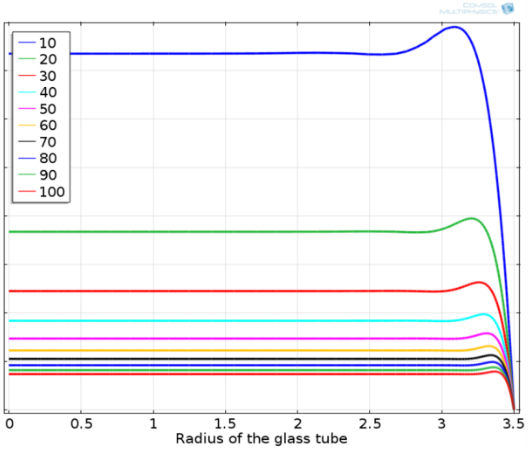

Figure 8. Velocity profiles by varying the frequency from 10 to 100Hz.

The electrostatic and particles tracing modules have been added to the acoustic Model (without thermal and viscous losses, to reduce the computational time), in order to perform a preliminary assessment of the behavior of the charge carriers when acoustic waves and electric field are simultaneously present. In Fig. 9, the potential of the external electric field is represented.

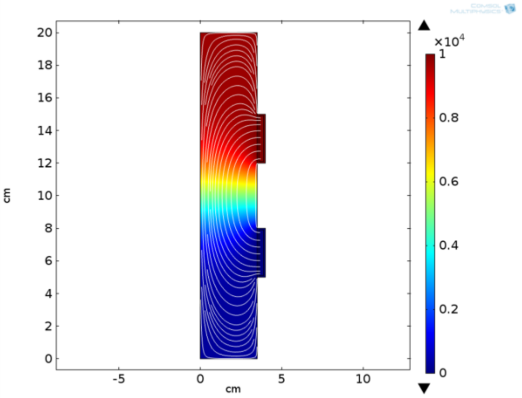

Figure 9. Electrical potential (surface) and Electric Field (streamline).

A number N=10000 of negative charges with density 2200 [kg/m^3] and diameter 1 [μm] has been uniformly released at $t = 0$ in the whole volume of the gas, and their time evolution have been observed. After a transient duration of 1 [s], the charge distribution reached a regime of dynamic equilibrium. In Fig. 10, three different charge distributions are reported in correspondence of three different time instants: the start, the middle and the end of the transient.

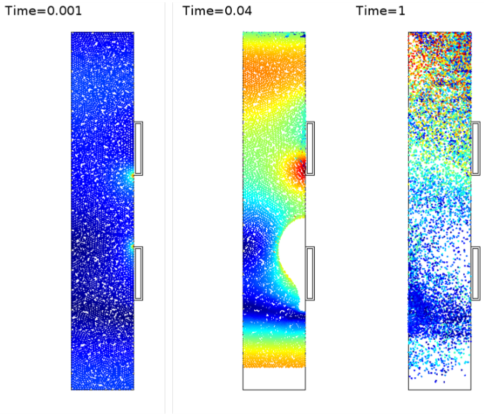

Figure 10. Particle trajectories at t = 1 ms, t = 40 ms and t = 1 s (red : high velocity, blue : low velocity).

Thus, the behavior of this particles under the influence of both the external electrical field and the acoustic perturbation has been observed. The negative charges, as expected, tends to thicken near the positive plate of the capacitor under the action of the electric force. It has been observed that, after a transient, the charges distribution reaches a dynamic equilibrium. Furthermore, the particles move forward and backward along the duct due to the acoustic wave, giving rise to an alternating current in the fluid along the axis of the duct.

As it can be noted, under the combined effect of acoustic perturbation, external field and mutual repulsive forces among charge carriers, these are distributed in the whole cross section of the duct, while along the axis they have the maximum concentration within the sleeve. This preliminary result represents a first fundamental step for the assessment of the process suitability. In fact, it shows that the charge carriers do not stick on the wall of the plates, so that they can participate to the vibrating motion of the neutrals and the give rise to an alternate electric current, which the energy conversion process is based on.

7. Discussion

The study described in the previous session aims to inquiry the qualitative behavior of the charge carriers when they are simultaneously subject to an acoustic wave and an electrostatic field. On the basis of the obtained results, a second step can be performed, where the trial design parameters are applied to the model in order to broadly estimate the performance of the real system. As said above, in order to confine a sufficiently large quantity of charge carriers in the gas, the plates have to be characterized by a large ratio surface/volume. This property can be obtained by adopting a sieve, rather than a sleeve, as shape of the plates. In Fig. 11 the sieve shape is obtained by means of a set of parallel sheets, electrically connected among them by a peripheral ring. The inter-distance between two consecutive sheets will depend on both the required quantity of charge to confine, and the profiles of charge density and velocity that correspond to the design values of wave frequency and applied voltage.

The weft in the cross section of the plate adopted in Fig. 11 is only the simplest one. A large number of different shapes can be defined [3] having higher surface/volume ratio, which is the main requirement for the stack, for both the thermo-acoustic and charge confinement purposes.

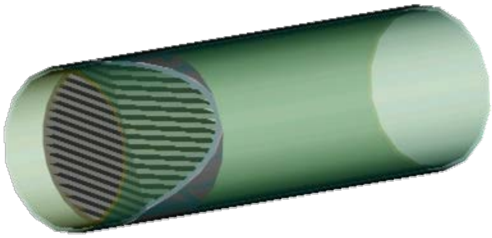

Figure 11. Sieve-shaped plate for charge carriers confinement.

8. Conclusions

In this paper, the behavior of charge carriers immersed in a gas and subject to an acoustic wave and an electrostatic field has been investigated. This specific problem is of paramount importance for the feasibility of a new conceptual design of electric generator, which exploits the thermo-acoustic effect and the magneto-hydrodynamics in order to statically convert heat into electrical energy. The feasibility of this energy conversion process depends on how the unbalanced charge carriers spread into a volume where an electrostatic field is applied. A multi-physics study has been performed, where a set of charges of the same sign immersed in a gas are simultaneously subject to an external electric field, the mutual repulsive force and an acoustic wave traversing the gas. The results show that the charge carriers are trapped in the volume where the electrical field is applied, but they do not stick on the wall of the volume. As a consequence, the charge carriers are involved in the vibration motion, giving rise to an alternate current which makes possible the transfer of energy by means of the electromagnetic induction.

9. References

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