Voice Coil Generator for a Free-Piston Stirling Engine

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Abstract- **In this paper we present a new solution for converting of mechanical energy developed by a free piston Stirling engine into electrical energy using a voice coil type generator. There are presented the using of a free piston Stirling engine in a cogeneration plant and the main steps in the design of a voice coil linear generator. The design procedure for voice coil type linear generator starts with the design of the free piston Stirling engine and finally uses the Faraday law of induction. The magneto-static magnetic field generated by permanent magnets is analyzed by means of Finite Element Method in order to evaluate the magnetic flux density in the air gap, which is a design data imposed in the design stage, and the results are compared.**

Keywords: **free-piston Stirling engine, permanent magnets, voice coil generator, magnetic fields analysis.**

I. Introduction

Micro combined heat and power (m-CHP) based on biomass for residential use is part of the broader field of renewable energy. This paper is related to such a micro cogeneration system based on a wood or pellets boiler integrated with a Free Piston Stirling Engine (FPSE) and a permanent magnet Voice Coil Linear Generator (VCLG). Such a system generates thermal energy for heating and electricity for residential using [1].

This paper presents the methodology for designing of Free Piston Stirling Engine and the permanent magnet Voice Coil Linear Generator.

The Stirling engine is an example of the broader class of thermal machines designed for to convert thermal energy. Internal combustion engines, engines Otto or Diesel, uses a fuel combustion of inside pressurized volume, while Stirling engine uses an external heat source to heat the working fluid.

The heat may come from combustion of the fuels, from the sea, from the combustion of biomass or any other source. All you need to get a Stirling engine to go is a temperature difference of some sort that expands and contracts the enclosed gas. Compared with the internal combustion engines, at the Stirling engine, fuel supply and flue gas discharge may be missing. If a clean external heat source is used, the Stirling engine can become an alternative to internal combustion engines which emit some hydrocarbons and other pollutants.

The Stirling cycle compared with the Carnot cycle between the same given limits of pressure, volume, and temperature, is shown in figure 1. The shaded areas 2C-2-3 and 1-4C-4 indicate the additional work available by replacing two isentropic processes with two constant-volume processes. This fact indicates that Stirling cycle efficiency is close to efficiency of Carnot cycle.

Research on Stirling engines are widely reported in the literature [2, 3].

The Stirling engines can be classified into three types: alpha, beta and gamma. Figure 2 displays an outline of each type of engine.

Alpha Stirling engines have two pistons type of work placed in separate cylinders, which are connected in series with a heater, a regenerator and a cooler.

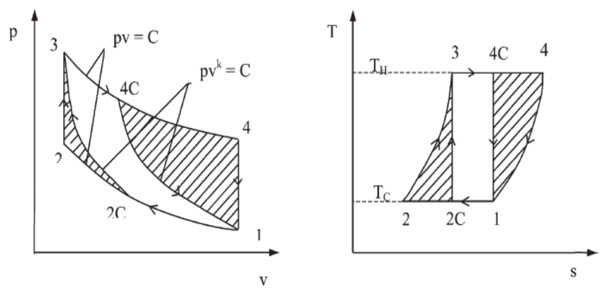

Fig. 1. Stirling and Carnot Cycle [1].

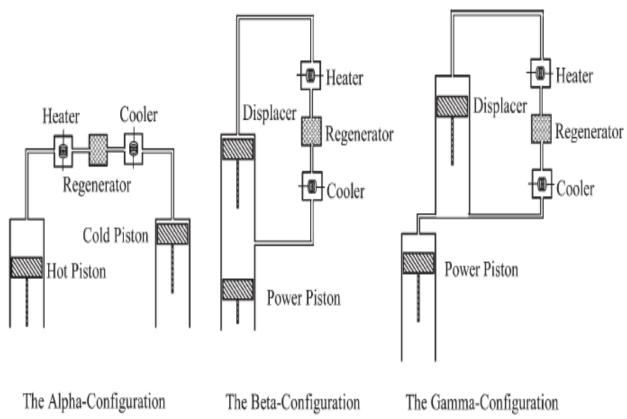

Fig. 2. Three basic mechanical configurations for Stirling engine [1].

The Stirling engines Beta and Gamma uses a displacer piston, the engines Beta have the displacer piston and working piston in the same cylinder, while Gamma engines have the displacer piston and working piston in separated cylinders.

The Stirling engine could be used in many applications and is suitable where [4]:

- multi-fueled characteristic is required;
- a very good cooling source is available;
- quiet operation is required;
- relatively low speed operation is permitted;
- constant power output operation is permitted;
- slow changing of engine power output is permitted;
- a long warm-up period is permitted.

The Stirling engine or hot air engine was invented by Robert Stirling in 1815. They were widely commercial available before 1900. The internal combustion engine and later electrical motors gradually superseded both Stirling and steam engines, so that today Stirling engines are virtually unknown to the general public and even to the most engineers [3].

Stirling engines have reappeared on the market after the development of the modern Free Piston Stirling Engines (FPSE).

In the following will be presented the study and design of a Free Piston Stirling Engine which will directly drive a Voice Coil Linear Generator (VCLG).

II. THE FREE-PISTON STIRLING ENGINE DESIGN

In this configuration, the power piston placed in expansion space is not mechanically connected to an output shaft. It bounces alternately between the expansion space containing the working gas and a spring (usually a gas spring). In many designs, the displacer is also free to bounce on gas springs or mechanical springs.

This configuration is called the Beale "free-piston" Stirling engine after its inventor, William Beale [5].

Piston stroke, frequency, and the timing between the two pistons are established by the dynamics of the spring/mass system coupled with the variations in cycle pressure.

To extract power, a magnet can be attached to the power piston and electric power is generated as it moves past stationary coils [4]. These Stirling engine/alternator units are called "free-piston" Stirling converters.

In figure 3 is presented the constructive scheme of a free piston Stirling engine conceived by Wiliam Beale [5].

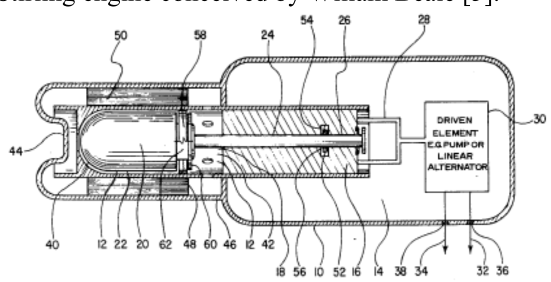

Fig. 3. The Beale free piston Stirling engine [5].

There is a big diversity of free-piston Stirling engines. This kind of Stirling engine has two spaces, a compression chamber 42 and an expansion chamber 40, whose volumes are cyclically varied. All version of this type of engine comprise three separate masses, piston 16, cylinder 22 and the displacer 20. Usually, the cylinder is rigidly fixed to a solid foundation of so great mass as to represent an infinite mass compared with the other two [3].

Consider a free-piston Stirling engine presented in figure 3.

Let the system be initially at rest in an arbitrary position.

The pressure and the temperature are the same in all the spaces. Now let the expansion space to be heated by the heater. If the temperature in the expansion space is increased, the pressure in the working space will also be increased and the displacer and the piston will be moved in the cylinder, but the displacer accelerates more than the piston because it has a much lower mass (10:1).

The working fluid is therefore moved out of the expansion space through the regenerator to the compression space. When the working space has no fluid the gas spring pressure will force the piston and the displacer to go back. In some free piston engines instead of this gas spring is used membrane springs or other planar springs. Now the gas will begin to flow again from the working space to the expansion space, by heating and the cycle is repeating. This is a simplified explanation of how a free piston works. It can be seen that free piston engines are self starting engines.

Figure 4 presents a "free-piston" Stirling engine conceived by the authors.

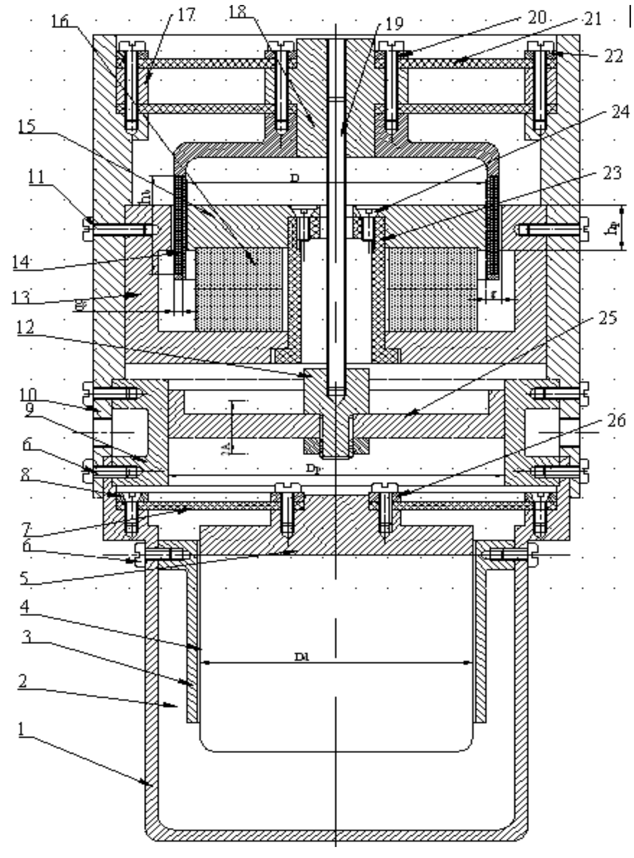

Fig. 4. The designed free-piston Stirling engine.

In the figure 4 above can be seen the heater 1, the displacer 4, the expansion space2, the working space under the piston 25, the cooling cylinder 9, the displacer spring 7, the moving coil 14 and the permanent magnets 16 of the voice coil generator. The moving coil is rigidly coupled with the power piston 25, and the moving system is suspended and centered by the membrane springs system 21.

The FPSE design will begin with the power piston diameter calculation, after that the rest of dimension will be adopted from constructive reasons.

The main design data is the developed power P=100W. Beale indicated that the power output of several Stirling engines observed could be calculated from the equation:

$$P = 0.015 \cdot p_m \cdot f \cdot V_p \qquad (1)$$

where: 0.015 is the Beale number, P is the engine power output in Watts, p_m the mean cycle pressure in bar, f the cycle frequency in H_z, and V_p is the displacement of power piston in cm^3.

The Beale formula was modified by West [3, 6] as follows:

$$P = F \cdot p_m \cdot f \cdot V_p \cdot \frac{T_H - T_C}{T_H + T_C} \qquad (2)$$

where the factor F=0.25-0.35 can be used for practical use, T_H is the hot side temperature and T_C is the cold side temperature.

From this we can calculate the displacement of the power piston:

$$V_p = \frac{P}{F \cdot p_m \cdot f} \cdot \frac{T_H + T_C}{T_H - T_C} = \frac{100}{0.33 \cdot 3 \cdot 10} \cdot \frac{766}{180} = 43cm^3 \qquad (3)$$

where P=100 W is the power rate of the engine, $p_m=(0+6)/2=3$ bar, f=10 H_z, $T_H=473$ K and $T_C=293$ K , all are imposed as design data.

The oscillating amplitude is imposed as:

$$A = 0.005m = 0.5cm. \qquad (4)$$

The oscillating amplitude A give us the swept volume of power piston.

$$V_p = A \cdot A_p, \qquad (5)$$

where A_p is the power piston area:

$$A_p = \frac{V_p}{A} = \frac{43cm^3}{0.5cm} = 86cm^2. \qquad (6)$$

Now we can calculate the power piston diameter:

$$D_p = \sqrt{\frac{4 \cdot A_p}{\pi}} = \sqrt{\frac{4 \cdot 86}{\pi}} = 10.6cm = 106mm. \qquad (7)$$

The rest of dimensions are adopted from the constructive ratios, for example the displacer diameter $D_d = 86mm$.

The moving mass of the displacer was estimated from the design stage $m_d = 0.84kg$. Now we can calculate the rigidity of the displacer spring:

$$k_d = m \cdot (2 \cdot \pi \cdot f)^2 = 0.84 \cdot (2 \cdot \pi \cdot 10)^2 = 3.31N/mm \qquad (8)$$

This value allows us to design and manufacture the displacer spring, the solutions is presented in figure 5.

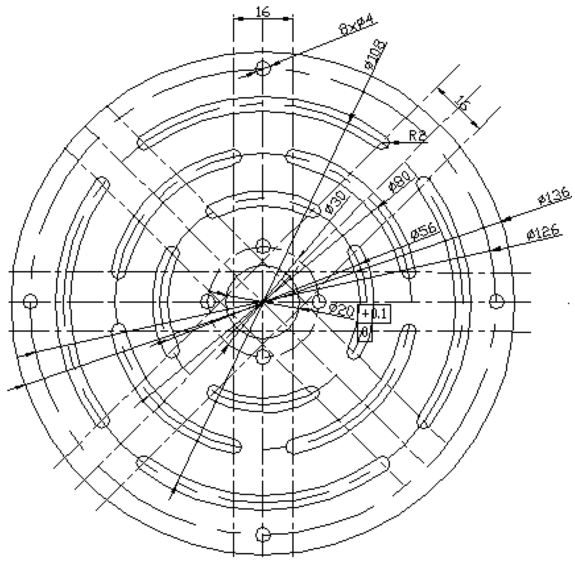

Fig. 5 The displacer spring.

III. THE VOICE COIL GENERATORS DESIGN

Because the free piston Stirling engines like all Stirling engines develop a reciprocating motion, in order to avoid the crankshaft for adapting to the rotating electric generators is suitable to drive directly a linear oscillating generator.

By eliminating the crankshaft mechanism which converts linear oscillating movement of Stirling engine into rotating motion, will be reduced the friction and the construction complexity and will lower the maintenance needs.

In this way the entire construction of the linear system Stirling engine generator can be inserted into a sealed housing, thus reducing the problems of tightness of the construction. Another advantage of the FPSE is that it can be made flexible elastic diaphragms instead of piston-cylinder system in order to eliminate gas leakage along the piston and the need for a lubrication system.

Now, in the construction of electrical machines often are used permanent magnets [7]. There are three types of permanent magnets linear generators (PMLG):

- PMLG with fixed coil and moving magnets;
- PMLG with fixed magnets and moving coil;
- PMLG with fixed coil and magnets and moving iron.

In this paper will be studied only the solution with fixed magnet and moving coil, which is known as Voice Coil Generator (VCG) [8].

The conceived solution is presented in the upper part of figure 4. Can be seen that the FPSE and the VCG are assembled in a single construction unit, the oscillating motion from power piston of FPSE is transmitted to moving coil of VCG by the rod 19 (Fig. 4).

Usually the dimensions of the electric generator are larger than the dimensions of Stirling motor [2, 3]. In this case for an demonstrative prototype we have chosen the same radial dimension, but with a lower rated power P_g=20VA. This is the main design datum for the Voice Coil Generator.

A. Magnetic circuit design

From the magnetic flux conservation law, applied around the air-gap, we can write:

$$k_\sigma \cdot B_g \cdot S_g = B_m \cdot S_m, \quad (9)$$

where: $k_\sigma = (\Phi_m)/\Phi_g = 1.25$ is the leakage coefficient of the air-gap (the whole magnetic flux divided by air-gap flux, it takes into consideration the leakage magnetic flux Φ_σ which not passes through the air gap; B_g is the air-gap magnetic flux density, S_g – is the air-gap transversal area; B_m – is the permanent magnet operation flux density and S_m – is the permanent magnet transversal area.

From the Ampere law [8] we can write:

$$\begin{aligned} &H_m \cdot h_m + H_g \cdot g + H_{Fe} \cdot l_{Fe} = \\ &= H_m \cdot h_m + k_{Fe} \cdot H_g \cdot g = 0 \end{aligned}, \quad (10)$$

where H_m – is the permanent magnet magnetomotive force in the operation point; h_m – is the permanent magnet height; H_g – is the magnetic field strength in the air-gap; $g=5mm$ – is the air-gap length; H_{Fe} – is the magnetic field strength in the iron; l_{Fe} – is the average length of the portion of magnetic flux line inside the iron; $k_{Fe}=1.1$ - is the iron coefficient, which takes in account the magnetic force fall in the iron, dependant also on the saturation level in the iron.

So we can write the relation (10) in the following form:

$$H_m \cdot h_m = -k_{Fe} \cdot H_g \cdot g, \quad (11)$$

By multiplication of relations (9) and (11) it is obtained:

$$(B_m \cdot H_m) \cdot V_m = -k_{Fe} \cdot k_\sigma \cdot \frac{B_g^2}{\mu_0} \cdot V_g, \quad (12)$$

where $(B_m H_m)$ is the maximum energy product of permanent magnet material (TABLE I); $V_m=S_m*h_m$ – is the permanent magnet volume; $V_g=S_g*g$ – is the air gap volume and $\mu_0=4*\pi*10^{-7} H/m$ – is the magnetic permeability of the air.

In order to calculate the permanent magnet volume, we shall choose the magnetic material. From [9] we chose Nd-Fe-B permanent magnets type N-35M with the following characteristics:

TABLE I MAGNETIC CHARACTERISTICS PERMANENT MAGNETS OF THE TYPE EURONEOS 82X52X15,

Material	B_r *[T]*	H_c *[kA/m]*	BH_{max} *[kJ/m³]*	*D [mm]*	*d [mm]*	*h [mm]*
N35	1.2	868	280	82	52	15

From the Faraday induction law [8] we can write the voltage induced in the moving coil at amplitude A of oscillation of the moving coil with frequency f:

$$\sqrt{2} \cdot U = B_g \cdot l_c \cdot v_0, \quad (13)$$

where l_c is the moving coil conductor length and v_0 is the amplitude of oscillating speed of moving coil [10]:

$$v_0 = \varpi \cdot A = 2 \cdot \pi \cdot f \cdot A. \quad (14)$$

From (13) and (14) results:

$$U = 4.44 \cdot f \cdot A \cdot B_g \cdot l_c. \quad (15)$$

The moving coil conductor volume is:

$$V_c = s_c \cdot l_c, \quad (16)$$

where s_c is se cross-section area of moving coil conductor.

The moving coil current I has the expression:

$$I = J_a \cdot s_c \quad (17)$$

where $J_a=16 A/mm^2$ is the admissible current density in the moving coil conductor, this large value comes from the better cooling condition because of small thickness of the coil, the aluminium support and the moving in the air.

Starting from design datum P_g and (15-17) we obtain the expression:

$$P_g = U \cdot I = 4.44 \cdot f \cdot A \cdot B_g \cdot V_c \cdot J_a, \quad (18)$$

where f=10Hz, A=5mm from the FLPSE design, B_g=0.6T as imposed design data

From here we can calculate the moving coil conductor volume needed for the voice coil generator to develop a power of 20 VA:

$$\begin{aligned} V_c &= \frac{P_g}{4.44 \cdot f \cdot A \cdot B_g \cdot J_a} = \\ &= \frac{20}{4.44 \cdot 10 \cdot 0.005 \cdot 0.6 \cdot 16 \cdot 10^6} = \\ &= 9.3 \cdot 10^{-6} m^3 = 9.3 cm^3. \end{aligned} \quad (19)$$

From figure 4 can be establish a relation between the moving coil conductor volume in the air-gap and the air-gap volume:

$$V_g = \frac{V_c}{k_{fu}} \cdot \frac{g}{g_c} = \frac{9.3 cm^3}{0.6} \cdot \frac{5mm}{3.5mm} = 22.1 cm^3, \quad (20)$$

where k_u=0.6 is the filling factor at wiring of the moving coil winding and g_c=3.5 mm is the thickness of moving coil winding.

From constructive reasons we adopt the central magnetic core diameter D=92mm. The average air-gap diameter is:

$$D_m = D + g = 92 + 5 = 97 mm. \quad (21)$$

The height of air-gap is:

$$h_p = \frac{V_g}{\pi \cdot D_m \cdot g} = \frac{22.1}{\pi \cdot 9.7 \cdot 0.5} = 14.5 cm. \quad (22)$$

From (12) now we can calculate the permanent magnets volume V_m:

$$V_m = \frac{k_{Fe} \cdot k_\sigma \cdot B_g^2}{(BH)_{max} \cdot \mu_0} \cdot V_g = \frac{1.1 \cdot 1.25 \cdot 0.6^2}{280 \cdot 10^3 \cdot 4\pi \cdot 10^{-7}} \cdot 22.1 = \quad (23)$$

$$= 31.1 cm^3$$

The volume of a single magnet (TABLE I) has the value:

$$V_{m1} = \frac{\pi \left(8.2^2 - 5.2^2\right)}{4} \cdot 1.5 = 37.86 cm^3, \quad (24)$$

so we need only one such a permanent magnet, but because from energy point of view we are at limit, we choose two magnets to cover some calculations inaccuracies.

From mechanical point of view, the voice coil generator must oscillate with the same frequency as the displacer.

Because we estimate the mass of moving equipment of voice coil generator to be two times heavier than the mass of displacer, we choose two planar springs identically as the displacer spring in order to have the same resonance frequency, see formula (8).

B. *Moving coil design*

The RMS value of moving coil current will be:

$$I = \frac{P_g}{U} = \frac{20VA}{12V} = 1.67A, \qquad (25)$$

where U=12V is the RMS value of coil voltage expected to be obtained at the voice coil generator.

The moving coil conductor cross section area will be:

$$s_c = \frac{I}{J_a} = \frac{1.67A}{16A/mm^2} = 0.104mm^2. \qquad (26)$$

The moving coil conductor diameter is:

$$d = \sqrt{\frac{4s_c}{\pi}} = \sqrt{\frac{4 \cdot 0.104}{\pi}} \approx 0.36mm. \qquad (27)$$

The moving coil conductor length will be after (15):

$$l_c = \frac{U}{4.44 \cdot f \cdot A \cdot B_g} = \frac{12}{4.44 \cdot 10 \cdot 0.005 \cdot 0.6} = 90m. \qquad (28)$$

The moving coil conductor volume is:

$$V_c = l_c \cdot s_c = 90m \cdot 1.04 \cdot 10^{-7} m^2 = 9.36cm^3, \qquad (29)$$

the same value as previous (19).

The moving coil average turn length is:

$$l_t = \pi \cdot D_m = 3.14 \cdot 97mm = 305mm. \qquad (30)$$

The moving coil number of turns are:

$$N = \frac{l_m}{l_t} = \frac{90}{0.305} = 294turns. \qquad (31)$$

With the isolated conductor diameter of d_c=0.45mm, the moving coil winding thickness of g_c=3.5 allows 6 layers (must be an even number in order to have both the coil terminals on the upper side of the coil), so one layer must have N_l number of turns:

$$N_l = \frac{N}{6} = \frac{294}{6} \approx 50turns. \qquad (32)$$

The height of active coil will be:

$$h_b = N_l \cdot (d + c) = 50 \cdot (0.45 + 0.1) = 27.5mm, \qquad (33)$$

where c=0.1mm is the average clearance between two conductors. This results is correct because the magnetic field exists also close to the air-gap.

IV. THE VOICE COIL GENERATOR MAGNETIC FIELD ANALYSIS

Will be used the two-dimensional software FEMM (Finite Elements Magnetic) delivered free by David Meeker [11], used for defining, solving and post-processing 2D planar and axis-symmetric problem of magneto-statics.

In the figure 6 is presented the cross-section of the magnetic circuit for the voice coil type generator designed in the previous paragraph.

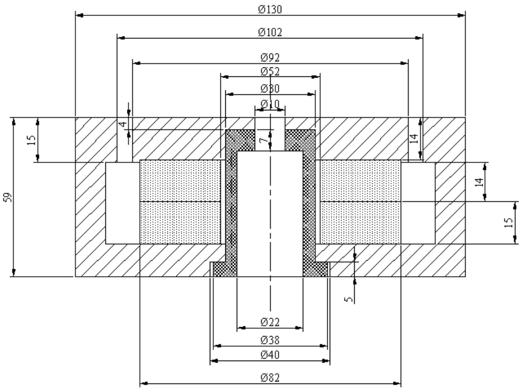

Fig. 6 The magnetic circuit of Voice Coil type generator designed.

From this figure can be seen that the magnetic field has an axis symmetry, so will be analyzed only the right half of the section, like in figure 7.

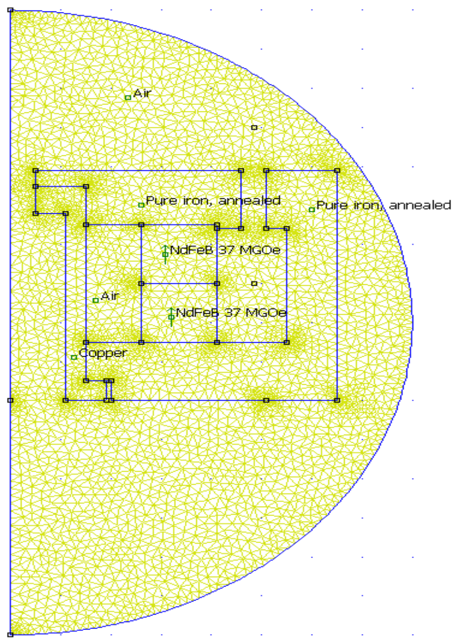

Fig. 7 The magnetic field calculation domain.

The Maxwell equations adapted to this problem are:

$$\nabla \times \overline{H} = \overline{J}. \qquad (34)$$

$$\nabla \cdot \overline{B} = 0. \qquad (35)$$

$$\overline{B} = \mu \cdot \overline{H}. \qquad (36)$$

$$\overline{B} = \nabla \times \overline{A}. \qquad (37)$$

$$\nabla \times \left(\frac{1}{\mu(B)} \cdot \nabla \times \overline{A} \right) = \overline{J}. \qquad (38)$$

where:

- **H** is the magnetic field intensity;
- **B** is the magnetic flux density;
- **A** is the magnetic vector potential.

Were considered the following boundary conditions:
1) Dirichlet conditions A = 0, on the outer boundary of the field and to the axis of symmetry;

2) Neumann conditions $\frac{\partial A}{\partial n} = 0$, conditions implied by magnetic metal surface.

Mesh field is automatically created and is shown also in figure 7. The permanent magnet is introduced through equivalents currents calculated by soft, based on magnetic material N37. The results of magnetic field simulation are shown in figure 810.

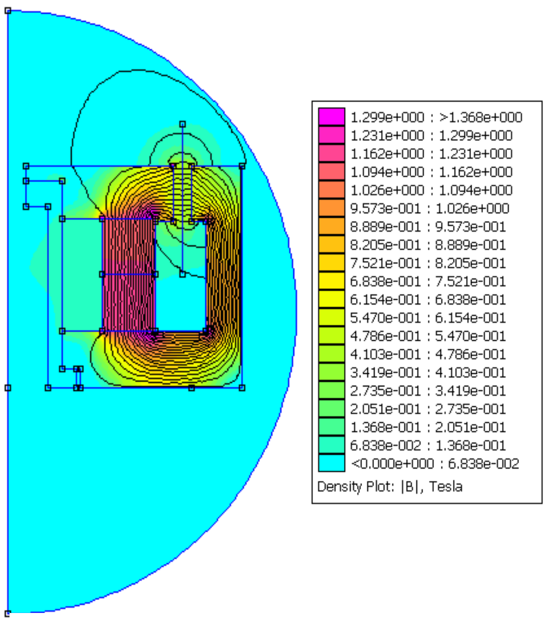

Fig. 8 The magnetic field simulation results.

In figure 9 is presented the magnetic flux density distribution in the air gap.

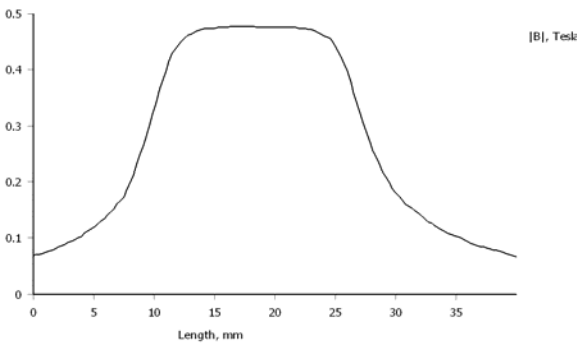

Fig. 9 The magnetic flux density in the air gap.

It can be seen that the average value of magnetic flux density in the air gap 0.5T is very closed to the value of 0.6T taken in the design stage.

V. CONCLUSIONS

The paper presents the design and analysis of a free piston Stirling engine which drives a voice coil type linear generator. There are presented the design methodology for the free piston Stirling engine and for the voice coil type linear generator. Finally, starting from the design dimensions of the voice coil type linear generator, a magnetic field analysis is performed by Finite Element Method. The average value of magnetic flux density in the air-gap obtained by FEM analysis 0.5T is very closed to the value adopted in the design stage.

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