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Initiated Surface Microwave Discharge as an Efficient Active Boundary-Layer Control Method

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The first-step result of experimental works on verification of advanced method of boundary-layer control based on localized plasma generation is presented. Boundary-layer control is executed by means of vortex structure creation near streamlined body surface. Experiment has been performed in specially designed wind tunnel. The microwave radiation remotely feeds a resonant distributed system, initiating and sustaining the point discharges, generating the vortex structure in the stream. Measurement data together with results of modeling confirms the feasibility of initial idea.

Nomenclature

MW	=	microwave
EM	=	electromagnetic
E	=	amplitude of electric field
E_0	=	amplitude of electric field of MW radiation
E_{cr}	=	critical value of electric field amplitude
E_{DCcr}	=	DC critical electric field
c	=	light velocity
ω, λ	=	MW radiation circular frequency and wave length
k	=	$2\pi/\lambda$ - wave number of MW radiation
F	=	repetition frequency
p	=	air pressure, Torr
p_{br}	=	breakdown pressure
V_{fl}	=	flow velocity
U	=	
T	=	static gas temperature
T_{stag}	=	stagnation gas temperature
λ_z	=	period of discharge system
τ_{rel}	=	electron energy relaxation time in a gas
P_{MW}	=	MW generator power
τ_p	=	mw radiation pulse duration
t_{exp}	=	expose time
ξ	=	coefficient of full hydraulic resistance

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I. Introduction

IN the paper we present final results of three-years investigations of a new active flow control method based on application of span wise array of initiated microwave (MW) discharges on an airfoil surface, and sponsored by EOARD, CRDF Grant # UKE2-1508-KV-05. Preliminary results of work were reported in Ref.[1,2,3].

A method of least intrusive boundary-layer control was developed based on a turbulent scale modification in a vicinity of a surface. Tested for subsonic flows, it proved to be efficient in terms of gained favorable effects versus required energy consumption. In practice, the method is realized using any type of vortex generators mounted spanwisely over a surface. However passive ways of boundary-layer control using vortex-generators, roughness elements or riblets being simple and effective are tuned to a narrow range of basic flow parameters. As a result, they cause unjustified deterioration of flow conditions and consequent energy losses beyond this range. Therefore an active method of boundary-layer control was developed based on application of a temperature boundary condition, T(z). Laminar and turbulent flows over surfaces with spanwise-regular temperature distribution were investigated numerically and experimentally.

For the first time the idea was successfully tested with use of flush-mounted resistively heated elements creating a wavy temperature distribution in a spanwise direction which initiates corresponding transverse velocity fields characterizing formation of streamwise vortices. Heated sections over a body can be independently controlled with a given vortical scale λ_z and temperature gradients. Those experiments showed very good agreement between results of numerical simulation of the considered approach and realistic tests in a wind tunnel.

To further raise the functionality and practicalities of the approach, generation of properly organized temperature fields is proposed using point plasma discharges. Initiated with MW radiation, such discharges provide the remote control of temperature in a boundary layer and, accordingly, of kinematic and dynamic fields around a model. In addition, being generated near a surface, they directly heat the fluid rather than the material of a model thus promising a less inertial response of the flow to imposed temperature fields.

Such formulation of the problem makes it possible to apply the developed method to corrosive fluids as well as to moving or rotating elements and systems, in particular, to improve the performance of low-pressure turbine blades with their well known drawback of early flow separation.

In practice, the novel approach is realized using localized plasma discharges initiated in the vicinity of the surface with a microwave field as it is schematically shown in Fig.1. Here, flow disturbances are introduced thermally like in case of resistively heated arrays discussed above. Basic control factors are the λ_z distance between the MW actuators, amplitude characteristics corresponding to applied voltage and an operating mode of plasma discharges. This kind of applied boundary conditions affects accordingly the scales and intensity of generated vortices and enables the remote control due to the initiating MW field.

It is a multidisciplinary research with a separate electro-dynamic part related to the creation of plasma arrays (spanwise-organized thermal sources) with given properties as a practical diversified tool for flexible flow management. In this connection,, investigations have been undertaken by two teams. The aerodynamic experiment has been realized with a help of aerodynamic wind tunnel of National Aviation University under a supervision of experts from the Institute of Hydrodynamics NANU, Kiev, Ukraine. Experiments on a development of a technique ensuring creation of required MW discharge system and these discharges features investigations have been carried out in Moscow Radiotechnical institute RAS, Moscow, Russia.

II. Experimental facility

A new experimental complex intended for undertaking of experiments in the wind-tunnel is shown in Fig.2. This complex is equipped by the MW radiation source and is intended for undertaking of automated measurements of the model aerodynamic coefficients in conditions of MW initiated discharges generation on its surface.

A test section is metallic. The wind-tunnel is the direct type with a drawing fan. Together with other standard equipment it insures a sufficiently low level of turbulence (smaller than 0.1). The test section for MW experiments undertaking has been modernized by inserting of a hermetic Eiffel chamber into design.

An inlet nozzle, a diffuser, a honeycomb up the flow and a grid down the flow are all-metal or made of metallic materials connected so that they could ensure bulk electromagnetic screen and protect an environment from MW radiation. The diffuser has an oval form in the beginning part and a round cross section with a radius R = 805 mm in the end, this corresponds to a radius of jointing unit of the fan.

A carrier of the aerodynamic model and the model itself are made of radiotransparent materials. The construction in whole has a reliable grounding.

The Eiffel chamber is one the main parts of the aerodynamic installation which has a form of a parallelepiped with sizes 800 mm (along the flow) x 300 mm (a width of the chamber) x 1200 mm (a height of the chamber), in

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which the required pressure is ensured. Its testing section has a height of 600 mm and it is limited by special perforated walls from above and from below.

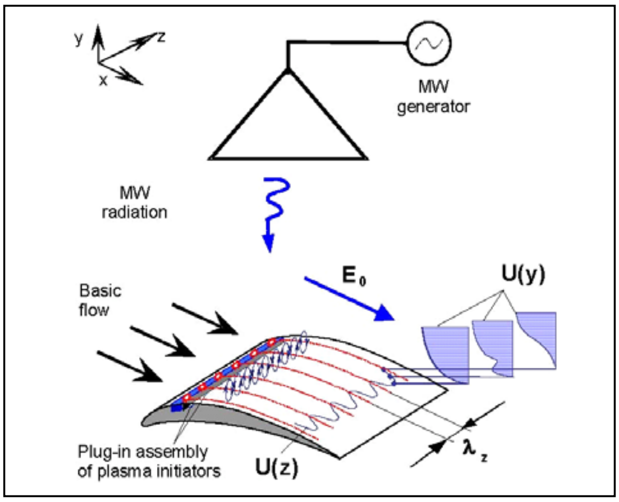


Figure 1. Boundary layer control with an application of plasma regions initiated by the MW radiation

The Eiffel chamber is made of steel plates 3 mm thick with reinforcing ribs. A transparent window with sizes 250x250 mm is installed in one of the walls of the test section for ensuring of processes visualization in the chamber. The space between double-layer walls of this window is filled water, which is a wonderful absorber of MW radiation. End elements of MW system (including a magnetron and a radiating horn antenna) are mounted in the upper part of the Eiffel chamber.

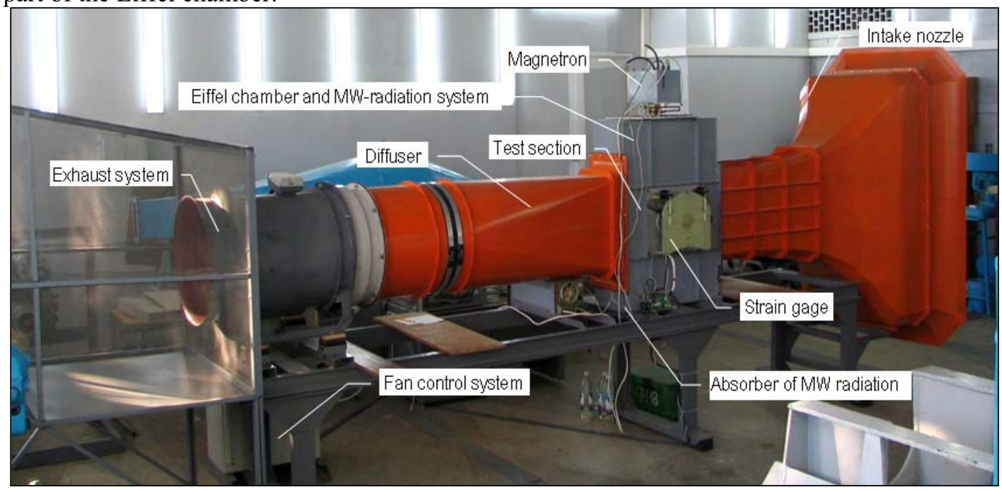


Figure 2. Aerodynamic complex equipped by MW radiation source with the protection system

A new design of the wind tunnel ensures a calculated velocity of a free stream about 40 m/s (compared with 20 m/s, achieved in earlier experiments), and also the following parameters:

- a coefficient of full hydraulic resistance $\xi = 1.46$;
- pressure losses = 1430 Pa;
- Fan engine power = 10.2 W;
- Flow flux = 7.2 m^3/s.

In Fig.3 one can see a principle scheme of an experimental installation on creation of MW discharge system and investigations of discharge features in MRTI RAS.

The installation consists of the following main parts. A microwave generator with a wavelength of $\lambda = 12.3$ см insures a quasi-continuous or pulse-periodic working mode with an average power P_{MW} no greater than 1.5 kW. Energy is delivered to the working chambers from the outlet of the generator over a waveguide transmission line. A switch placed in the waveguide transmission line allows to on-the-fly switch energy between the working Chamber

1 and Chamber 2.

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.

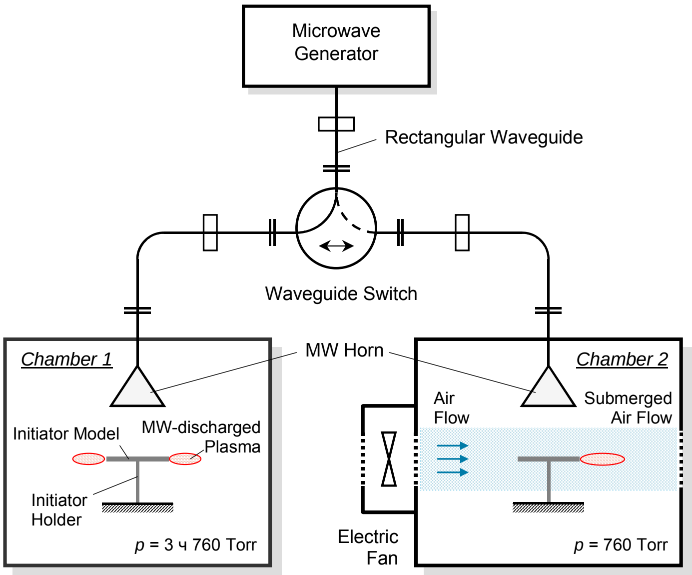


Figure 3. An experimental installation's scheme for investigations of deeply subcritical streamer surface MW discharge in a flow

The microwave generator with antenna system ensures electric field strength about of 100 V/cm in the working area of the installation. The indicated *E* field value corresponds to the existing area of deeply subcritical MW discharge.

III. Design of initiators system

An application of initiators is required for realization of such a discharge.

Two contradictory conditions have to be satisfied at solution of a problem of a discharge creation on a dielectric surface of a model being in a flow at atmospheric pressure. The initiator on the one hand has to create a sufficient field for realization of air breakdown (30 KV/cm), on the other hand the power level released in the discharge has to be not large in order not to create unnecessary heat loads to a surface of a model and an initiator. One sees the realization necessity of two incompatible conditions. A breakdown of the atmosphere requires high level of E_0, but the power releasing in the discharge rises sharply (as E_0^2). In this connection we have undertaken investigations on search of an optimal initiator's type.

Three types of initiators were chosen: (a) linear EM vibrator, (b) linear EM vibrator with a central gap and (c) linear EM vibrator (with a central gap) turned in a ring. All of them represent elementary antennas.

Investigations have shown that all three initiator types are the resonant systems. The resonance frequency at that is defined by the well known formula

$$\omega = \frac{1}{\sqrt{L \cdot C}},$$

here L is inductance defined by geometric sizes, C is a capacitance defined by a linear capacity and by a capacity of a gap, etc. An initiating ability depends of EM field value in the gap, which at other equal conditions is defined by a quality factor of a resonant system.

It is well known that a quality factor of a resonator is Q = ρ/R, where $\rho = \sqrt{L/C}$ and R is a resistance of losses. The greatest put in a value of R gives an antenna radiation resistance R_Σ. This parameter characterises a part of the power re-emitted by the antenna with respect to the falling one. Investigations have shown that the linear vibrator turned in a ring has the smallest R_Σ of all investigated vibrators[4]. It has the highest quality factor, so it initiates a discharge most effectively.

We have investigated in details resonant characteristics of this initiator in different conditions. Also we have investigated influence of a dielectric surface on the resonant features of these initiators since they have to be located near a surface during the aerodynamic experiment. Characteristics of three typical configurations of ring initiators shown in Fig.4 have been measured.

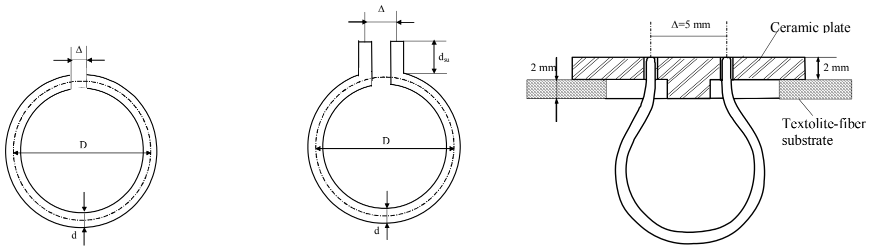


Figure 4. Ring initiators: a) a ring with a gap; b) a ring with a lug in a gap; c) a ring with a lug fixed in a ceramic surface

In Fig.4a one can see a linear vibrator (with a gap) turned in a ring, in Fig.4b is represented a linear vibrator turned in a ring with a lug in a gap, and in 4c there is the same vibrator fixed in a thin dielectric plate.

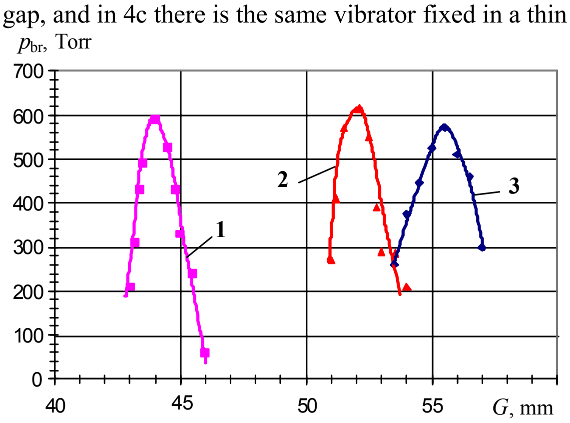


Figure 5. Resonant characteristics of linear vibrators turned in a ring for samples: Fig.4a –curve 3; Fig.4b – curve 2 and Fig.4c – curve 1

In Fig.5 resonant characteristics of these initiators are represented. They were measured according with the following method. Several samples with different perimeters G were made for each initiator type. Each of them was located in the chamber of the first channel (Chamber 1). At fixed power of MW generator we undertook measurements of a pressure p_{br}, at which a breakdown in a gap was ensured. Measuring results showed strong impact of a dielectric surface and a geometry of an initiator on its resonance size. At that the quality factor visibly changed and hence the initiating ability of the initiator, that follows from represented above equations.

IV. Study of initiated discharges

A set of experiments on determination of MW surface discharge in a flow was carried out on a base of the ring initiator (Fig.4c) placed on a dielectric surface. These experiments were also used for choice of a radiotransparent dielectric material of a surface. Tests were carried out in the working Chamber 2.

A flow velocity at which is necessary to create MW discharges in aerodynamic experiment does not exceed

35 m/s. It means that a flight time in a gap space of a ring initiator is not smaller than 140 μs even at the gap size Δ = 5 mm. Typical times of physical processes responsible for creation of deeply subcritical streamer MW discharge structure and main characteristics are for orders of magnitude larger. So the physical feature of the discharge in the flow with this velocity stays of course the same. Experimental investigations of bright discharge structure in wide range of velocity and MW power level have been carried out for estimations of a type and scale of these changes.

In Fig.6-I one can see integral in time discharge photos at the flow velocity V_{fl} equal to: (*a*) 0 , (*b*) 15 and (*c*) 25 m/s. The MW power is P_{MW} = 1,2kW, radiation pulse duration is τ_p = 0.5 s, exposure time τ_{exp} is ≈ 1/30 s. It can be seen that the discharge creates a luminous area in a form of an arc between the electrodes in the motionless air. Apparently convection is a reason for such a form of the discharge. The discharge channel is more pressed to the surface at rise of the flow velocity, especially near the upper electrode with respect to the flow. Decrease of delivered power does not cause visible change of the luminescent discharge area. Only brightness of channel's luminosity and their width is only practically changed.

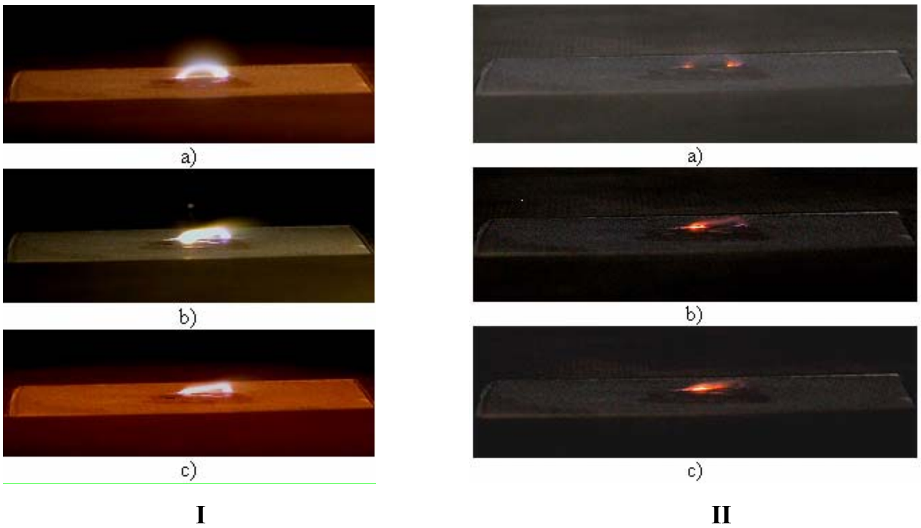


Figure 6. An appearance of MW discharge area at a flow velocity vfl = 0 m/s (a), 15 m/s (b) and 25 m/s (c); I) – t_{exp} = 33 ms, II) – t_{exp} = 250 μs

In Fig.6-II one can see photos made in similar conditions, but with exposure time of τ_{exp} = 250 μs. It can be seen in them that the discharge structure is different at different V_{fl} . The sizes of the channel across the flow are about 0.35 mm. This is noticeably smaller than the luminescent discharge area in the integral in time photos. One can suppose that the discharge in each part of time represents a relatively thin strongly heated plasma channel. This channel's position in space slightly changes with time. Thus the area exposed in the integral photo is lager than a separate channel.

Investigations of the discharge trail in the flow after MW surface discharge have been made. Temperature measurements were carried out with a help of a special thermocouple adopted for pulse measurements in conditions of strong EM field. A method of T_{stag} thermocouple measurements was developed in earlier fulfilled project. Measurements were carried out with application of the initiator's model represented in Fig.4c. For insuring of temperature measurements in the trail across a flow we have developed and manufactured a device for controlled displacement of the thermocouple on a working table of Chamber 2 – see Fig.7.

A ceramic insert with a ring vibrator fixed to it is glued flush with a substrate of glass-cloth laminate. The substrate is placed on the working table. A thermocouple is located down the flow with respect to MW discharge along the axis of the discharge trail. The thermocouple moving in three orthogonal planes is fixed to a carrying bar of a special positioning device. The device of the thermocouple displacement in spite of its simplicity insures the controlled positioning of thermal junction with an accuracy no worse than ±0.5 mm.

Temperature distributions of the discharge current across the flow were measured at P_{MW} = 1.2 kW, MW pulse duration of 0.4 s and the flow velocity of V_{fl} = 25 m/s. A distance between the lower (with respect to the flow) electrode of the initiator and the thermal junction was 1.5 mm and its height over the surface – 0.5 and 1.0 mm. Temperature measurements were carried out for two ring versions. A distance between the ring electrodes was 1 mm in the first case (Fig.8a), and 4 mm in the second case (Fig.8b).

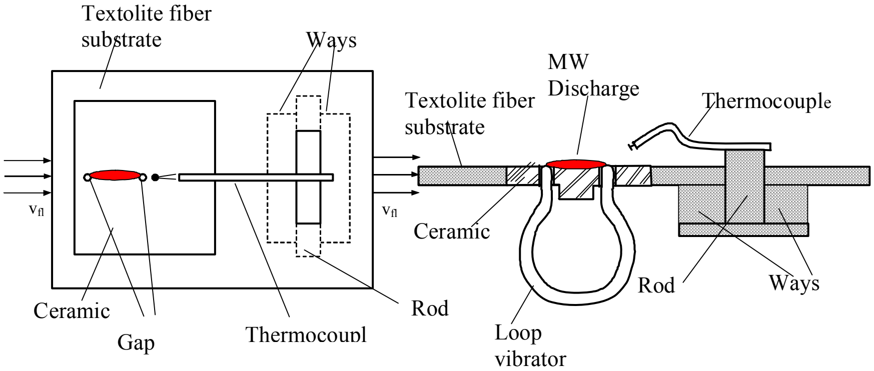
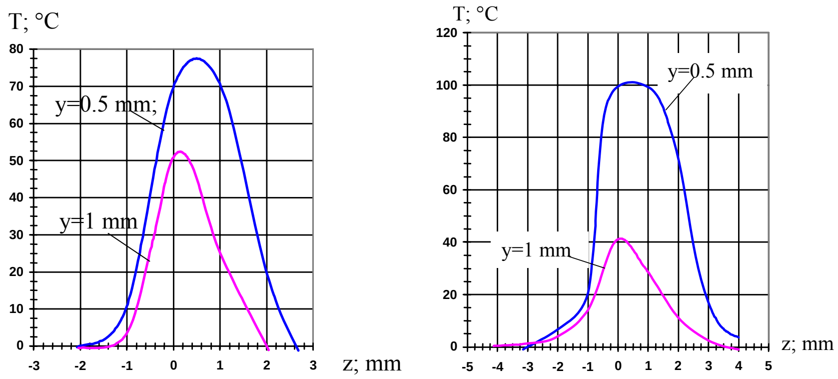


Figure 7. A scheme of temperature measurements in the trail after MW discharge

Experiments have shown that temperature levels reach values only about a hundred of C° degrees in the discharge trail already at a distance of several mm from the discharge area down the flow. At the same time a temperature near the electrodes of the initiators is rather high. In Fig.9 we represent an example of the dielectric surface made of mica already after 20 discharge cycles. I this connection we carried out a large investigation cycle on choice of a material for such a surface.



(a) (b)

Figure 8. Temperature distribution in the trail after the discharge across the flow, Δ = 1 mm (a) and 4 mm (b)

In the result experiments brought us to the development of a design, which draft is represented in Fig.10. The ring initiator in it is a simple cut ring which is fixed to the glass-cloth laminate dielectric surface with a help of a high-temperature phosphate molding compound. The design has a sufficiently high quality factor and it initiates the discharge well. At the same time its thermal stability is rather high. This version was taken as a basic one for development of a multi vibrator system of discharges initiation in the aerodynamic experiment.

Figure 9. Mica sample surface after 20 discharge cycles in the flow

It was marked above that for a discharge initiation in a working area it is necessary to ensure a level of EM field strength no smaller than some definite value. Thus there rises a following problem in the experiment: we inevitably come to a situation when the discharge stops to be initiated at an attempt to decrease a level of power released in the experiment. Besides, combining separate initiators into a linear system leads to decrease of a quality factor of its each separate element. So the greater level of EM field is required for ignition of the discharge bar.

MW generator has been developed in order to ensure experiments undertaking in these conditions. The modernized generator can ensure not only a continuous working mode with different levels of power, but also the pulse-periodic mode with the pulse duration τ_p from 100 μs to 1000 μs at the repetition frequency up to 1000 Hz and the outlet pulse power of MW source up to 6 kW.

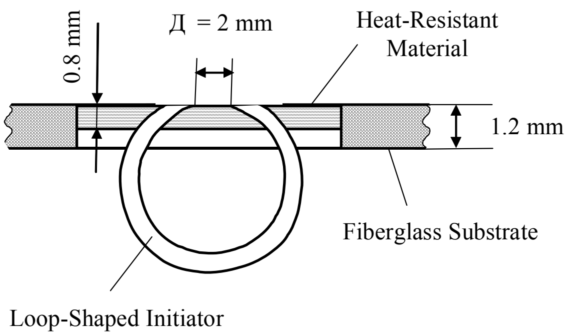
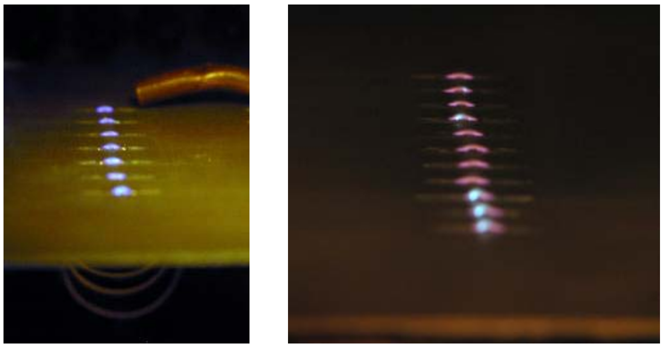


Figure 10. Final version of the ring initiator's design

A new high-voltage modulator of MW radiation source has been developed. A spice of the scheme consists in inclusion of a commutating element in series with the magnetron and the high voltage rectifier parallel to the ballast resistance in the cathode circuit of the magnetron. This essentially simplifies a scheme of the modulator and makes it cheaper in comparison with "classical" version of the high voltage parallel commutation. For the commutating element we have applied a comparably new class of semiconducting devices, namely, the bipolar transistor with an isolated gate known under the abbreviation IGBT (Insulated Gate Bipolar Transistor). In initial version we used a transistor IRG4PH50UD with maximum working voltage collector-emitter 1200 V.

Made changes allowed substantially increasing the stability of the whole scheme's work and widening its dynamic characteristics range – to increase the maximum amplitude of the controlled voltage and to enlarge duration intervals of the radiation source to the side of smaller durations.



(a) (b)

Figure 11. An appearance of MW discharges system initiated on a surface in the pulse-periodic mode of work: with a step Δ = 15 mm (a) и 10 mm (b)

A transition to shorter microwave radiation pulse durations at simultaneous increase of the magnetron output pulse power and preservation of average power have widened experimental capability of the developed stand and ensured reliable ignition of MW discharge of the whole initiator's bar on a surface of the investigated model.

A model of multi initiator system for discharge creation on a dielectric surface of a model in the aerodynamic experiment was created on a basis of the ring (loop) initiator's design. The system of MW discharges in the flow was realized on a bar of these initiators at a distance of 15 mm between them. In Fig.11a one can see a typical appearance of such a discharge system at a velocity V_{fl} = 25 m/s for pulse-periodic mode of work, MW pulse duration τ_p = 200 μs, pulse repetition frequency F = 100 Hz and radiation source power P_{MW} = 5 кВт. Following perfection of the modulator (application of even more highvoltage IGBT-transistors, for example, IXGH32N170A and similar ones with working voltage up to 1700 V and more и более) allowed to rise pulse outlet power of the radiation sourse up to 6-6.5 kW.

For deleting of constructive elements of the working chamber influence in a “traveling wave” mode we have tested different radiating horn antennas with an aperture sizes from 90×90 to 200×200 mm

A schematic image of the electrodynamic system final version including a radiating horn antenna with a cross section of an aperture 200×200 mm and a focusing metallic mirror with a curvature radius of 425 mm and a chord diameter of 400 mm is located at a distance of ~ 465 mm (in the lower part of the testing chamber) is represented in Fig.12. An investigating model with initiators is located in a loop of EM field at a distance of 297 mm from the antenna opening.

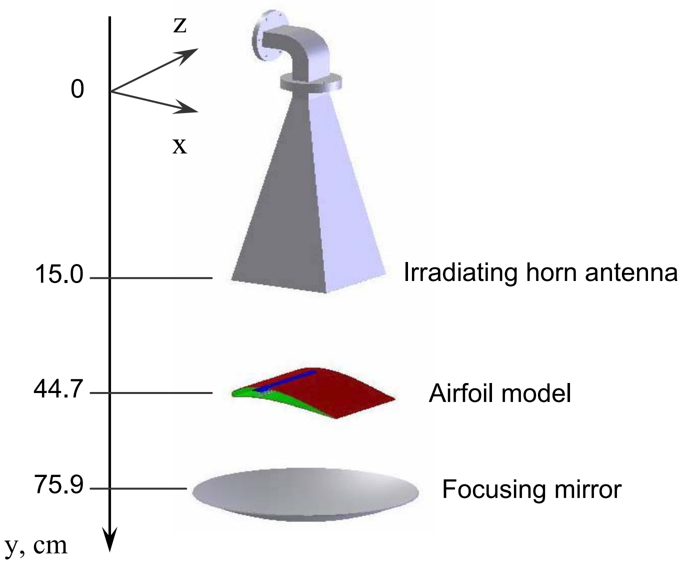


Fig.12. Optimal displacement of electrodynamic system’s elements.

Simultaneously we realized a development of the electrodynamic line of the experimental stand, namely, an optimization of the radiating horn antenna and the spherical focusing mirror installation. The development of the electrodynamic system was fulfilled on a basis of numerical modeling with application of specialized program package CST Microwave Studio.

(a) (b)

Figure 13. An appearance of an aerodynamic model and a design of ring EM vibrator’s bar fixing to it

Described optimization of the experimental stand allowed to realize a reliable ignition of MW discharges system in a flow at a distance of 10 mm between the initiators (see Fig.11b) that completely satisfies the conditions of the aerodynamic experiment. Temperature measurements in the trail after such a discharge system have shown that they form a regular temperature profile transversally the flow with parameters necessary for the experiment.

In the result of fulfilled investigations we have developed MW part of the experimental installation for increase of the outlet power of MW source in the pulse-periodic mode of its work and improvement of stability and efficiency of the hole stand functioning.

On a basis of obtained data we manufactured a new model with a bar of the ring vibrators for initiation of MW discharges system on its surface. The appearance of the model and a draft of initiator's fixing to its surface design is shown in Fig.13a and Fig.13b, respectively.

V. Experiment on boundary layer MW control

A set of works fulfilled by joint efforts of two teams allowed to realize a system of localized discharges on a surface of the model and to start investigations of the proposed method of the boundary layer control.

Primary efforts in wind-tunnel experiments were focused on generation of stable plasma arrays. Wind-tunnel tests encountered with a number of electro-dynamic problems. Firstly, they deal with generation of a sufficiently uniform MW field to ensure stable discharges over all the plasma actuators along the model span. In its turn, it is connected to the power of MW generator and a radiation mode; as a result, a pulse mode was chosen under the condition that both running and standing waves are to be tested (the latter supposes installation of a mirror on the test-section bottom). Another difficulty of this sort deals with a distance between plasma actuators to correspond to a favorable a scale of initiated disturbances in a boundary layer that was shown to be for the given conditions, λ_z = 5mm and no more than λ_z = 10mm. It was found that decreasing spacing between the ring actuators one could provoke initiation of discharges not over an open loop of an individual actuator but between neighboring rings of the array. It breaks the spanwise regularity of localized thermal sources that is a necessary condition of the research strategy. After corresponding facility modernization allowed to solve these problems, a z-regular set of localized discharges was obtained with actuators located at 10 mm from each other (Fig14).

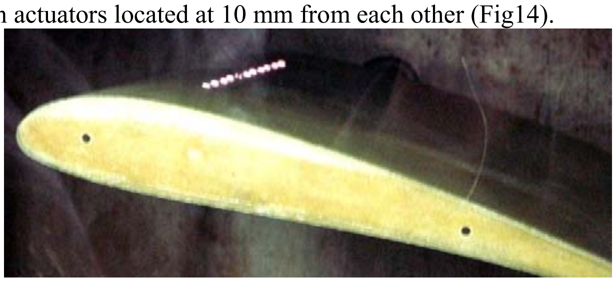


Figure 14. Wing model in a flow under an angle of attack with stable MW discharges over its surface, λ_z = 10 mm

Aerodynamic simulations were carried out to match wind-tunnel experiments for different control parameters of pulse MW radiation: τ_p = 100µs, repetition frequency F= 1000 Hz. Fig.15 shows the development of thermal situation in the flow just after the thermal sources (plasma discharges) were switched off at the end of the EM pulse. Two such cycles were computed that enabled to see the interaction of successively generated portions of vortices at their downstream propagation (Fig.16).

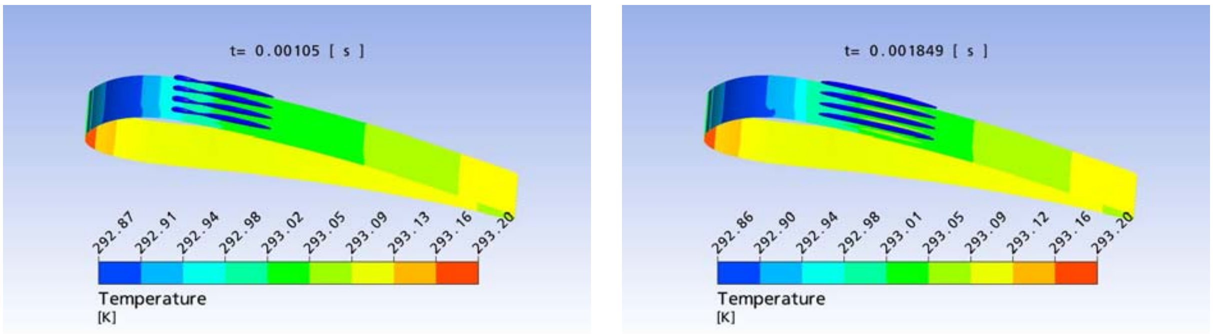


Figure15. Surface temperature and isosurface of T = 300°K; V_{fl} = 20 m/s, α = 5°, τ_p =100 µs, repetition rate F = 1000 Hz

Figure 16 shows that the generated streamwise z-regular vorticity can be optimized with a proper choice of pulse duration and repetition rate. Propagating downstream within a boundary layer, the two successive portions of streamwise vortices merge. It is an encouraging result taking into account the rapidly decaying temperature in the discharge wake: properly chosen pulse parameters enable to enhance the thermal effects due to the downstream merging of the vortices with a given scale.

Thus the available experimental equipment can be sufficient to produce necessary modification of the near-wall flow structure and, accordingly, to obtain expected optimization of lift and drag characteristics of the model.

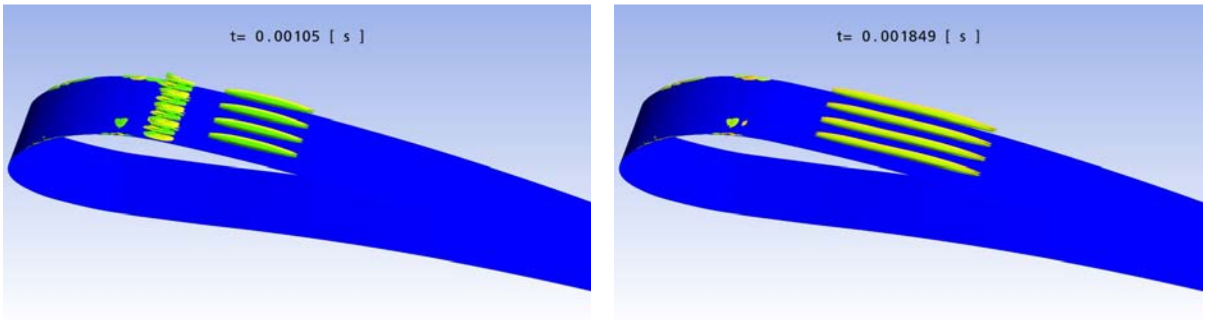


Figure16. Longitudinal vorticity isosurfaces (± 100 s^{-1}); V_{fl} = 20 m/s, α = 5°, τ_p =100 µs, repetition rate *F*= 1000 Hz

After all joint efforts on modernization and tuning up both electrodynamic and win tunnel equipment we could pass to final stage of work on the project.

The wind-tunnel results for measured lift and drag are shown in Fig.17 and Fig.18. These measurements were carried out for the model with 11 plasma initiators located at 25% of the cord with a spanwise step λ_z = 10 mm at different free-stream velocities V_{fl}=15, 20 and 30 m/s, for various angles of attack and combinations of pulse duration and repetition rates. The data are shown for the pre- and post-stall regions, free-stream velocity 15 m/s, pulse duration 0.1 ms and repetition rate 1000 Hz. Pressure coefficients are shown for drain port positions 2% and 10% of the chord.

Thus, the last results of wind-tunnel measurements of aerodynamic coefficients under generation of spanwise-regular MW-initiated discharges evidently prove feasibility of the proposed MW active boundary-layer control method.

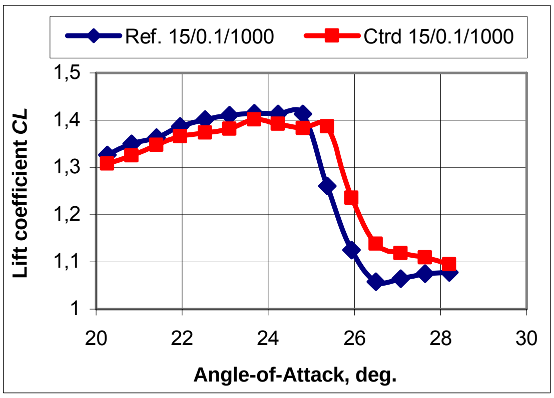


Figure 7. Lift coefficient for reference (Ref) and controlled (Ctrd) case

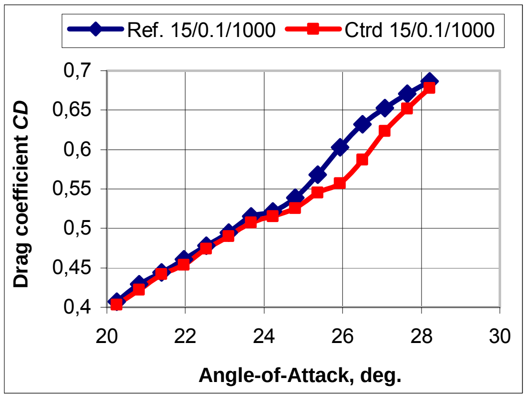


Figure18. Drag coefficient for reference (Ref.) and controlled (Ctrd) case

VI. Conclusion

The developed concept of the near-wall flow control is based on a modification of a naturally dominant structure (streamwise vortices) of the flow under body forces. Choosing a scale of the generated vortical structure, one can intensify mixing processes near the wall in an optimal way without essential increase of drag.

The obtained results proved feasibility of the developed flow-control strategy. Two tested active flow control methods are combined with this strategy of selective boundary-layer heating using (1) flush-mounted streamwise elements regularly spaced in a spanwise direction and (2) spanwise arrays of localized plasma discharges. The second approach required creation of a new experimental complex aimed at measurements of aerodynamic forces under conditions of microwave radiation and plasma generation. The new wind-tunnel facility enables experiments both with single models of airfoil- or blade-type and with turbine blade cascades.

The aerodynamic research approach consists in matched experimental and numerical tasks. It provides a possibility of results verification as well as of supplementing investigations like numerical modeling of a fine flow structure which cannot be measured with available instrumentation.

In particular, it was shown that inherent to flow streamwise vortices can be energized to result in efficient control of boundary-layers under relatively low energy outlay. Combinations are expected to be found of control parameters which will improve the aerodynamic performance (lift-to-drag ratio) of the plasma-controlled model. The developed remote mode of active flow control using MW-initiated plasma arrays is beneficial due to its greater operational flexibility.

At following stage of work all efforts are directed on further improvement and development of the proposed technology. As to "electrodynamic part" of the multidisciplinary project one has to solve a number of important science and engineering problems basing on ***already available*** wind-tunnel design and MW power equipment. In this concern, it is necessary to:

- develop a new antenna system including new irradiation horn, focusing lens and mirror and, thus, significantly improve an electrodynamic "interior" of the Eiffel chamber which is not optimal yet;
- develop and test new, more efficient MW-discharged initiator system;
- additionally increase, if possible, output pulse and average power of the MW generator based on available low-power magnetron.

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