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A Microwave Discharge Initiated by Loop-Shaped Electromagnetic Vibrator on a Surface of Radio-Transparent Plate in Airflow

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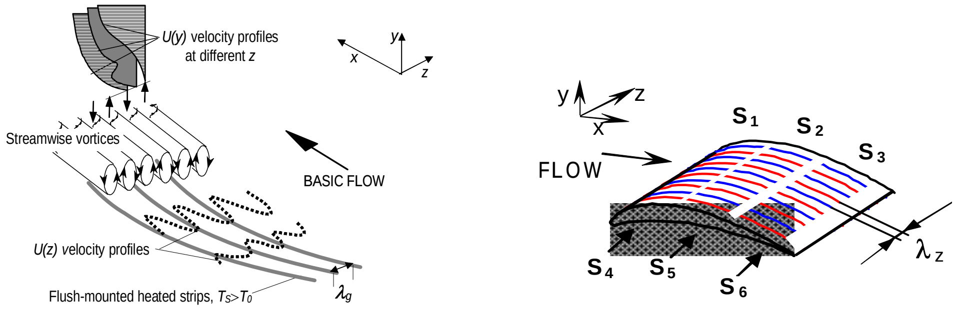
A review of new experimental results on realization of initiated microwave streamer discharge in deeply subcritical form on a surface of radio-transparent dielectric plate is presented. Experiments were carried out in the beam of electromagnetic radiation created by a generator of average power no greater than 1.5 kW with the wavelength 12.3 cm. A new type of an initiator has been applied in the experiment for microwave discharge realization. It represents a streamlined EM vibrator rolled in an open ring. Such loop-shaped initiator generates two-electrode discharge. Initiator of this type possesses some advantages with respect to known and applied before. It has been specially developed and investigated for executing of the given experimental program. The microwave discharge of deeply subcritical type was realized on the dielectric surface in the airflow with the velocity up to 25 m/s at atmospheric pressure. We have obtained data on power level necessary for this discharge realization in various electrodynamic and gasdynamic conditions. We have investigated discharges over various radio-transparent dielectric plates at different levels of delivered microwave power in a wide range of subsonic airflow velocity. We have investigated spatial and temporal structures of this discharge and have measured parameters of a discharge trace in the flow. We have obtained first experimental results on creation of a line of these discharges with fixed step between them in the system of the open-loop initiators. Such discharge structure will be applied in experimental investigations on analysis of new ways of boundary layer control.

I. Introduction

A method for boundary layer control under action of volumetric forces was developed in Ref.[1,2,3,4]. From a point of view of the best ratio of aerodynamic effect and energy inputs the designed method is rather efficient in a range of subsonic flows. The method is based on a control of flow characteristics by a selective maintaining of a vortex structure inherent in a flow (Fig.1a), when its spatial scale and intensity are modified for an achievement of a required goal.



a) b)

Figure 1. Schematic representation of the flow control based on a vortex structure generation in flow with a characteristic scale λg (a) and creation of regular transversal temperature distribution on a streamlining surface (b)

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A transition and turbulent boundary layer flow control was realized in the experiment by regular transversal temperature distribution creation on a streamlining surface. Such distribution was realized in experiment by a system of heating elements placed regularly in a direction transversal to the flow (Fig.1b).The model was made of a low thermal conductive material. Heating elements are tiered in separate sections and connected with an electric power supply. These sections were perpendicular to the stream direction; and their elements were placed along the flow with given transversal step. A voltage was delivered to the heating elements by independent layout. A temperature distribution formed by such a system lead to corresponding velocity profiles U(y) formation similar to those, which are represented in the upper part of Fig. 1a. Such systematic profiles also as wave profiles U(z) indicate a presence of vortices in the flow with a given spatial scale λ_g.

However, an electric supply of the heating element system applied in the experiments is rather complicated. In addition, this method of temperature distribution creation possesses long heating inertia. A method of temperature distribution creation with a help of microwave discharge system is free of these disadvantages. The discharges heat mainly air and a surface in a less degree. A realization scheme is represented in Fig.2. Microwave surface discharge initiators are located in the aerodynamic model. They are placed regularly along the surface of the model, transversally to the flow.

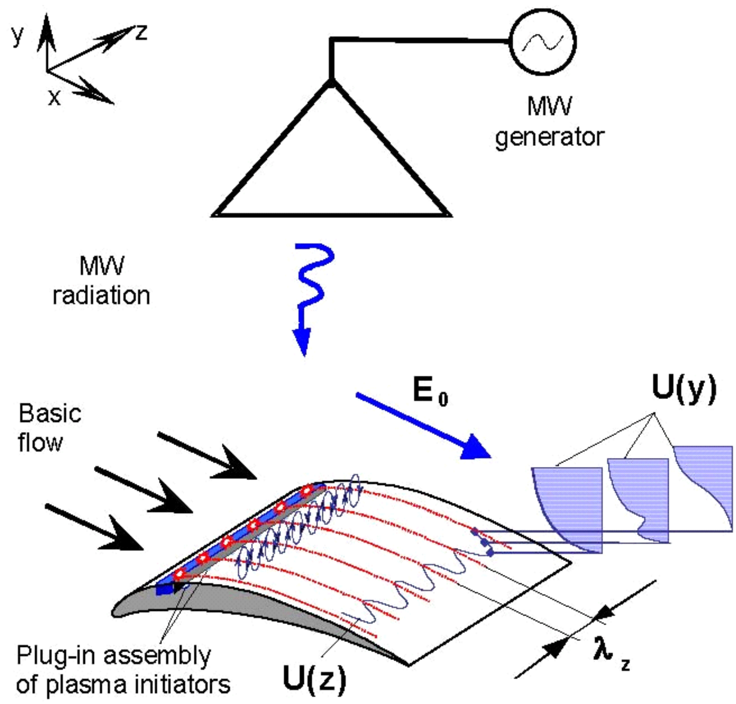


Figure 2. Boundary layer control with an application of plasma regions initiated by the microwave radiation

Deeply subcritical streamer discharge is initiated in air flow by an irradiation of the initiator system from outside by MW radiation. Thus the transversal temperature distribution is realized. Results of this type MW discharges investigations are represented in this paper.

II. Experimental set up for investigations of MW streamer deeply subcritical surface discharge in a flow

Investigations are carried out by two scientific teams. Aerodynamic experiment corresponding to the scheme of Fig.2 will be carried out in a wind tunnel of National Aviation University of Ukraine under direction of Institute of Hydrodynamics NANU, Kiev, Ukraine. Investigations on a development of a technology ensuring discharge system creation and discharges themselves were carried out in Moscow Radiotechnical Institute RAS , Moscow, Russia.

In Fig.3 one can see a principle scheme of an experimental set up for investigations on creation of the discharge system and MW discharges feature. In consists in the following. A MW generator with a wavelength of λ = 12.3 cm ensures a quasi continuous or pulse-periodic mode of work with a mean power $\mathbf{P_{MW}}$ no greater than 1,5 kW. Energy is delivered from the generator's output to the working chambers over a waveguide tract. A switch placed in the waveguide tract slows to switch promptly energy between the working chambers, Chamber 1 and Chamber 2.

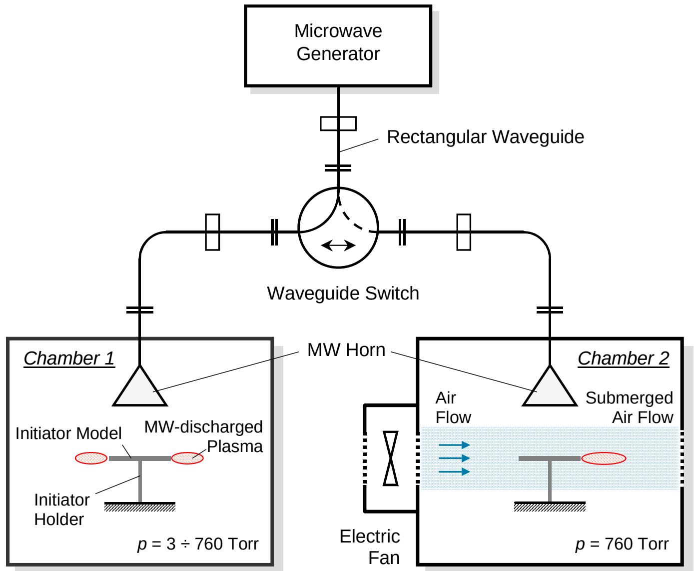


Figure 3. A scheme of the experimental set up for investigations of MW streamer deeply undercritical subcritical discharge in a flow

Chamber 1 is a vacuum chamber with a volume about of 0.5 m^3. It is equipped with a system of pumping and pressure measurements; and it allows to work in pressure range pfrom 3 to 760 Torr. A horn antenna and a device for fixing and positioning of investigating objects are placed inside the chamber. The antenna forms a quasi-optical wave beam of linearly polarized TEM wave in the working area. The chamber is aimed first of all to investigation of elecrodynamic problems appearing at a development of a discharge system creation on a plane technology. With its help we chose a type of an initiator, investigated its resonance characteristics, multi initiator system, etc.

Chamber 2 is aimed for investigations of discharges in a flow at atmospheric pressure. It represents a non hermetic volume of about 0.2 m^3. A horn antenna and a device for fixing and positioning of investigating objects are placed inside it. The antenna also as the antenna in the Chamber 1 forms a quasi-optical wave beam of linearly polarized TEM wave. Pressure fan placed on a wall of the chamber insures a submerged air stream in the working chamber; its diameter is about 10 cm, and a velocity is up to 25 m/s. In Fig.4 one can see an appearance of the experimental set up.

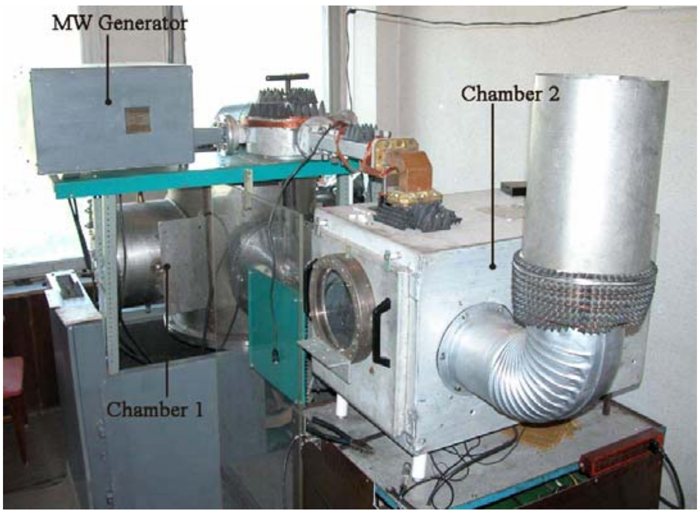


Figure 4. A scheme of the experimental set up for investigations of MW streamer deeply subcritical surface discharge in a flow

III. Microwave discharge initiators experimental investigation results

A microwave generator with an antenna system insures a field electric component value about of 100 V/cm in the working region of the set up. This value corresponds to the existence area of a subcritical microwave discharge as it follows from the known diagram of microwave discharge existence areas with respect to dependence of EM field E on air static pressure p. It is represented in Fig.5.

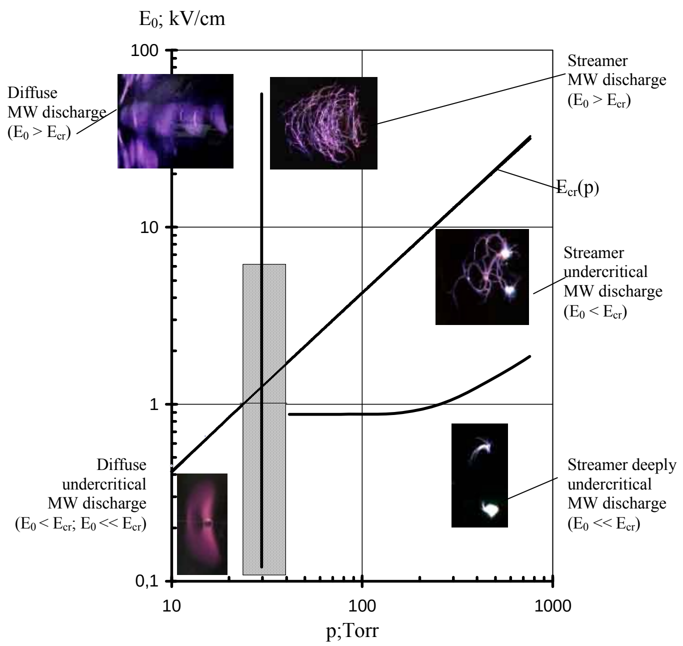


Figure 5. A diagram of MW discharge existence areas

An application of an initiator is necessary for realization of this discharge type. Two contradictory requirements have to be fulfilled at solution of a problem in a flow at atmospheric pressure on a dielectric surface of a model. From one hand the initiator has to create a field sufficient to ensure air breakdown (E=30 kV/cm). From another hand a level of power released in the discharge has to be not large in order not to create excessive heat loads on surfaces of the model and initiator. One can clearly see here two contradictory requirements existence. Breakdown of atmosphere requires high level of a field E_0, but the power released in the discharge at that strongly rises (as E_0^2). So we undertook investigations on search of an initiator optimal type.

We chose three types of initiators for investigations. All of them represent elementary antennas. They are schematically represented in Fig.6. They are: (a) linear EM vibrator, (b) linear EM vibrator with a central gap and (c), linear EM vibrator turned in a ring with a gap. Investigations have shown that all three types represent resonance systems. At that a resonance frequency is determined by known formulae: $f = (LC)^{-1/2}$ **.** Here L is an inductance, which is determined by geometrical sizes, C is a capacity, which is determined by a linear capacity, a capacity of a gap, etc.

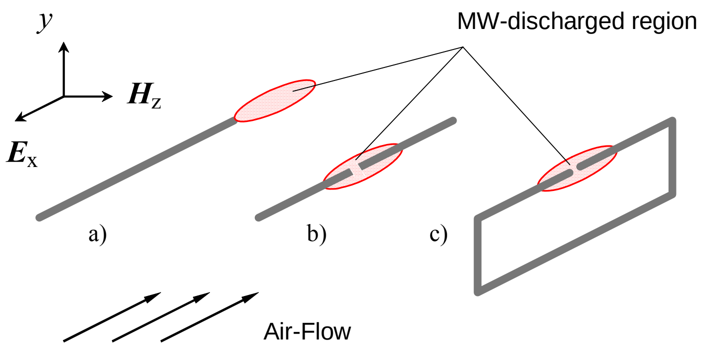


Fig.6. Schemes of three types of initiators

The initiating ability depends on a value of EM field in a gap, which is determined by a quality factor of the resonance system at other equal conditions. The quality factor, as it is well known is $Q = \rho/R$, where $\rho=(L/C)^{1/2}$, and R is a resistance of losses. So called antenna radiation resistance R_Σ gives the greatest put into a value of R. This parameter characterises a part of reradiated by the antenna power with respect to the coming one. A linear vibrator turned in a ring has the smallest R_Σ from all the inirtators. It has the greatest q-factor and it most effectively initiates a discharge, respectively. Undertaken measurements confirmed this.

Resonance characteristics of this initiator type have been also studied in details in different conditions. We staudied specially influence of a surface on initiating properties of the initiator since we supposed to apply initiators in aerodynamic experiments. Characteristics of three ring initiator typical configurations have been measured. Their schemes are represented in Fig.7.

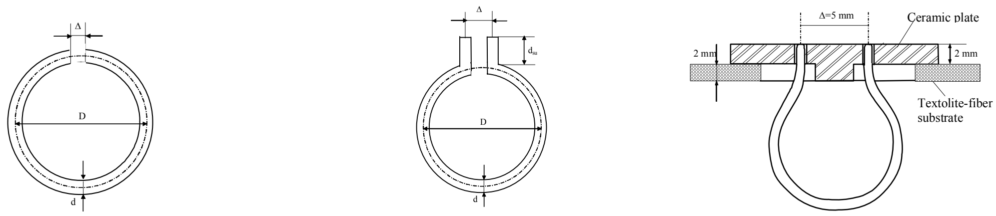


Figure7. Ring initiators: a) a ring with a gap ; b) a ring with lugs; c) a ring with lugs fixed to a ceramic surface

In Fig.7a one can see a linear vibrator turned in a ring with a gap; in Fig.7b one can see a linear vibrator turned in a ring with linear lugs in a gap; and in Fig.7c one can see a linear vibrator turned in a ring with linear lugs in a gap fixed to a ceramic surface. All the initiators have the same wire material and width and the same gaps. In Fig.8 resonance characteristics of these initiators are represented. They were measured with a help of a following method.

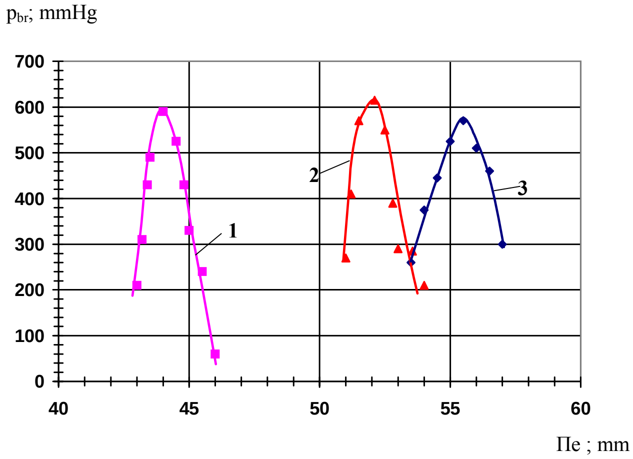


Figure 8. Resonance characteristics of turned in a ring for samples: a - curve 3; b – curve 2 and c – curve 1

Several samples with differerent perimeter value Пe were manufactured for each type. Each of them was placed in the Chamber 1, and measurements of pressure value at which the breakdown took place were made at a fixed power of MW generator. Results of measurements indicate a strong influence of a dielectric surface and a geometry of an initiator itself and on its resonance size. This is first of all connected with a variation of own capacity of the samples. Besides, we discovered that the quality factor also noticeably decreases at that, and hence the initiation capability of the initiator, this follows from relations represented earlier.

IV. Investigation experimental results of MW discharges

A series of experiments for determination of MW surface discharge characteristics in a flow was made on a basis of the ring initiator placed on the dielectric surface (see Fig.7c). These experiments were also used for experimental choice of radiotransparent dielectric material of a surface. Experiments were carried out in the working Chamber 2.

A flow velocity range, in which is necessary to create MW discharges in aerodynamic experiments is no greater than 35 m/s. It means that the flight times in interelectrode space of a loop initiator is no smaller than 140 μs even at Δ = 5mm. Physical processes responsible for a formation of a structure and main characteristics of streamer deeply subcritical MW discharge have typical times, which are quicker by several orders of magnitude. So the discharge physics in a stream with such a velocity will surely stay the same. But the discharge structure and its spatial localization can be changed. So, experimental investigations of a luminescent discharge structure have been carried out for estimation of a type and a scale of these changes in the velocity and MW power level ranges.

An experimental model tuned in resonance was placed on a working table of the Chamber 2. Photographing of the surface MW discharge was carried out. In Fig.9 one can see integral in time discharge photos at the flow velocity of (a) $v_{fl} = 0$ m/s, (b) $v_{fl} = 15$ m/s and (c) $v_{fl} = 25$ m/s. MW power was $P_{MW} = 1.2$ kW, radiation pulse duration was $\tau_{pul} = 0.5$ s, and exposure time was 1 s.

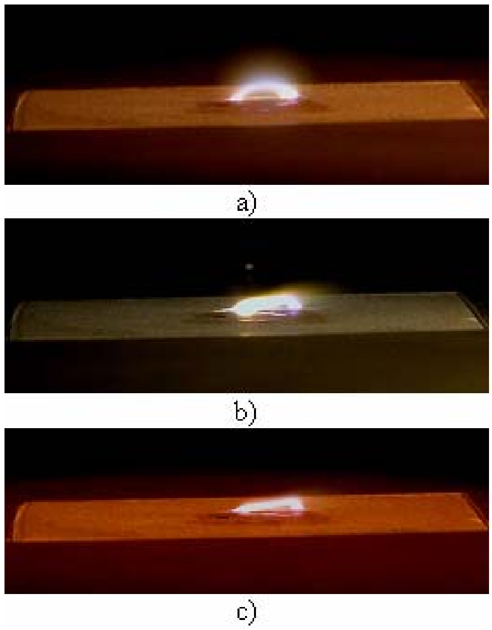


Figure 9. Appearance of MW discharge area at a) vfl = 0 m/s, (b) vfl = 15 m/s and vfl = 25 m/s. PMW = 1,2 kW. texp = 0,033 s

It can be seen in the photos that a luminescent discharge area creates a discharge in a form of an arc between electrodes in dead air. Convection, evidently, is a reason for an appearance of such a discharge form. The discharge channel is pressed more to a surface at an increase of a flow velocity, especially near an upper electrode down the flow. A luminescent trail is observed after the discharge down the flow.

Decreasing of a delivered power does not cause visible variation of a luminescent discharge area. Practically, only brightness of channel luminescence and a channel width is changed. It can be seen from Fig.10 in which P_{MW}=0.7 kW.

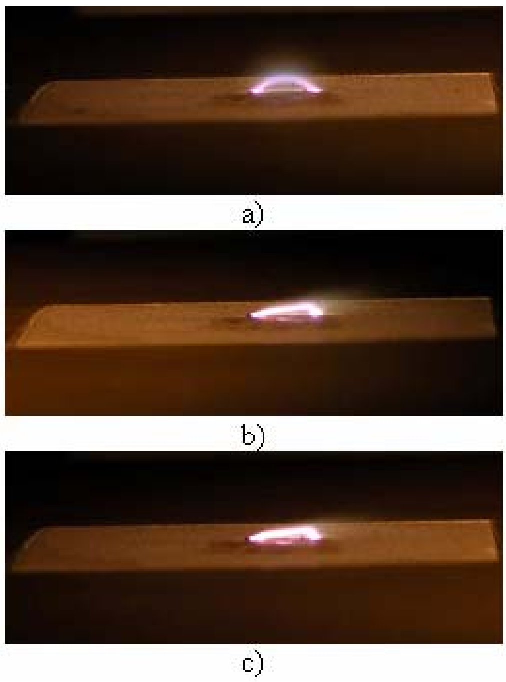
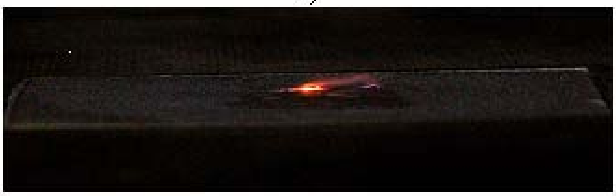


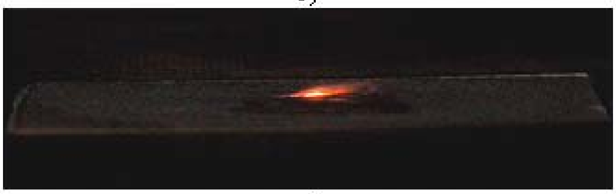
Figure 10 Appearance of MW discharge area at vfl = 0 m/s (a), vfl = 15 m/s (b) and vfl = 25 m/s (c); PMW = 0.7 KW, texp = 0.033 s

In Fig.11 one can see photos made for conditions analogous to those of Fig.10, but with an exposure time t_{exp} = 250 µs. It is seen that, first, the discharge structure is different at different $\mathbf{v_{fl}}$. The channel sizes are about of 0.35 mm across the flow. It is noticeably smaller than the luminescent discharge area visible in the integral in time photos. One can suppose that the discharge represents a thin heated plasma channel in each definite time interval. A location of this channel somewhat changes in space during time. So, a light struck area in the integral area exceeds by its sizes each separate channel.

a)



b)



c)

Figure 11. Appearance of MW discharge area at a) vfl = 0 m/s, (b) vfl = 15 m/s and vfl = 25 m/s. PMW = 1,2KW. texp = 250 µs

Discharge trail investigations were carried out in the flow after MW surface discharge. Temperature measurements were carried out with a help of a special thermocouple adapted for pulsed measurements in conditions of an intense microwave field. A method of such thermocouple measurements of $\mathbf{T_{stag}}$ was developed during a project fulfilled earlier, results of which are represented in Ref.[5]. Measurements were carried out with a help of the initiator's model represented in Fig.7c. A device for controlled thermocouple removal on the working table of the Chamber2 was designed and manufactured for ensuring of temperature measurements possibility in the trail transversally the flow. A scheme of the experiment is represented in Fig.12. A ceramic insert with a loop vibrator placed on it was flush glued in the glass-fiber plastic substrate.

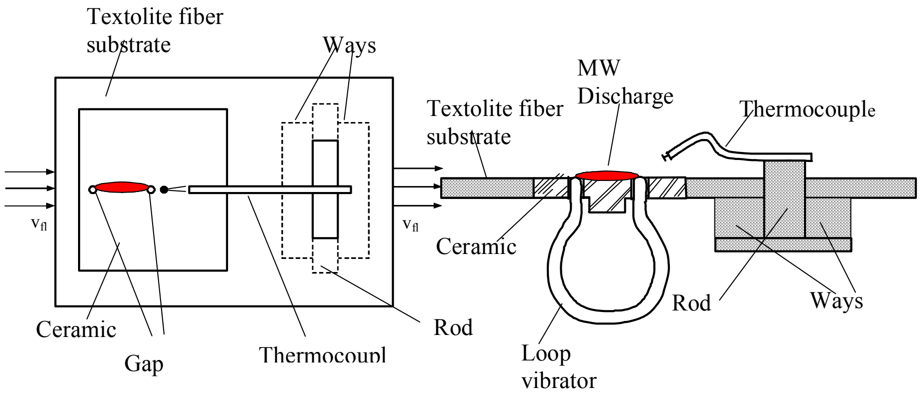


Figure 12 .Experimental scheme on temperature measurements in a trail after a discharge

The substrate was placed on the working table. The thermocouple was positioned down the flow with respect to MW discharge approximately on an axis of the discharge trail. A position of its thermojunction over a surface could be regulated. A distance to the discharge area could be also changed. The thermocouple was fixed to carrying bar of the removal device. This device represents two guides fixed to the low surface of the substrate between which the carrying bar is sliding. A thermocouple is connected with it through a cut in the substrate. In spite of a simplicity the device of a thermocouple removal ensures the controlled positioning of the thermo-junction with accuracy not worse than ± 0,5 mm.

Discharge trail temperature measurements transversally the flow were made at $P_{MW} = 1.2$ kW, $\tau_{pul} = 0.4$ s, $v_{fl} = 25$ m/s. A distance between the initiator's electrode lower with respect to the flow and the thermojunction was 1.5 mm, and its height over a surface was 0.5 and 1 mm. Temperature measurements were carried out for two variants of a loop. A distance between the electrodes of the loop was 1 mm (Fig.13 a) in the first case, and 4 mm (Fig.13b) in the second case. An appearance of the discharge area is represented in Fig.14.

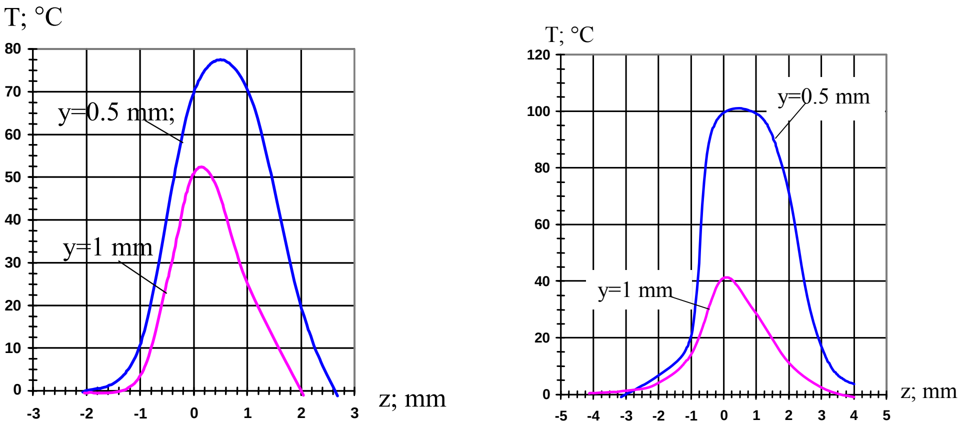


Figure 13 A temperature distribution in the trail after the discharge, transversally to the flow: a) Δ = 1 mm, b) Δ = 4 mm

Figure 14. A discharge appearance

Experiments have shown that a temperature level reaches values of only about of hundreds Celsius in the discharge trail at a distance of several mm from the discharge area down the flow. At the same time a temperature near the electrodes of initiators is rather high. In Fig.15 one can see an example of erosion of a dielectric surface made of mica after 20 discharge cycles. In this connection a large number of experiments were made on a selection of a material for such surface.

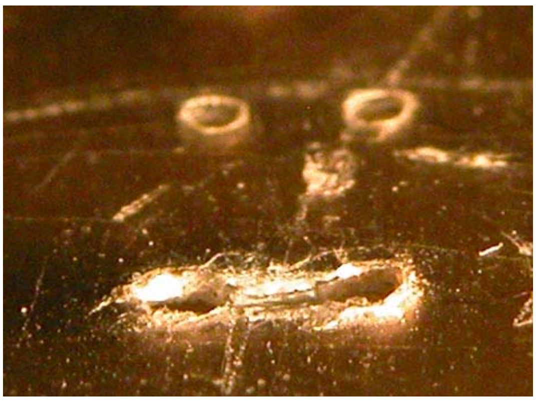


Figure 15. A surface of a sample of mica after 20 discharge cicles in the flow

Finally experiments have lead to a design, which draft is represented in Fig.16. A ring type initiator represents a simple cut ring, which is fixed in a fiber-glass plastic dielectric surface with a help of high temperatured fosphate molding compound.

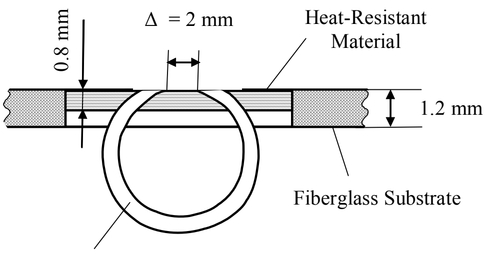
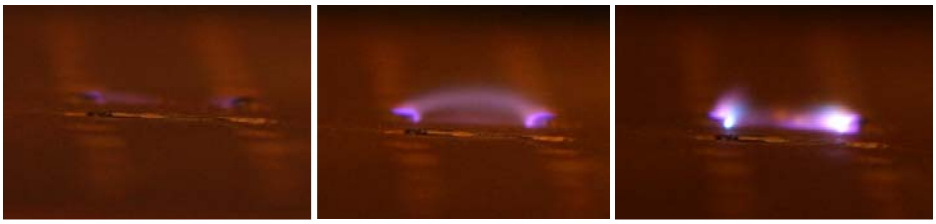


Figure 16. Final version of a ring initiator design

The design has a rather high Q-factor and initiates the discharge well. At the same time the heat proof ir rather high. This variant was taken as a basis for a development of a system of discharge multi-initiator realization in the aerodynamic experiment.

As it was marked above, it is necessary to ensure EM field level no lower some definite value in order to initiate a discharge. So a following problem arises in the experiment. We inevitably come to a situation when the discharge stops to be initiated at attempt to decrease more a level of the power released in the discharge. In addition a combining of separate initiators into a linear system leads to a decrease of Q-factor of each separate element. So a higher level of EM field is now required for ensurence of discharges ignition.

Microwave generator has been developed in order to ensure experiments undertaking in these conditions. The modernized generator ensures not only a continuous mode of work with different levels of a power, but also a pulse-periodic mode with τ_{pul} from 100 μs to 1000 μs at a repetition frequency up to 1000 kHz and pulsed MW power up to 6 kW. An appearance of the discharge realized in this mode is represented in Fig.17. In Fig.17a and Fig.17b it is represented for single pulses at P_{MW} = 6 kW , 100 μs and 1000 μs, respectively. In Fig.17c one can see an integral view for a case τ_{pul} = 100 μs and f_{rep} = 1000 Hz. The model of the multi initiator system was created on a basis of the initiator design (see Fig.16) for creation of discharges on a dielectric surface in the aerodynamic experiment, as it was marked above.



a) **b)** **c)**

Figure 17. Appearance of pulsed and pulse periodic discharges on a single initiator

A system of MW discharges in a flow was realized with a system of these initiators at a distance of 15 mm between them. In Fig.18 one can see a typical appearance of such a system at a velocity of V_{fl} = 25 m/s for pulse-periodic mode of work τ_{pul} = 200 μs, f_{rep} = 100 Hz and P_{MW} = 6 kW.

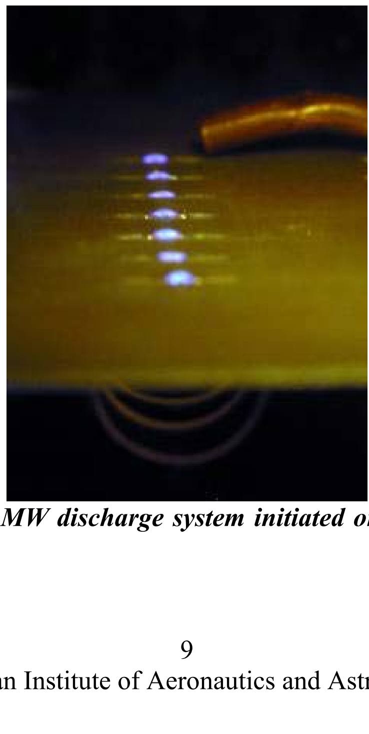


Figure 18. An appearance of MW discharge system initiated on a surface in pulse-periodic mode of work

Temperature measurements in the trail behind such discharge system in flow have shown that they form regular temperature profile transversally to the flow.

V. Conclusions

Thus, we have obtained the following main results in the course of undertaken experimental results:

MW discharge has been realized in with a help of single loop-shaped initiator and the system of the initiators; MW discharge initiated in a flow on a radiotransparent surface has been realized in the continuous and pulse-periodic operation modes; resonance characteristics of the single initiator and the system of initiators have been investigated their breakdown capability has been studied; temperature distribution in the trail after the discharge in the flow has been investigated for the case of the single initiator and the system of the initiators.

VI. Acknowledgements

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