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Experimental research for the mass flow control of the metal vaporized and ionized with microwave used in electric propulsion

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This research presents a method of mass flow control of the metal vaporized and ionized with microwave field in a cylindrical waveguide having propagation mode TM_{012}. The vaporized metal quantity (in particular lead) is controlled using microwave pulses of adjustable time duration. The experiment is realized in air at normal atmospheric pressure. The electrical current value measured for the lead thread show that an end wire is in the high electromagnetic energy region from cylindrical waveguide.

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1. Introduction

In this paper is presented a method for the control of the mass flow control of a vaporized and ionized metal (in particular lead) with a microwave field (2.45 GHz) in a cylindrical waveguide having as propagation mode TM_{012} .This research can be applied to ion thrusters which use as propellant metals.

Comparative with the gaseous propellants (Xe, Kr), metals as (Pb, Bi) have these advantages: bigger atomic weight and lower ionization energy, low storage volume, and low price.

So far, the research in this field demonstrated the possibility of directly vaporization and ionization with microwave field of the solid lead threads having 0.6 mm diameter [1]. Lead threads were vaporized and ionized in cylindrical waveguide having propagation mode TM_{011}. The power of the microwave field in the waveguide was 800 W with repetition rate 50 Hz.

For an earlier solid propellant (the Hall Effect) thruster, Zinc and Magnesium were used [2]. For the thruster in [2] having a consumable plate anode, the propellant was first heated with resistive heaters. Then the anode voltage was increased to ignite the thruster. Once a plume was established, resistive heaters were turned off. The mass flow of metal propellants had two controllable parameters, the open surface area and propellant temperature.

The problem this work wants to solve is the controllable mass flow vaporization and ionization of solid lead threads with microwave field using little energy. For this, were made two experiments. In the first experiment **(A)** we tried to decrease the microwave field power through the decrease of the anode voltage from magnetron having 10 ms pulse duration and 50Hz repetition rate. The second experiment **(B)** consisted in decreasing the microwave field power having 50Hz repetition rate through the decrease the pulse duration. The lead threads used in this work have a 0.3 mm diameter.

2. Experimental

To use as little energy as possible for the vaporization and ionization processes of lead thread located in the waveguide, one must check if energy is lost from the system. The energy lost can be estimated from the efficiency the magnetron and efficiency cylindrical waveguide. The parameters the magnetron can not be changed but efficiency of the cylindrical waveguide can be improved if we modify the quality factor of the waveguide. Theoretical quality factor for cylindrical waveguide having the propagation mode TM_{01l}, l > 0 is given by formula (1) [3]

$$Q = \frac{\lambda}{\delta} \cdot \frac{\sqrt{p_{01}^2 + (l \cdot \pi \cdot a/d)^2}}{2\pi(1 + 2 \cdot a/d)}; \; l > 0 \quad (1)$$

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \sigma}} = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}}$$

where:
Q is quality factor
δ is the skin depth of the waveguide walls
λ is the wavelength in the cavity
a is the radius of the cavity
d is the height of the cavity.
p_{01} is Bessel function , for TM_{01l}; p_{01} = 2.045

From formula 1 we can see that if we increase cylindrical waveguide length, the quality factor will increase too. When we compare quality factor for the TM_{011} and TM_{012} modes of a cylindrical waveguide [1], quality factor for TM_{012} is with almost 60% higher. So the energy loss from a waveguide having TM_{012} mode propagation is lower than waveguide TM_{011}. For the two experiments, we used a magnetron (type 2M253) having 800W microwave power and 50Hz repetition rate as the microwave source.

The cylindrical waveguide from ours experiments has 100mm diameter and 170mm length. High energy electromagnetic region for TM_{012} propagation mode is at distance 12 cm from magnetron antenna.

A.) In the first experiment, we achieved the decrease of the microwave field power through the decrease of the anode voltage (Fig 1). For the magnetron powering, we used two separate transformers. Low voltage transformer powered the filament from magnetron and high voltage transformer powered the anode of the magnetron. The filament of the magnetron heated the electron emitting cathode. This way, if we modify voltage from anode, we will not affect the electron density inside of the magnetron.

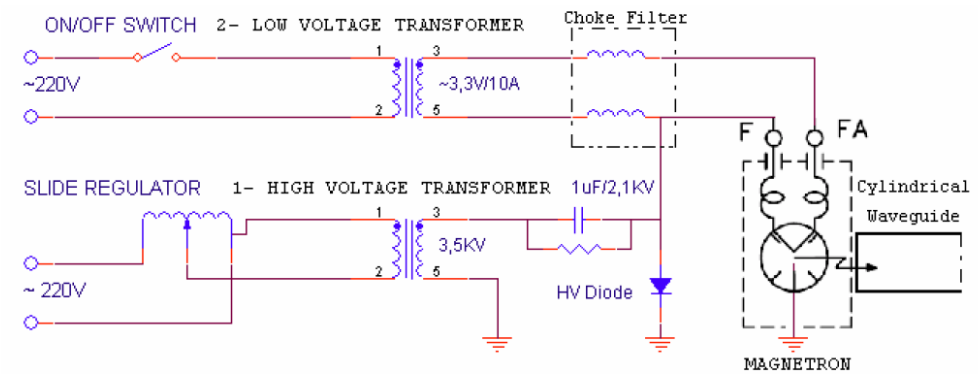

Fig.1 Electrical schematic for the first experiment.

Knowing that the magnetron emits microwaves pulses, the power of a pulse can be calculated with from (2) and (3) [4].

$$DF = t_p \cdot n \tag{2}$$

$$P_p = \frac{P_{mean}}{DF} \tag{3}$$

where:

DF is duty factor

t_p is pulse duration in seconds

n is the pulse repetition rate in Hz

P_p is power pulse anode

P_{mean} is the power average consumed in the magnetron anode

For 10ms duty factor and P_{mean} = 73W, the power of the pulse will be 146W.

This power is not sufficient for the vaporization and ionization of the lead thread. Experimental research has showed that if we decrease power microwave field inside the cylindrical waveguide the thread lead will vaporize incomplete (fig.2). So, we can conclude that this method is not feasible.

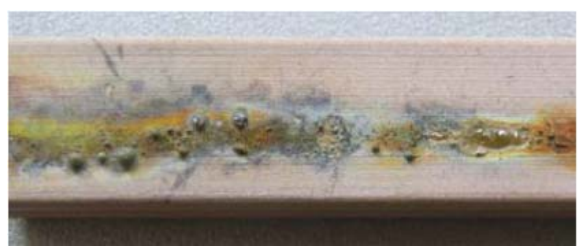

Fig. 2. The lead sample vaporized and ionized.

The lead thread is introduced inside of the cylindrical waveguide on a ceramic support.

B.) In the second experiment we modified the pulse duration. Mean power and repetition rate has same values as the first experiment.

An effective method used for controlling the average power to a load (the high voltage transformer) using a triac is through the phase control. Phase control is a method utilizing the triac to apply the AC voltage to the load for a controlled fraction of each cycle. Each time the triac is triggered the current rises from zero to the load limited current value in a very short time. The figure 3 shows the voltage applied to high voltage transformer versus the microwave field inside the cylindrical waveguide.

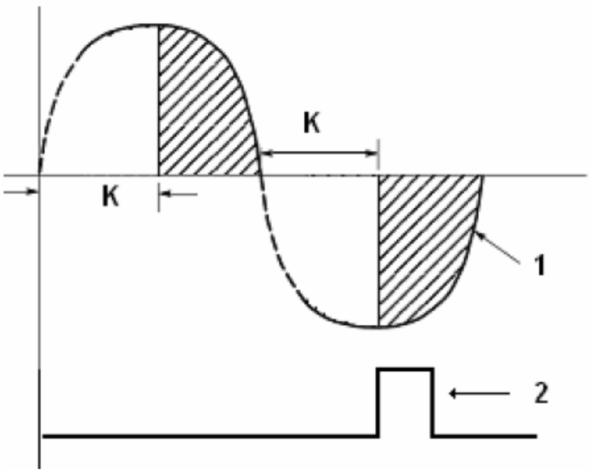

Fig. 3. 1- AC sine wave applied on the high voltage transformer, 2- The microwave field inside the cylindrical waveguide

The triac is held in an off or open condition at a time in the half cycle determined by the control circuitry. In the on condition, the circuit current is limited only by the load, the entire line voltage is applied to the load.

By varying the angle K one controls the portion of the sine wave which is applied to the high voltage transformer (shaded area), and so the power flow applied to load will be modified. The effect of varying the angle K from 10% to 95% of the ac sine wave will modify the pulse duration microwaves from cylindrical waveguide. So we can control lead flow mass vaporized and ionized. In figure 4 is showed electrical schematic for the control of the microwave field from the waveguide using adjustable duration pulses.

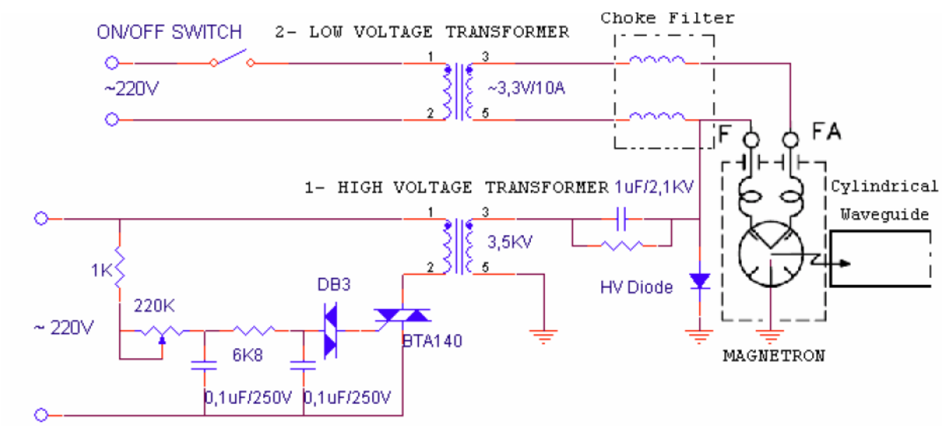

Fig. 4. The electrical schematic for the control lead mass flow using adjustable during pulses.

With same parameter from first experiment: mean power (73W) and repetition rate (50 Hz) but 2 ms pulse duration, using formulas 2 and 3 will get 730 W pulse power. In fig.5 is showed that the lead thread is integral vaporized and ionized. So, the lead mass flow can be controlled using adjustable duration pulses of microwave field.

Fig. 5. The lead thread vaporized and ionized through modified pulse duration.

In the second experiment the vaporization and ionization process starting from 22 W mean power. In the first experiment the vaporization and ionization process is not possible at 22 W. Table 1 showes some lead flow mass versus mean power from second experiment.

Table 1

$P_{filament}$ (W)	P_{mean} (W)	$I_{lead.thread}$ (μA)	Flow mass (mg/s)
33W	44	23	0.02
	66	26	0.17
	72.6	27	0.22
	77	28	0.31
	88	31	0.74
	99	34	1.33
	110	37	1.52

The total power consumed for burning (vaporization and ionization) process is power filament + mean power anode. During the vaporization and ionization process, on the surface of the lead thread flows an electrical current which appears only if one end of the wire is in high energy electromagnetic region. This current is larger when the electromagnetic energy from cylindrical waveguide is not consumed for the vaporization and ionization processes. The current from the lead thread can give information if the lead thread is in burning process. In Table 1 we give the values for the current from the lead thread for some lead mass flow when an end wire is in burning process. Fig. 6 shows the cylindrical waveguide having propagation mode TM_{012}. The wall of the waveguide has been made of copper. For 73 W mean power, 50 Hz repetition rate and 2 ms pulse duration inside of the waveguide is vaporized and ionized 0.22 mg/s lead. The lead thread is brought in the high energy electromagnetic region from the waveguide through a teflon pipe. In our experiments we used teflon because it is a transparent material for the microwave field.

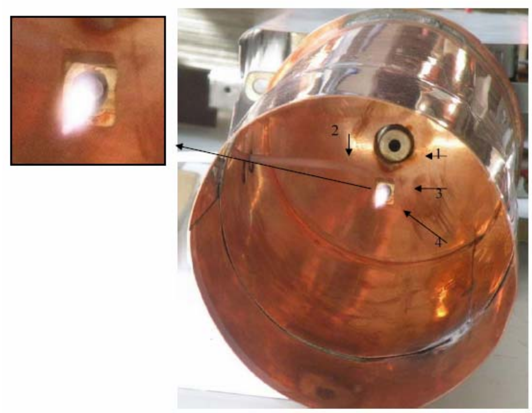

Fig. 6. Vaporization and ionization of the lead thread in cylindrical waveguide 1- Magnetron antenna, 2- Teflon pipe, 3- ceramic support, 4 –plasma

3. Discussion

Because the current from the lead thread is low when a end wire is in burning process and high when the lead thread is not in burning process, the current value from the lead thread can be an effective input for the electronics of the thruster. A feed system can detect the current's value and push the lead thread in high electromagnetic region.

4. Conclusions

This work showed that it is possible to control the lead mass flow if one modifies the microwave pulse duration in cylindrical waveguides.

This concept for the control of the vaporization and ionization of the lead threads using microwave field can be applied at electric thrusters which use metal as propellant.

We also demonstrated that if we use a cylindrical waveguide with TM_{012} propagation mode, we will have a little loss of energy in the waveguide.

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