PROSPECTS OF APPLICATION OF MICROWAVE DISCHARGES ON A DIELECTRIC NET EXCITED IN THE FIELD OF A QUASIOPTICAL ELECTROMAGNETIC BEAM FOR PLASMA-SUSTAINED COMBUSTION

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Abstract

At present for solution of a number of aerodynamic and combustion problems various plasma technological approaches are considered. In this report possibility of application of microwave (MW) discharge generated on a dielectric net in the combustion zone of a channel of a ramjet engine is analyzed in detail.

New experiments on generation of similar MW discharges on a wire-dielectric net highlighted that even in this case streamer channels also propagate only along dielectric fiber surface. This unique property and characteristics of microwave discharges on dielectric nets demand detailed research. However already today there are all bases to raise the question about application of this-type discharges in the combustion chamber of the modern ramjet engine. At that probably the need of braking of air flow at the engine channel inlet will disappear, the fuel burning efficiency will increase and its combustion zone length will decrease.

1. *Introduction*

Toady for solution of some aerodynamic problems new approaches based on application of various plasma technologies are thoroughly investigated and discussed. In this work prospects of application of electric gas discharges excited in supersonic ramjet engines in the field of quasi-optical microwave (MW) beam are analyzed.

The simplified scheme of such ramjet engine is depicted in Fig.1.1. In input contractor of its channel the speed of incident airflow reduces to Mach number M = 1. Behind critical section of the channel the stream additionally slows down; fuel is injected in this area. Here formed flammable mixture is ignited and burns down. Than the flow accelerates to M = 1 and finally accelerates in output diffuser section of the engine.

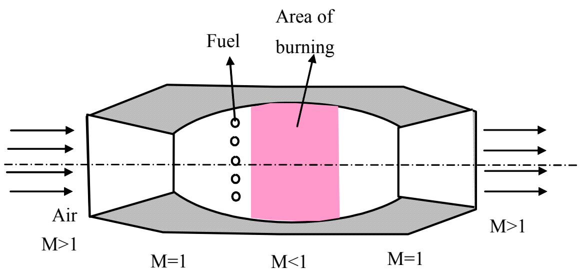

Fig.1.1.

A number of serious problems should be solved in the area of burning mixture. First, it is necessary to ignite the mixture, and stabilize its burning area in space. Meanwhile it is very desirable to provide small extent of this area. Considered below physical phenomena have obvious prospects of non-traditional way for solution of these problems.

2. *MW discharge excited in the field of quasi-optical electromagnetic beam*

A typical scheme of creation of electric gas discharges in quasi-optical MW beams is shown in Fig.2.1. It contains MW generator and special system forming quasi-optical focused electromagnetic beam of required intensity at a given distance from the focusing lens or mirror.

If in a certain (focus) region of this beam magnitude of E-component of electromagnetic wave $\boldsymbol{E}_0$ is greater than the field $\boldsymbol{E}_{\mathbf{br}}$ required for electric gas discharge at given pressure $\boldsymbol{p}$, there will be microwave gas breakdown and created MW discharge will further develop in space.

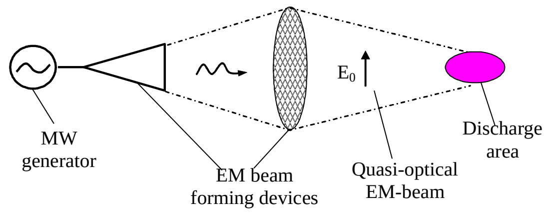

Fig.2.1.

Experiments indicated that in the band of EM radiation frequencies $\boldsymbol{f} \approx 2\div15$ GHz, corresponding to region of wavelengths of TEM-mode electromagnetic beam $\boldsymbol{\lambda} = (2\div15)$ cm, all types of realized MW discharges are in fact identical [1]. Thus, for example, in air at pressures of tens-hundreds of Torr MW discharges represents a volumetric system of plasma channels. The illustrating photo of such type discharges is shown in Fig.2.2.

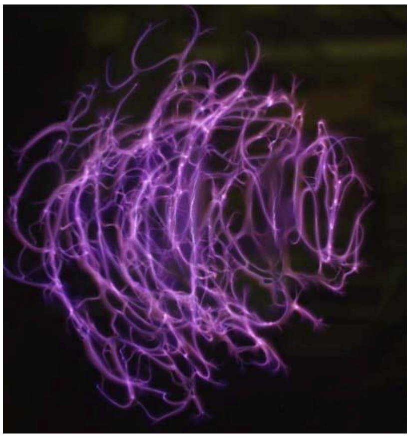

Fig.2.2.

This discharge structure was generated at air pressure $\boldsymbol{p} = 100$ Torr, wavelength $\boldsymbol{\lambda} = 8.9$ cm, magnitude $\boldsymbol{E}_0 \approx 6.5$ kV/cm and MW pulse duration with quadrilateral envelope $\boldsymbol{\tau}_{pul} = 40$ μs. In this photo, as in other presented below similar photos, vector $\boldsymbol{E}_0$ is vertical, and radiation comes to discharged area from left to right.

Characteristic transverse size of the discharge area in Fig.2.2 approximately equal to 15 cm. From the electrodynamic point of view separate plasma sections of such a discharge represent resonant electromagnetic vibrators.

The most interesting feature of this type MW discharge is that it effectively interacts with the microwave radiation excited it, and gas temperature in its resonant parts reaches several hundred and thousands degrees centigrade. Therefore these MW discharges can provide efficient volumetric ignition of fuel mixtures.

However, realization of such freely localized MW discharges at high gas pressures $\boldsymbol{p}$ in practice is not so simple thing. For example, the minimum breakdown (critical) electric field in air can be calculated by the following formula:

$$E_{\text{br min}} = E_{\text{cr}} = 42 \cdot p \text{ , [Torr, V/cm],}$$

and at air pressure $\boldsymbol{p} = 1$ atm ≈ 760 Torr the required field magnitude $\boldsymbol{E}_{cr} = 32$ kV/cm. In linearly polarized traveling wave the EM energy flow density determines by the formula:

$$I = E_0^{\,2} / \left(2 \cdot Z_0\right), \text{ [W/cm}^2\text{]}$$

where $Z_0 = 120 \cdot \pi$ Ohm. At calculated earlier value $\boldsymbol{E}_{cr} = 32$ kV/cm this results in $\boldsymbol{I} = 1.3 \cdot 10^6$ W/cm^2. From theory it follows that maximum focused EM beam in focus area has characteristic transverse size about $\boldsymbol{\lambda}$. For example, at $\boldsymbol{\lambda} \approx 10$ cm a square of this cross-section $\mathbf{S}_{beam} \approx \lambda^2 = 10^2$ cm^2. So, for execution of air breakdown at atmospheric pressure the MW beam power $\boldsymbol{P}_{beam} = \boldsymbol{I} \cdot S_{beam} \geq 130$ MW (!)

Nevertheless numerous experiments have proved that such kind of MW discharges can be realized also at high gas pressures. For this purpose the condition of breakdown should be provided only in local area of MW beam, i.e. gas electric breakdown must be *initiated*.

3. Subcritical MW discharge with spatially developed streamer structure

One of the most efficient ways of breakdown initiation in weak MW fields with $E_0 < \boldsymbol{E}_{cr}$ is insertion into the MW beam along its vector $\boldsymbol{E}_0$ of metal cylindrical electromagnetic vibrator [2]. For instance, it is well known that even at insertion in the MW field of a simple small metallic ball with diameter $2a \ll \lambda/4$, the induced field on its poles, where the vector E_0 is perpendicular to ball surface, $\boldsymbol{E}_{pol} = 3\boldsymbol{E}_0$.

If one takes a linear cylindrical vibrator with spherically rounded ends with of total length $2L$ the field $\boldsymbol{E}_{pol}$ will strongly increase, especially when the vibrator length corresponds to electrodynamic resonance: $2L_{res} \approx \lambda/2$. As a result even at the incident wave field $\boldsymbol{E}_0 << \boldsymbol{E}_{cr}$ the resulting field $\boldsymbol{E}_{pol}$ can exceed $\boldsymbol{E}_{cr}$. Such vibrators are capable of initiating MW gas breakdown at high high pressures $\boldsymbol{p}$.

Experiments showed that in some range of sub-criticality at comparatively high values $\boldsymbol{p}$ the developed after initiation discharge has the same spatially-developed plasma-channel structure like in case of super-critical discharges (Fig.2.2). For example, at $\lambda \approx 10$ cm and atmospheric air pressure $\boldsymbol{p}$ it has such structure already at $\boldsymbol{E}_0 \geq 2$ kV/cm [1]. Typical photo of such discharge at $\lambda = 8.9$ cm, $\boldsymbol{E}_0 \approx 6$ kV/cm and $\boldsymbol{\tau}_{pul} = 40$ μs is presented in Fig.3.1.

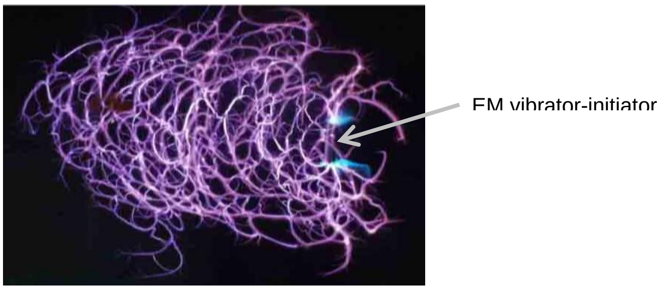

Fig.3.1.

On the right side of the discharge area there is a cylindrical vibrator-initiator with diameter $2a = 3.5$ mm and length $2L = 2.5$ cm. On this photograph vibrator's edges are of blue color and glow more brightly. Its size $2L$ can serve as image scale in the picture.

Detailed studying of properties of such kind discharge showed that they represent dynamically developing plasma formations. Springing and branching streamer channels form discharge area. Channels, arising on initiator poles, sprout mainly towards and across EM radiation, filling volume of EM beam.

Obviously from the point of view of aerodynamics these values of front velocities are rather considerable. Just for this reason the executed experiments on ignition of such discharges in airflow with speed $\mathbf{v}_{fl} \leq 500$ m/s have demonstrated that in this case the discharge structure and its property practically do not vary [3].

Some individual parts of considered discharge plasma channels having length commensurable with $\lambda/2$ represent resonant electromagnetic vibrators which have the big effective area of power interaction with incident EM wave $\mathbf{S}_{eff}$.

As a result depending on experimental conditions as well as in case od super-critical discharges, the gas temperature in these channels can rise to thousands degrees centigrade. Just for this reason experiments on creation of such discharges even in high-speed flammable air-propane flows have proved that these discharges effectively ignite such gas mixtures. The corresponding photo illustrating this exciting phenomenon is placed in Fig.3.2 [4].

Fig.3.2.

In the photo radiation wavelength $\lambda = 2.5$ cm, $\boldsymbol{E}_0 = 3$ kV/cm, $\boldsymbol{\tau}_{pul} = 100$ μs and static gas pressure of stoichiometric composition $\boldsymbol{p} = 100$ Torr. The gas flow speed $\boldsymbol{v}_{fl} = 500$ m/s and is directed from bottom upwards. In that experiment the burning area had the horizontal size about 4 cm.

Series of such experiments showed that this MW discharge in different conditions ignites air-propane mixture spread through its area, this burning area is stabilized in space up to $\mathbf{v}_{fl}$ of several hundred m/s, and its tempo of burning is very high. Another remarkable fact is that very lean fuel mixtures are also ignited and fully burn out, in which propane concentration is less than the threshold limiting a zone of air-propane mixture ignition in usual conditions. In the near zone of streamer channels the flame front speed may reach 150 m/s.

Many listed features of mixture burning process which is ignited by the considered-type MW discharge say that as a result of plasma-chemical processes streamer channels are sources of hard ultra-violet (UV) radiation. Thus, molecular composition of flammable mixture also greatly modifies.

There is no doubt that such type of the MW discharge can be used for fuel ignition in ramjet engines as it is shown in conditional scheme in Fig.3.3.

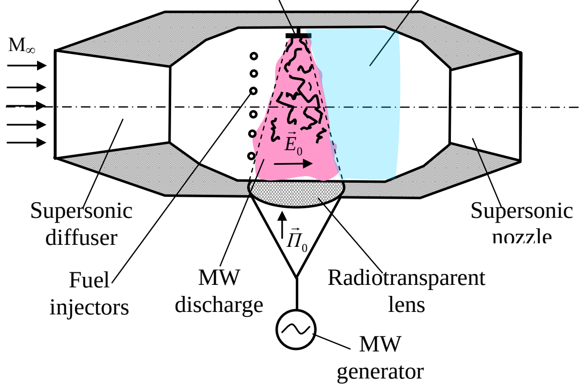

Fig.3.3.

Herewith it is necessary to remember the following aspects. Even in case of ultimately focused microwave beam for ignition of discussed discharge the power of MW beam $\boldsymbol{P}_{beam}$ should be very high. So, for example, Fig.3.1 corresponds to $\boldsymbol{P}_{beam} \approx 2$ MW, and Fig.3.2 – $\boldsymbol{P}_{beam} \approx 100$ kW.

In practice realization of such values $\boldsymbol{P}_{beam}$ is possible only in the pulse mode of operation at pulse duration τ_{pul} about tens microseconds, and at average power, which is determined by pulse repetition rate, $\boldsymbol{P}_{av}$ about several kilowatts. Naturally, during $\boldsymbol{\tau}_{\mathbf{pul}}$ the discharge should cover all the cross-section section of an engine channel. In practice the situation can become complicated at big cross-sections of burning channels. In this case there is the problem about search for new possible ways of increase in speed $\boldsymbol{v}_{fr}$.

4. Subcritical MW discharge on a dielectric surface

In the course of investigations of properties of the considered type discharge special experiments were carried out in which the dielectric plate with an EM vibrator fastened on its surface was placed in the MW beam focus area. In one of series of those experiments the plate was located along the EM beam optical axis in the plane $\boldsymbol{E}_0$–$\boldsymbol{k}$ ($\boldsymbol{k}$ is propagation vector of incident MW radiation). Experiments showed that in this case discharge streamer channels, extending mainly towards to EM radiation and across it, do not come off a dielectric surface [5]. The characteristic appearance of such MW discharge is presented in Fig. 4.1.

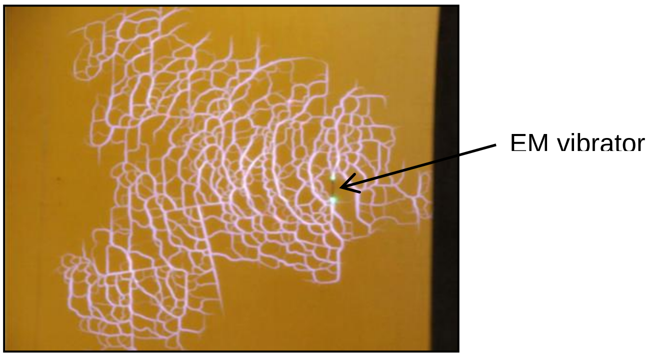

Fig.4.1.

In that test wavelength λ = 8.9 cm, $\boldsymbol{E}_0 \approx$ 6 kV/cm, τ_{pul} = 40 μs and air pressure $\boldsymbol{p}$ was 1 atm. The discharge propagates on a fiber-glass plastic plate surface of 1 mm in thickness. The linear vibrator-initiator with diameter $2a$ = 0.3 mm and length $2L$ = 14 mm was applied. In the photo it is pals on the right, and its ends shine a littlie brighter.

Maximum propagation velocity of this discharge along dielectric surface is about $v_{fr} \approx 5 \cdot 10^5$ cm/s. In identical experimental conditions it approximately in 1.5 times higher than corresponding value $\mathbf{v}_{fr}$ of the initiated subcritical discharge with the volumetric developed streamer structure.

However, today practical application of such MW discharge in ramjet engines is hardly possible. At same time it is good idea to analyze the scheme of usage of similar MW discharges on dielectric surface, if this surface has a mesh-type structure, and streamer channels still propagate exactly along its surface. Special experiment was carried out for clarification of the last assumption. In that experiment the flat dielectric net with rectangular cells of 5×5 mm, made of capron threads 0.3 mm in diameter, was placed along the MW beam axis in the plane $\boldsymbol{E}_0$–$\boldsymbol{k}$. Experiments were carried out on installation with λ = 8.9 cm at $\boldsymbol{E}_0$ = 6 kV/cm, τ_{pul} = 40 μs and air pressure p = 1 atm.

MW breakdown was also initiated by metallic EM vibrator with diameter $2a$ = 0.3 mm and $2L$ = 40 mm. The typical photo of the discharge realized in these conditions is shown in Fig. 4.2. Again the vibrator with shining ends is located on the right of this photograph.

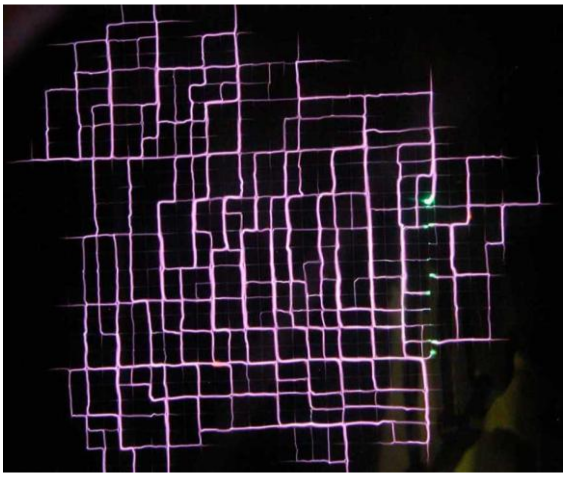

Fig.4.2.

Executed experiments have demonstrated that in this case the discharge is also formed by branching streamer channels which propagate only along surface of dielectric threads.

5. Conclusion

Thus, MW discharge excited in the field of a quasi-optical EM beam on a dielectric net after detailed investigations of its properties can have realistic prospect of application in plasma aerodynamics including new-generation ramjet engines. The simplified scheme of such engine design with MW ignition system is depicted in Fig.5.1.

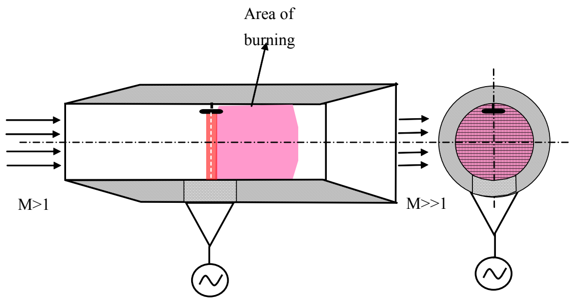

Fig.5.1.

In such a design the net almost will not create aerodynamic resistance. Also air flow deceleration at an engine entrance may not be demanded. Plasma-chemical modification of molecular composition of a flammable mixture will allow to reduce extension of burning area. Various ways of fuel injection in flow through internal channel in dielectric net and its mixture with air can be considered.

However, first of all detailed studying of fundamental properties of this new kind of MW discharges on various dielectric and covered metallic nets is strongly required. It will include:

1. Determine of discharge properties depending on such net parameters as its step, diameter and material of threads, shape of its transversal cross-section, etc.
2. Determine of propagation velocity of discharge front $\mathbf{v}_{fr}$ along the net in different conditions
3. Obtain data of influence of net blow by high-speed air flow and propane-air mixures at their various percentages on discharge characteristics.
4. Measurements of propane-air burning area extension and degree of gas mix combustion.

References

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