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Microwave Discharges and Possible Applications in Aerospace Technologies

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There are many types of gas discharges in the field of microwave radiation: diffusion and streamer, overcritical and subcritical, volumetric, surface, and attached to an initiator. The physics and features of each type of microwave discharge are described. In contrast with the conventional approach, the designed theory of streamer discharge development is based on the adequacy of the following factors: self-consistency of the electromagnetic field at the streamer presence, the ionization balance in the microwave electric field, Ohm heating, and electron diffusion. The influence of ultraviolet radiation from the streamer head is secondary and is not being taken into account. The simplest estimations of the main parameters of discharges, based on this theory, are compared with experimental data. The possible applications of the most interesting types of discharges (namely, subcritical discharges, initiated by electromagnetic resonant vibrators) are discussed. Such discharges can be used for remote energy deposition into a gas for flow control and for combustion initiation in high-speed flows of combustible mixes.

Nomenclature

a_v, a_{av}, a_s	=	radii of the initiator, avalanche, and streamer
c, e, m	=	light velocity, electrical charge, and mass of the electron
D	=	electron diffusion coefficient
E	=	effective amplitude of the electric field of microwave radiation
E_{cr}	=	critical value of the electric field
N, p	=	number density and pressure of gas
n	=	electron number density
V_s, V_{flow}	=	streamer propagation and flow velocities
λ, ω	=	microwave radiation wavelength and circular frequency
ν_i, ν_a, ν_{tr}	=	frequencies of ionization, attachment, and transport collision of the electron
σ	=	electrical conductivity, s^{-1}
τ_{av}	=	time of avalanche development

I. Introduction

AMONG the many different types of electrical gas discharges, the freely located discharge in the focus of converging microwave (MW) radiation represents one of special interest. This type of discharge is not only a very intriguing subject, but it is very important from the point of view of possible applications in a wide spectrum of technology directions. The typical scheme for the creation of a freely located MW discharge is shown in Fig. 1. The discharge arises in the focus of converged microwave radiation, where the amplitude of the MW electric field is maximal.

The freely located MW discharge in the focus of MW radiation was first observed by Khodataev in 1957 [1]. A photograph of the first discharge, published in [1], is provided in Fig. 2. This discharge was at low gas pressure and had a diffusive character. Later, freely located discharges were observed at intermediate and even high gas pressure [2–5] up to several atmospheres [6]. The experimental observations showed an extremely wide diversity in the types of MW discharge. The image of the discharge strongly depends on parameters such as gas pressure, MW radiation level and polarization, wavelength, pulse duration, repetition frequency, etc. From the very beginning, investigators tried to design a classification system to describe this diversity [7–10]. It was shown that the types of discharges are the same in various gases, both molecular and inert, and a qualitative diagram was proposed, separating the areas of existence of each type [11]. For air, the variety of discharge type is reflected in the quantitative diagram presented in Fig. 3, which was published in [12]. The diagram generalizes experimental data obtained in an installation with a radiation wavelength of ~8.9 cm and pulse duration up to 43 μs. Other experiments show that this diagram is representative for wavelengths from 1 to 10 cm [13].

The discharge presented in Fig. 2 is a diffusion type, which is characterized by one or more smoothed clouds of weakly ionized gas located in the focus region. This diffusion discharge is observed at low gas pressures (domain I in Fig. 3) below some threshold (line 1 in diagram) that equals 20–70 torr, depending on the wavelength of MW radiation.

At intermediate and high gas pressures, the MW discharge has a streamer nature. This type of discharge appears as a complicated net of thin filaments. The plasma created in the streamer channels has a high temperature and comparatively high electrical conductivity [14]. Streamer discharges are observed in areas II and III of Fig. 3. Line 2 in this figure, which is the well-known Pashen's curve modified for MW discharges [15], separates overcritical discharges (domain II) from subcritical discharges (domains III and IV). Below line 3 is a region in which the so-named attached subcritical discharges are observed (domain IV). Subcritical discharges can be created in the domains III and IV through the use of a discharge initiator. A time-integrated photograph of a subcritical discharge is shown in Fig. 4. In this photograph, MW radiation enters from the left and the initiator of the discharge is located on the right.

In the following sections, we will discuss the physics and properties of each type of MW discharge.

II. Overcritical Discharges

A. Initial Stage of Microwave Discharge (Avalanche)

If the electric field is overcritical in a location in which a free electron exists, the process of avalanche ionization begins. This process is quite correctly described by the diffusion equation with source caused by the ionization by electron impact in an external MW electric field:

$$\frac{\partial n}{\partial t} = (\nu_i - \nu_a) \cdot n + D \cdot \Delta n$$

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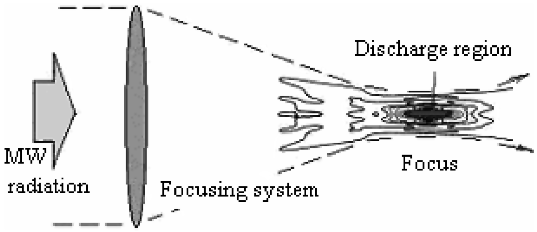


Fig. 1 Typical scheme of the MW freely localized discharge in the focus of a convergent beam with isolines of electric field amplitude in the focus vicinity.

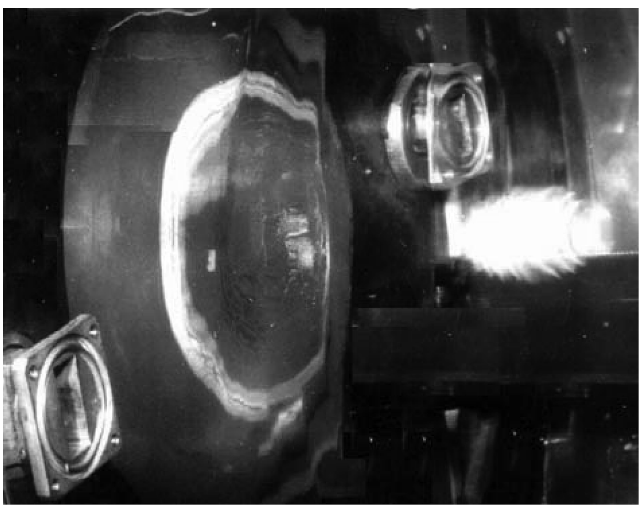


Fig. 2 First freely located gas discharge in the focus of MW radiation. The focusing dielectric lens is on the left and the discharge is on the right in the focus of the lens; gas pressure is several torr and λ ≈ 3 cm.

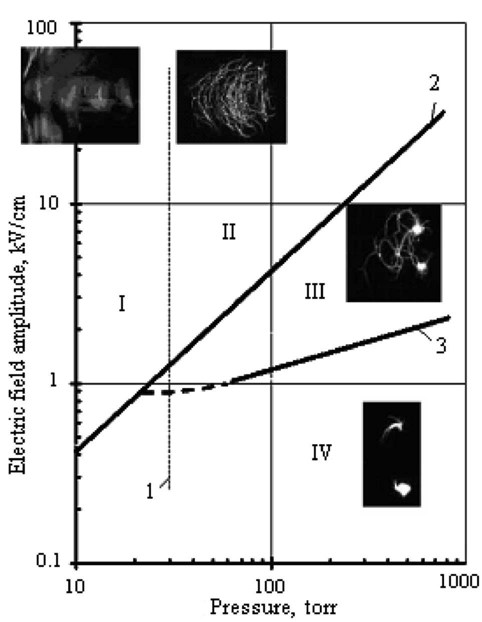


Fig. 3 Type classification of MW discharges in still air.

The solution of this equation at spherical symmetry is known:

$$n = \frac{A}{(4\pi D t)^{3/2}} \exp\left((\nu_i - \nu_a)t - \frac{r^2}{4Dt}\right) \quad (1)$$

where n is the electron number density, D is the free electron diffusion coefficient, ν_I is the ionization frequency that depends on

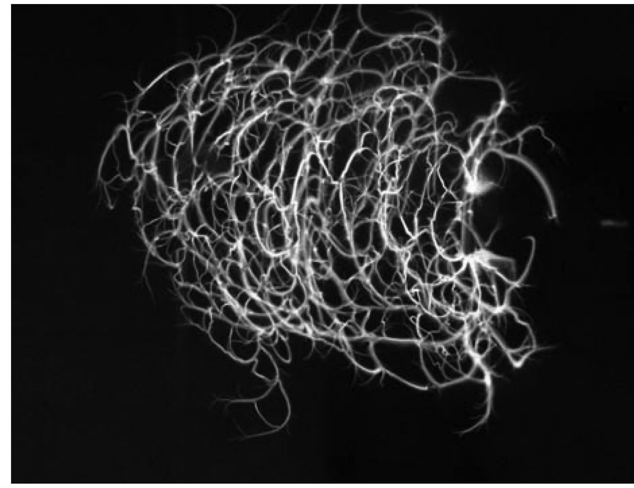


Fig. 4 Photograph by open lens of the volumetric subcritical MW discharge; MW radiation is directed from left to right; pulse duration of MW radiation is 40 μs, air pressure is 760 torr, wave length is 8.9 cm, and length of the initiator is 2 cm.

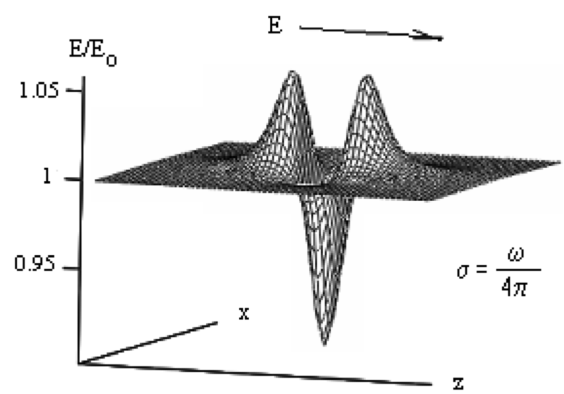


Fig. 5 Spatial distribution of electric field amplitude in the avalanche vicinity.

the electric field amplitude, ν_a is the frequency of electron attachment to gas molecules, t is the time, and A is a constant approximately equal to 1. Of course, an avalanche begins if $\nu_I > \nu_a$. In contrast with an avalanche in a dc electric field, the plasmoid average drift is absent. When conductivity of the plasmoid has increased to a value near $\omega/4\pi$ (ω is the circular frequency of MW radiation), the avalanche-cloud polarization field adds to the external field. The amplitude of the combined field on the poles of the plasmoid is greater, whereas in the center of one, the field is lower than the unperturbed field, as seen in Fig. 5, in which the calculated space distribution of field amplitude near an avalanche cloud is presented. Because a very small increase in field amplitude results in a strong increase in ionization frequency, an intense development of the plasmoid along the direction of the electric field results with little or no further increase in the transverse plane. Further development of the ionization channel occurs in one direction, forming a thin filament of ionized gas. The elementary estimation, based on the condition noted earlier, results in the formula for the time of development stage of the spherical avalanche [16]:

$$\tau_{\text{av}} \approx \ln\left(\frac{\omega m_e \nu_{\text{tr}}}{e^2} \cdot \left(\frac{D}{\nu_i(E) - \nu_a}\right)^{3/2}\right) \Big/ (\nu_i - \nu_a) \quad (2)$$

The value of logarithm in Eq. (2) changes weakly over a wide range of field frequency and gas density and varies in the range of 10 to 20, depending mainly on gas pressure. Correspondingly, the radius of the saturated avalanche a_{av} and of developing plasma filamentary streamer a_s is estimated by Eq. (3):

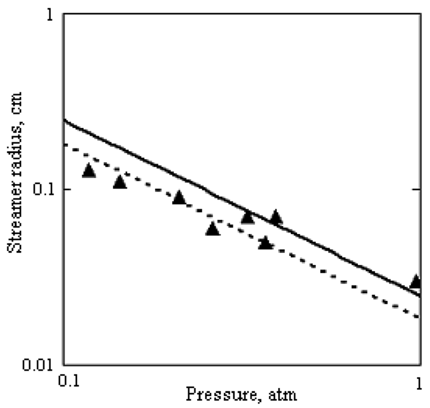


Fig. 6 Dependence of streamer radius on air pressure, estimated by Eq. (3) at $E_0/E_{cr} = 1.2$ (solid line) and $E_0/E_{cr} = 1.5$ (dashed line); triangles are measured values.

$$a_{av} = a_s \approx 2\,\ell n\left(\frac{\omega m_e \nu_{tr}}{e^2}\cdot\left(\frac{D}{\nu_i(E)-\nu_a}\right)^{3/2}\right)\cdot\sqrt{\frac{D}{\nu_i(E)-\nu_a}} \quad (3)$$

As seen from Eq. (3), the radius of the developing streamer ionization channel is inversely proportional to the density and pressure of the background gas. Measurements of the streamer radius presented in [6] are shown in Fig. 6 over a range of pressure at wavelength $\lambda = 8.5$ cm and are compared with Eq. (3).

B. Diffusion Microwave Discharge

If the radius of the saturated plasmoid, estimated by Eq. (3), is comparable with the inverse wave number of the radiation $\lambda/2\pi$, the influence of the plasmoid on the electric field distribution results in a structure with a spatial scale of the wavelength, as one can see in the upper left part of Fig. 3. The boundary separating the diffusion type of MW discharge from the streamer discharges is defined by this condition and can be established by the equality $a_{av} = \lambda/2\pi$ or, for air,

$$p_{ds} \approx \frac{20}{\lambda}\ \text{torr} \quad (4)$$

It is important to note that a diffusion discharge reflects MW radiation very well, and so it is not able to absorb MW radiation energy with a high efficiency. In general, discharges at low pressure cannot be used efficiently for gas heating, because the field in the plasma region is critical (i.e., it is proportional to gas pressure, corresponding to Pashen's curve). So the temperature of the heated gas must be proportional to $E_{cr}^2/p \sim p$. Thus, the general tendency is a proportionality of temperature rise to gas pressure.

It must be noted that if the pulse duration of MW radiation is long and the gas is still, the development of heat ionization instability causes the formation of a filamentary structure in a diffusion cloud [17]. If the gas is moving through the discharge area (in MW focus), so that the pass time is less than the reverse increment of instability, the discharge conserves its diffusion type.

C. Streamer Microwave Discharge

Overcritical MW streamer discharge can be created at gas pressures higher than p_{ds}. The detailed properties of freely localized electric discharge in air are described in [18,19].

The most clearly overcritical streamer discharge of high pressure is observed in a MW resonator, in which a sufficiently high electric field amplitude (more than the critical value) can be achieved [6]. As noted, the saturated avalanche develops along the electric field in both directions as a thin filament. The higher the gas pressure, the smaller the filament radius. The electric field at the ends of the developing streamer can be much higher than the original value and approximately proportional to the ratio of the streamer length to its diameter. This means that the ionization frequency, defined by the electric field, at the ends of the filaments achieves very high values. The longer the streamer extends along the electric field, the higher the amplitude of the local electric field at its ends. The development speed of the streamer ends can be estimated by Eq. (5),

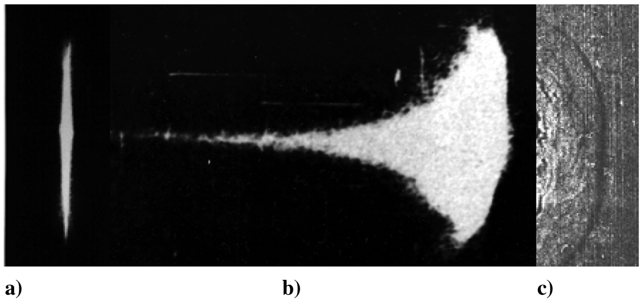


Fig. 7 Streamer overcritical discharge in the focus of the open MW resonator: a) photograph by open lens, b) sweep in time during 100 ns, and c) shadow photograph of a shock wave generated by an exploded streamer.

$$V_s = a_s \cdot \nu_i \quad (5)$$

and can achieve extremely high values (up to several thousands of kilometers per second). In Fig. 7, the discharge in an open MW resonator is shown. The full length of the developed streamer is approximately $\lambda/2 \approx 2$ cm and the time of development from one electron to the finish state is 100 ns. Thus, one can see that the maximum velocity of the streamer end is approximately 10^8 cm/s.

The most important property of the streamer discharge is its resonant nature at its finishing stage. The length of the well-conducting filament equals one-half of the wavelength λ, which corresponds to electromagnetic resonance. The resonant streamer has an effective cross section of its interaction with the electromagnetic radiation $S_{ef} \approx \lambda^2/2$. The interaction consists of both diffraction and absorption of the initial radiation. Usually, the resonant streamer has equal cross sections for diffraction and absorption $\lambda^2/4$. The absorption of energy captured by the streamer resonator limits the lifetime of the high field amplitude in the streamer region, which stops the light emission from the streamer. Simultaneously, the energy absorbed by the streamer causes the thermal explosion, which generates a shock wave, shown in Fig. 7c. For comparatively long MW pulse durations, the overcritical MW discharge development is observed as separate streamer channels, which arises in places in which free electrons exist, caused by either natural radiation or hard radiation from the discharge itself. The streamer channels are a source of UV bremsstrahlung radiation, which is one possible reason for the halo observed around the channel [20]. Usually, the electron temperature in MW streamer channels corresponds to a critical value of approximately 2 eV, with the gas temperature increasing to a value up to several thousands of degrees Kelvin.

At gas pressures about several atmospheres, the MW current induced in the resonant streamer can be sufficiently high for compression of the streamer channel by its own averaged magnetic pressure. This type of discharge can be achieved in a open resonator created using two spherical mirrors [21]. The MW pinch effect was first observed and described in [22]. In this case, the plasma temperature can be increased up to extreme high values, potentially reaching conditions sufficient for nuclear reactions.

III. Subcritical Discharges

Subcritical MW discharges are the most applicable types of discharges, because these discharges can be created in high-pressure gases using easily realizable MW facilities.

A. Volumetric Subcritical Discharges

Using a special initiator, the streamer microwave discharge is able to propagate in a MW field E, which is less than the critical value E_{cr}

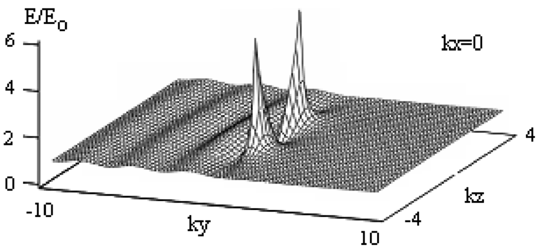


Fig. 8 Calculated electric field amplitude E around a thin resonant vibrator; radiation is directed from left to right.

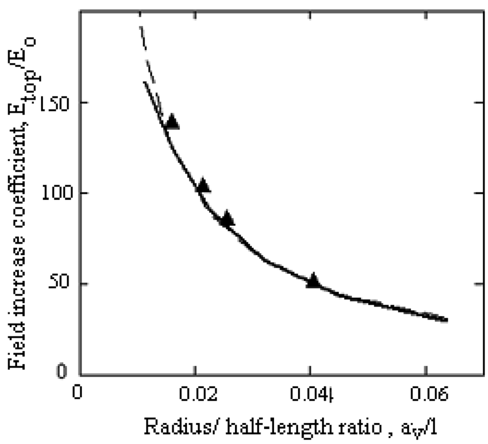


Fig. 9 Field increase dependence on vibrator radius a_v; half-length of vibrator $l \approx \lambda/4$ is resonant; triangles are measured values at $\lambda = 12.5cm$, the solid line is numeric calculation, and the dashed line is the estimation by Eq. (6).

and even at $E \ll E_{\mathrm{cr}}$. In this condition, the creation of the discharge requires only a local excess in the electric field over the critical electric field ($E > E_{\mathrm{cr}}$). This excess is provided by an initiator. A subcritical MW discharge can be excited by various ways: for example, by laser radiation [23,24]. However, a simpler way to initiate the discharge consists of placing sharp metallic bodies in the region with the MW field. The most effective realization of this type of initiator is a passive electromagnetic MW antenna placed into the radiation beam [25]. Such an initiator can be a metal rod with a length comparable to the wavelength of the MW radiation, oriented along the electric field. Such initiators are usually referred to as *vibrators* [26]. The electric current induced in the vibrator creates its own electric field, which can be much higher at its tips than the field of the incident MW radiation E_0. The calculated field distribution in the vicinity of a thin vibrator with resonant length $\lambda/2$ is shown in Fig. 8. The increase in the local electric field depends on the radius of curvature of the end of the vibrator and its length. The measured dependence of the field increase at the top of a resonant vibrator with a radius a_v is compared in Fig. 9 with the simple estimation

$$\frac{E}{E_0} = \frac{\lambda/2}{a_v} \tag{6}$$

The subcritical discharge has the appearance of a complicated net of thin bright filaments, the front of which propagates upstream against the MW radiation up to the region in which the field amplitude is below line 3 in Fig. 3.

The theory of a subcritical discharge initiated by a passive electrodynamic vibrator was developed in [27,28]. The subcritical streamer discharge develops based on row factors. The streamers in a subcritical discharge that have a sufficiently high electrical conductivity create a local increase in the electric field at their tips, similar to the vibrator and streamers for the overcritical discharge. If the field at the tip of the streamer is overcritical, ionization in this region and electron diffusion combine to result in the propagation of the streamer. Inside the streamer channel, the electric field is less than the field of the incident radiation, but the induced current heats the plasma in the channel. So the gas density in the channel decreases and the parameter E/N is supported at a more critical level. Without this heating, deionization will take place in the channel and the channel will lose its ability to increase the electric field at the tip of the streamer to values above critical.

The speed of the ionization front at the streamer tip is described by an equation such as Eq. (5). But the level of overcriticality in this case, realized on the tip of the streamer, differs from the unit only a little, being established at a level at which the speed of the ionization front corresponds to the rate of heating of the channel directly in the tip region of the streamer. The study of the MW subcritical streamer development by numerical modeling on a row of theory models allowed designing a system for simple estimations, proceeding from the following assumptions:

1) Heating, as well as ionization, occurs at the tip of streamer in a field that weakly exceeds the critical value E_{cr}.

2) Conductivity inside the streamer's head rises up to the value $\omega/4\pi$ by exponential law with the index $\nu_i t$.

3) Density in the same limits should fall up to the value in E_o/E_{cr} from the initial value.

4) The process is isobaric.

Ionization frequency at the head of streamer is estimated by Eq. (7), where p is the gas pressure, C_p is the specific heat at constant pressure, and $\omega = 2\pi c/\lambda$, c is the light velocity:

$$\nu_i = \frac{E_{\mathrm{cr}}^2}{C_p \cdot p} \cdot \frac{\omega}{4 \cdot \pi \cdot \ln(E_{\mathrm{cr}}/E_0)} \tag{7}$$

The radius of the streamer head is determined by the depth of the ionization front:

$$a_s = 2 \cdot \sqrt{\frac{D}{\nu_i}} \tag{8}$$

The most important parameter, the speed of the subcritical streamer, is described by Eq. (9):

$$V_s = 2 \cdot \sqrt{D\nu_i} \tag{9}$$

It is important to note that diffusion coefficient D in Eqs. (8) and (9) is of free electrons, because the ionization starts from very small values of electron density, and so the ambipolar field does not play a role [29]. One can see from Eq. (9) that the streamer velocity weakly depends on gas pressure p, because $D \sim 1/p$ and $\nu_i \sim p$ in known limits. The typical value for the streamer velocity for subcritical volumetric discharges is several kilometers per second [30]. Therefore, volumetric subcritical discharges can be created without difficulty in supersonic gas flow.

The lower the electric field E_0 of MW radiation, the lower the ionization frequency at the streamer head, which leads to an increase in its radius and a smaller field increase at the streamer head, defined by Eq. (6) as for the vibrator. A balance between the increase rate for the streamers and the subcriticality level of the MW radiation field defines the lower boundary for the existence of the subcritical discharges (line 3 in Fig. 3):

$$\frac{\lambda}{4 \cdot a_s} = \frac{E_{\mathrm{cr}}}{E_0} \tag{10}$$

Estimations of the lower boundary, provided by Eq. (10) together with Eqs. (7) and (8) for $\lambda = 8.9$ and 2.5 cm, are compared with measured values in Fig. 10.

Special discussion is warranted by the question about the ability of the subcritical discharge to propagate without limit against the MW radiation under the condition of area III in Fig. 3. As was already pointed out, the spot with a local overcritical field at the top of the streamer is needed for its propagation. This situation is the same as for the streamer channel in a direct current (dc) field, but only while the streamer length is less than $\lambda/2$ (i.e., the electrodynamic resonant

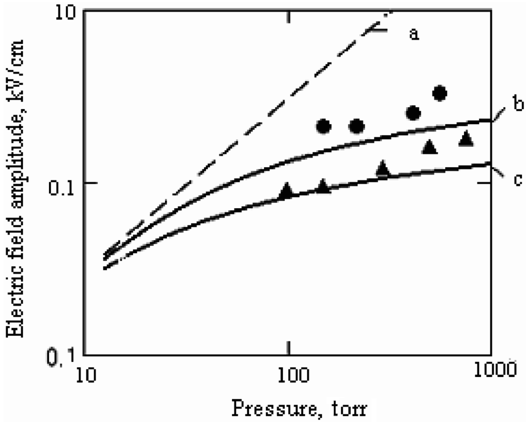


Fig. 10 Borders dividing areas of existence of subcritical streamer and deeply subcritical (attached) discharges; solid lines are the estimation by Eq. (8); $b - \lambda = 2.5$ cm and $c - \lambda = 8.9$ cm; points are experimental data (circles are $\lambda = 2.5$ cm and triangles are $\lambda = 8.9$ cm), and a denotes the critical field amplitude.

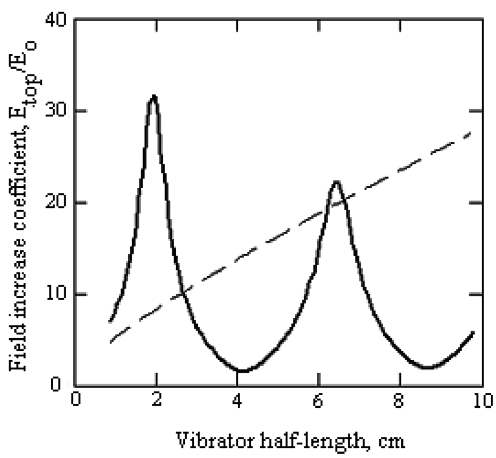


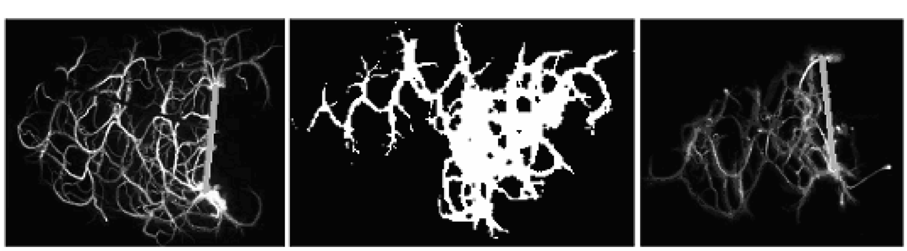
Fig. 11 Field increase at the ends of the metal cylinder with a radius of 0.07 cm, located along external electric field E_0 for a dc field (dashed line) and MW radiation with $\lambda = 8.9$ cm (solid line).

value). For the case with a dc electric field, the longer the filament length, the higher the local field increase at the end of the streamer. This trend is shown as the dashed line in Fig. 11. For the MW discharge, we have a completely different situation. If the streamer length is more than a half-wavelength of radiation, the electric field amplitude on top of the streamer decreases to a small value, shown by the solid line in Fig. 11. This circumstance creates different conditions for the development of the MW streamer discharge. A single streamer is not able to grow to a length of more than $\lambda/2$. This is the main reason why the unlimited propagation of the MW streamer discharge is realized only by means of a continuous branching of the filaments with the formation of a spatial structure such as a directed radio antenna. The photographs shown in Fig. 12 show the typical form of branching streamers. It is a sinusoidal snakelike structure with side branches attached at the points of extremum. The half-period and amplitude of this snakelike structure and the length of the branches have sizes of about $\lambda/8$. This character configuration arises at various conditions (gas type and pressure, wavelength of radiation, etc.). It is a bright example of the self-organization and spontaneous formation of a stable structure in a dissipative nonlinear medium with energy flow. The ability of the MW subcritical streamer discharge to self-organization was first noted by the authors of [31].

Numerical modeling of the streamer development by the formation of such structures confirms its ability to self-sustain an active spot continuously at its top or snake or branches and the inability to propagate in regions with forbidden branching [32]. The calculated temporal development of induced-current distribution in a branching streamer channel with the same space sizes is shown in Fig. 13. The discharge streamer system develops self-organizing for maximum interaction with the radiation. The formation of an antenna-shaped channel together with self-sustained optimal channel electrical conductivity (skin-layer equal to channel radius) provides resonant absorption of the radiation energy by the streamer channels [33].

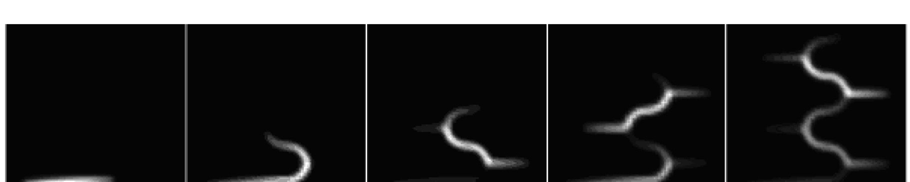
It must be noted that at short radiation wavelengths (of order 1 cm), when the diffusion scale is comparable with the inverse wave number $\lambda/2\pi$, the propagation of the MW discharge in a subcritical field is not caused by the streamer effect [34]. At these conditions, the discharge it caused by the ionization-overheating instability [17], which results in filamentation of the current. Inside the resulting hot filaments, the gas density is low, and so the parameter E/N is overcritical. This type of discharge defines the boundary between diffusion and streamer discharges.

The main property of the freely localized subcritical streamer discharge is its ability to absorb the energy of the exciting



λ=8.9cm λ=4.3cm λ=2.5cm

Fig. 12 The typical view of subcritical MW discharge initiated by a metal vibrator, oriented along the electric field of an external linear polarized electromagnetic wave; radiation propagates from left to right; air pressure is $p = 200$ torr.



0 μs 13 μs 27 μs 41 μs 55 μs

Fig. 13 Calculated temporal development of the current distribution in a branching streamer.

electromagnetic MW radiation with high efficiency. This property makes this discharge important from the point of view of practical applications. The volume of the plasma channels is much less than the volume of the discharge region that encompasses the discharge network of filaments. Immediately following this discharge, this energy is not averaged over the whole discharge volume, but it is localized in the thin plasma channels. In the resulting gas, temperature T inside these channels reaches several thousands of degrees. This feature allows the application of this discharge for ignition of fuel–air mixtures, and the average energy deposition in the discharge region makes possible the use of the streamer MW discharge for remote control of supersonic airflow by local energy addition [35,36].

B. Attached Subcritical Discharges

In contrast to volumetric subcritical discharges, which are capable of self-propagation, that lead to a net of hot conducting channels, the discharges at a lower electric field (named attached subcritical discharges or deeply subcritical discharges) stay attached to the place of initiation. A typical photograph of such a discharge initiated by an electromagnetic vibrator in still air is provided in Fig. 14. The attached subcritical discharge is of special interest because it can be created using MW radiation at a level that is several orders smaller than the critical one and can consequently be created in a gas of high pressure using MW sources with quite acceptable power [37]. An excellent example of such a discharge, which is maintained by MW radiation of extremely low intensity, is presented in [25,38]. Like the subcritical discharge, the attached discharges can be created and continuously sustained in high-speed flows over a wide range of gas pressures and flow velocities (up to and including supersonic flows). An example of an attached discharge is shown in Fig. 15, in which a photograph of a MW discharge initiated by vibrator in supersonic airflow is presented. In a speed flow the main heating of gas is laid near the sharp tip of vibrator, where discharge channel conductivity is small. However, MW currents inducted in a metal vibrator and in a discharge channel are connected by capacitive current through a very small gap between the surfaces of metal and plasma, which is about the Debue radius. As a result, the metal vibrator and plasma torch in speed flow are forming the united electrodynamic system with an effective length approximately equal to the resonant value, if the vibrator length is chosen correctly. The temperature in the attached discharge is also sufficiently high for the ignition of fuel–air mixtures, which opens wide opportunities for applying the attached discharge in various types of combustion devices [39]. The attached MW discharge was successfully used in experiments investigating the influence of energy addition in supersonic airflow. These experiments demonstrated that MW energy addition in supersonic flow could be used to reduce drag by several times [40] and to create lateral force for flight control [41,42].

The use of a vibrator loaded with an attached discharge provides a good means for effectively coupling incident MW radiation energy into a flowfield. Processing of measurement data in the wake of a discharge has shown that plasma-torch parameters of the attached discharge are optimum for maximum gas heating, and so heating power can be near the theory limit for single vibrator loaded by discharge (i.e., 0.25 of MW generator power [43]). Thus, a self-organization of the system also takes place in this case [43]. It should be noted that every level of MW radiation has a resulting optimum length of vibrator, such that the maximum effective coupling of the incident power and gas heating occurs.

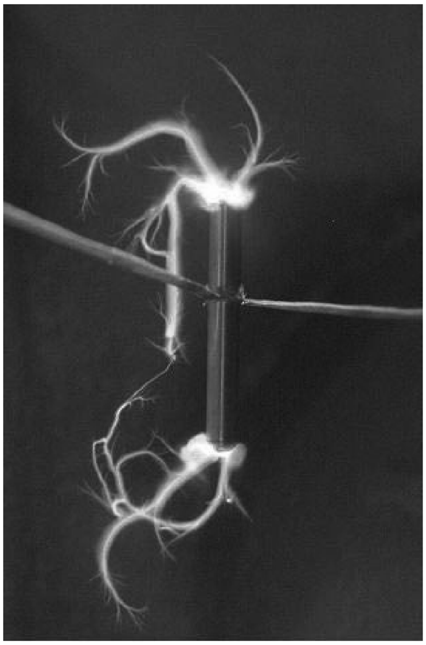


Fig. 14 Photograph by open lens of an attached subcritical discharge in still air.

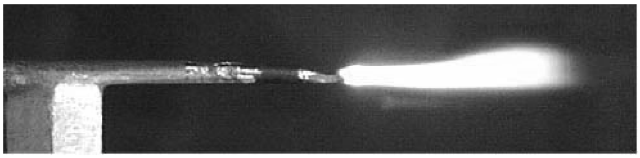


Fig. 15 Appearance of a deeply subcritical MW discharge, initiated by a thin sharpened vibrator, in supersonic airflow. The vibrator is supported in the middle part by a streamlined holder.

C. Surface Subcritical Discharges

A comparatively new kind of MW discharge is the surface discharge of high pressure [44,45]. This discharge can be created at the surface of the dielectric plate, which is located in the focus of a radiation beam. Figure 16 shows photographs of a surface discharge on a plate oriented transversely to the MW radiation beam (Fig. 16a) or along it, with the electric field parallel to the surface (Fig. 16b). In Fig. 16a, the discharge initiated beside the plate propagates against radiation and, meeting the plate, develops at the plate surface in the frame of MW beam caustics. In Fig. 16b, the initiator is located on the plate surface and discharge develops along the surface in both directions in the frame of MW beam caustics and stops at the boundary of the plate. The surface discharge can be classified as a subcritical discharge (area III on diagram Fig. 3), but line 3 in the diagram must be measured separately. Those measurements were executed particularly for surface discharge initiated by a system of vibrators at a wavelength of radiation of 3.15 cm and a pulse duration 3 μs [46].

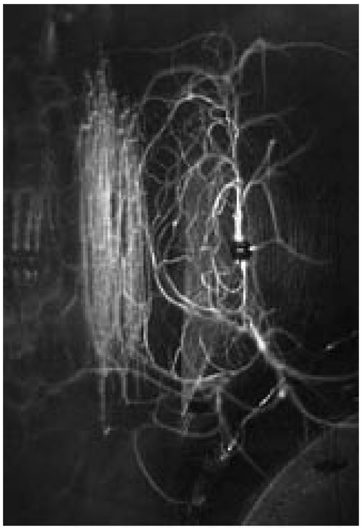
A high-pressure surface MW discharge with a streamer structure is a source of strong UV radiation. It was experimentally demonstrated that this type of MW discharge can be applied for surface processing of polymer films to increase adhesion [47].

Because the speed of propagation of a surface discharge at high pressure is very high (such as the volumetric discharge), this type of MW discharge can be created in high-speed gas flows and will likely find application in gas dynamics and combustion technologies. If further investigations confirm a good efficiency associated with the ability to absorb MW radiation, this discharge may also find application as a means for boundary-layer and flowfield control.

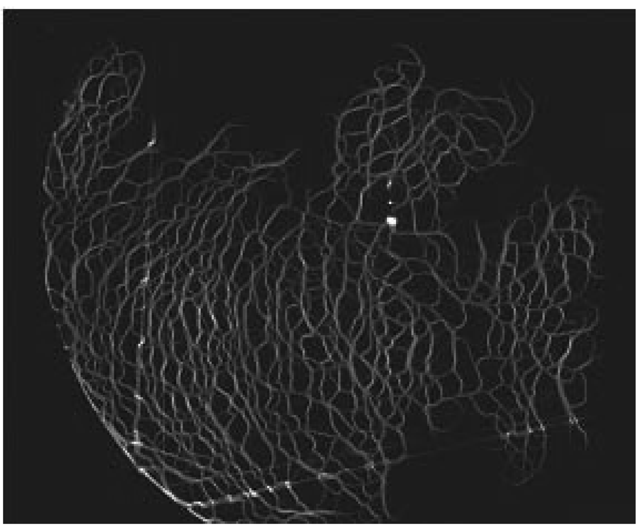
Microwave surface-diffuse discharge has also been observed at a low gas pressure [48,49]. In this case, the discharge has a diffusive nature and can be used in devices such as plasma-chemical reactors for surface processing, for demonstration of flowfield influence, etc.

IV. Possible Applications of Microwave Discharges

As discussed, microwave discharges enable an efficient means of coupling radiated energy into a gas. This characteristic of MW discharges may used to either serve as a technique for flexible energy deposition for aerodynamic flow control techniques. The filamentary nature of microwave discharges at moderate to high pressures also allows production of high-temperature regions that may be used as a



a)



b)

Fig. 16 Appearance of surface discharge on a quartz plate: a) the plate is oriented transversely to the MW beam and discharge is initiated by a metallic ball located outside of a surface of the plate and b) the plate is oriented along the MW beam. The electric field is parallel to the surface and the radiation source is to the left.

mechanism for ignition and flame-sustaining in combustion systems. Recent investigations in these two areas are described next.

A. Airflow Control

A number of authors have investigated the use of electrical discharges for the purpose of drag reduction at supersonic speeds. These investigations have led to the conclusions that for efficient drag reduction, the energy deposition must occur upstream of the bow shock wave in an area that is smaller than the diameter of the body. One candidate for this energy deposition is the MW discharge, wherein the radiant energy can be beamed upstream of the bow shock wave and the dimensions of the discharge can be controlled through proper selection of wavelength, pulse duration, initiation source, etc.

The influence of MW energy deposition into the supersonic flow around a body was investigated both theoretically and experimentally in [40] using an attached subcritical discharge. As seen in Fig. 17, the experimental facility consisted of a test chamber, Laval's nozzle, an injecting Mach 2 air jet, a vibrator (initiator) located upstream of a blunt cylinder, and a confuser. The test-section pressure was initially set to a level equal to the nozzle outlet pressure, and so the injected jet was working in a regime of the matched flooded jet. In this mode of operation, a relatively uniform Mach 2 stream at approximately 500 m/s interacted with the vibrator, initiating an attached MW discharge, and the blunt cylinder for a test duration of 1–2 s. Experiments were carried out using a magnetron source of a 12.5-cm wavelength with 2.1-kW MW beam power. The MW pulse duration was $\sim$1 s and was timed to coincide with the airflow.

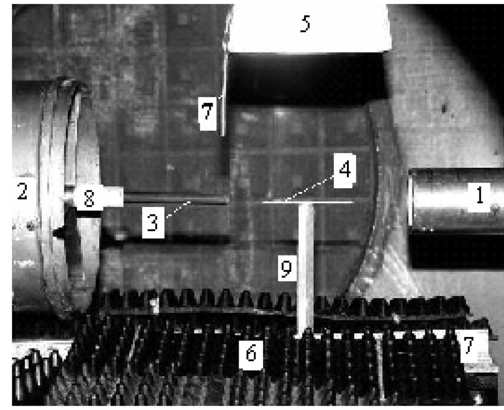


Fig. 17 Central part of the test chamber: 1 is the Laval nozzle, 2 is the receiving diffuser, 3 is the overflowed model, 4 is the initiating vibrator, 5 is the MW horn, 6 is the absorber of a MW radiation, 7 is the pressure tube measuring the static pressure in the chamber, 8 is the inlet of the balance, and 9 is the vibrator support.

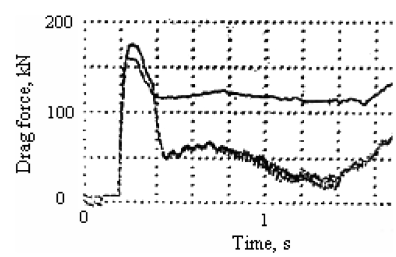


Fig. 18 Signal waveforms from the balance sensor recording the temporal dependence of the drag force of the cylindrical model placed in the supersonic flow without discharge (upper curve) and with discharge before the bow shock (bottom curve). The distance between the vibrator edge and the model is 1 cm.

Tests were performed with the trailing edge of the vibrator located 1–2 cm upstream of the 0.7-cm-diam blunt body. The measured drag on the blunt body with and without the MW discharge is shown in Fig. 18, in which it is seen that the drag decreases by as much as 75% with application of the MW discharge. Using an estimate that 20–25% of the radiated power coupled into the discharge, the energetic efficiency ($\eta = \Delta F_{\mathrm{drag}} \cdot V_{\mathrm{flow}}/P_{\mathrm{discharge}}$) was estimated to be in the range of 0.9 to 1.13, which agrees quite well with theoretical predictions for the case in which the diameters of the body and energy-deposition zones are approximately equal. Energetic efficiencies much greater than 1 can be achieved with thinner energy-deposition regions.

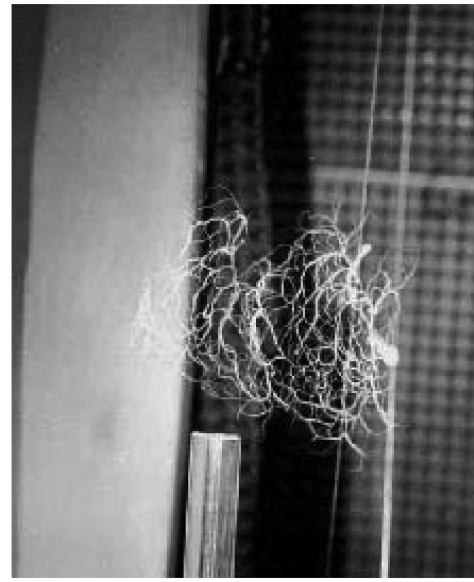
B. Combustion Initiation and Stabilization

The hot channels created in the filamentary MW discharge have been investigated as a source for ignition and flameholding in combustion systems. The ability of subcritical MW discharges to ignite premixed propane–air mixture at low speeds was investigated in [12], and sample results are shown in Figs. 19 and 20. In these figures, a vibrator is located in the focal region of MW radiation that enters from the left, and a premixed propane–air mixture can be introduced through the tube seen at the bottom of the photograph. In Fig. 19, an attached subcritical MW discharge is generated at the tips of the vibrator. In Fig. 20, a pulsed subcritical MW discharge is initiated using a vibrator located to the right of the propane–air tube. In the latter case, the discharge propagates toward the source of the

a)

b)

Fig. 19 Deeply subcritical discharge, initiated by the vibrator with $2a = 0.25$ cm and $2L = 4$ cm ($E_0 = 1.5$ kV/cm), without flow of the flammable mixture (top photograph) and with the flow of the flammable mixture (bottom photograph).



a)

b)

Fig. 20 Microwave discharge in dead air in radiation ($\lambda = 8.9$ cm, $\tau_{\mathrm{MW}} = 40$ μs, and $p = 760$ torr), without flammable-mix injection (top photograph) and with propane–air mix injection (bottom photograph).

MW radiation over the exhaust location of the tube. In both cases, the MW discharge is shown to ignite the fuel–air mixture.

After the basic ability of the MW discharge to serve as an ignition source had been demonstrated, the impact of flow velocity on the ignition characteristics of premixed and nonpremixed propane–air mixtures was investigated [50]. The experimental setup for these investigations is shown in Fig. 21. Atmospheric airflow is ducted through a Mach 2 nozzle into a test section in which an electric vibrator is located. An inflow valve upstream of the supply nozzle is used to control the flow velocity through the test section. The vibrator is built with internal passages to allow injection of either propane or propane–air mixtures from the base of the vibrator. Microwave radiation is provided from a source in a plane perpendicular to the airflow. Sample results are provided in Fig. 22 for airflow velocities between 3 and 500 m/s. The vibrator is located on the left side of these photographs, with the MW discharge occurring at its aft end. The combustion zone is seen as the region downstream of the vibrator. A probe use to measure the pitot pressure and temperature in the wake of the discharge and combustion zone can also be seen. The results show combustion for airflow speeds, but the combustion zone shortens significantly with increased flow velocity.

Having demonstrated the ability to ignite propane in cold high-speed flows, the efficiency of a MW discharge ignition system was investigated in [51]. Using the setup shown in Fig. 22, vibrators of various shapes were investigated to optimize the extent of the MW discharge in a flameholding zone. In particular, thick hollow vibrators with serrated aft edges were investigated as an efficient means to initiate the MW discharge at several locations simultaneously. The vibrator was also modified with a hole in its leading edge such that airflow could be captured by the vibrator and mixed with propane before ducting the mixture to the discharge zone. A photograph of this new vibrator under operation with the MW discharge and combustion is provided in Fig. 23. A sample thermocouple trace in the wake of the vibrator is also shown, illustrating a much higher temperature rise in the presence of a

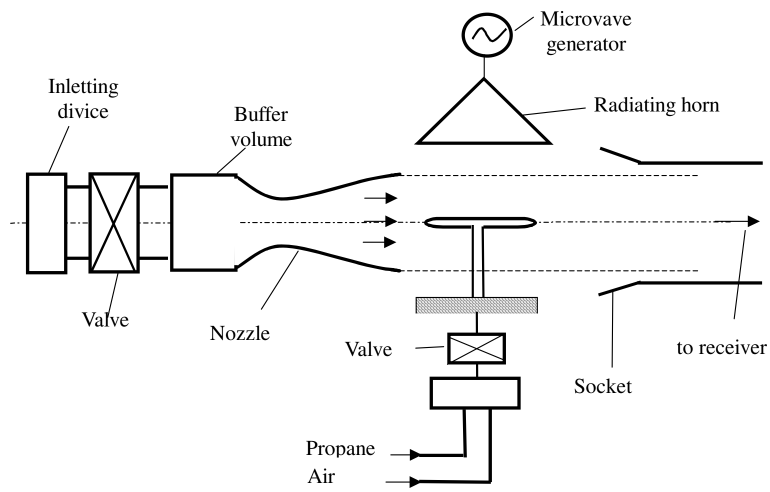


Fig. 21 Experimental setup for investigation of an attached subcritical MW discharge, initiated by a vibrator in a high-speed flow of air at propane–air mix ignition.

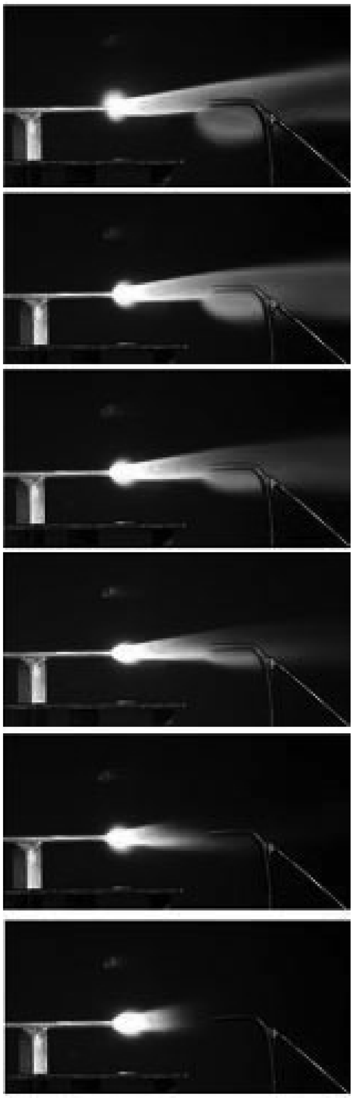


Fig. 22 Microwave discharge in airflow at varying velocities with pure propane injection at flow velocities 3, 12, 30, 50, 85, and 200 m/s (top to bottom); $\lambda = 12.5$ cm, $\tau_p = 0.5$ s, and $E = 100$ V/cm.

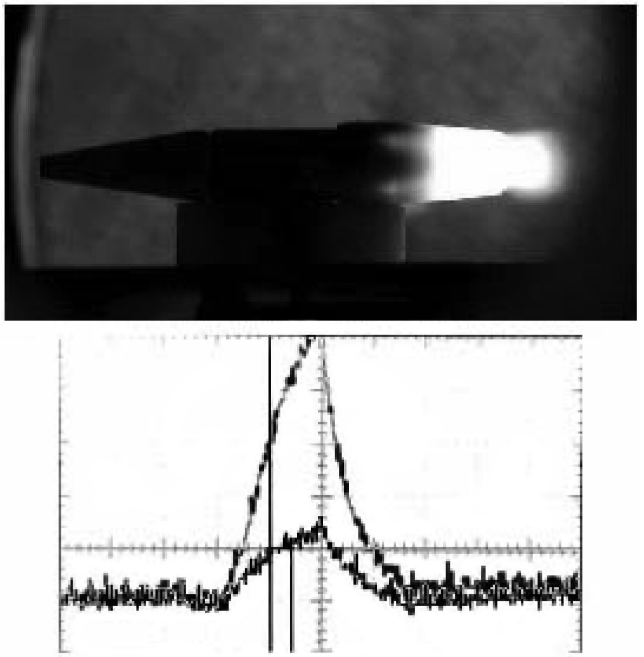


Fig. 23 Typical photograph of the energy-release region (top) and thermocouple waveforms (down) for only the discharge (lower waveform) and with injection of a flammable mixture (upper waveform).

combustible mixture. Detailed mapping of the pitot and temperature profiles in the wake of the vibrator were conducted to determine the amount of MW energy coupled into the airflow and the amount of propane combusted in the reaction zone. Using Mach 2 flow of ambient air and cold propane injection, this detailed mapping showed that 14% of the MW energy was coupled into the discharge and approximately 57% of the injected propane had reacted. Given the low ambient temperature and pressure, these results provide encouragement for the continued investigation of MW-based ignition systems at more representative conditions.

The impact of MW radiation wavelength on the discharge characteristics in high-speed air and air–fuel mixtures was investigated in [52]. Pulsed subcritical discharges with a wavelength of 2.5 cm and an amplitude of $E_0 = 3.7$ kV/cm were discharged into cold airflow at 500-m/s and 100-torr static pressure. The experiments demonstrated that a volumetrically developed streamer discharge was obtained in the high-speed flow that had characteristics similar to the discharge in static air at the same pressure. Experiments also demonstrated the capability of using the pulse MW discharge to ignite cold propane–air mixtures at these supersonic conditions. Results presented in [52] indicated that the flame-front propagation speed in the cold propane–air mixture was approximately 150 m/s, providing indication that the strong UV radiation produced in the discharge led to a significant increase in flame propagation speeds.

V. Conclusions

The characteristics of the MW discharges were investigated over a wide range of conditions, and several domains of operation have been defined. The filamentary nature of subcritical MW discharges leads to an efficient means of coupling MW radiation into a gas with both localized filament heating and volumetric energy deposition. Potential applications for the subcritical microwave discharge include aerodynamic flow control and combustion ignition and flame stabilization. Fundamental investigations on the use of MW discharges for aerodynamic flow control and combustion initiation, interesting in themselves, open a wide perspective for future technologies.

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