Visualization of interaction between gas-dynamic perturbation caused by spark discharge and detached supersonic airflow

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Abstract. The method of long spark discharge initiating near the surface of the aerodynamic model, streamlined by supersonic airflow, was investigated. It has been shown experimentally that when a special construction discharger is used, a spark discharge can be initiated with a frequency of the order of 1 kHz at energy in one pulse of the order of 0.1 J and duration of the order of 0.1 μs. The gas-dynamic perturbation caused by the discharge was visualized, instantaneous patterns of the flow in the presence of a discharge were obtained, and a technique for reconstructing the dynamics of the flow change after the discharge was proposed.

1. Introduction

Initiation of an electrical discharge in the air flow can lead to a significant change in the flow pattern and the aerodynamic characteristics of the streamlined model [1,2]. Among the problems that researchers are trying to solve are decreasing of aerodynamic resistance [3], decreasing the effects of stall and separation of the flow from the surface of the body and, thus, improving the aerodynamic characteristics of the body [4], increasing the efficiency of mixing fuel with the incoming airflow and igniting the combustible mixture by discharge [5], controlling of laminar-turbulent transition [6], controlling of jet noise and tangential discontinuities in flow [7], creating addition forces for control [8] and other problems. It should be noted that mostly at studies process of discharge initiation are considered when the supplied electric power is much less than the energy of the incoming airflow. It is assumed that the hydrodynamic perturbations caused by discharge in the flow thus lead to a redistribution of the flow parameters (for example, a local increase in temperature and pressure) or when constant action is not required and the discharge can be initiated in a pulse-periodic mode. In this case the instantaneous power released in the incoming gas flow turns out to be much greater than the incident flow energy per second, however, in average at time the input power is less than the incident flow power. This paper presents the results of visualization of the process of long spark discharge initiating of submicrosecond duration in an incoming supersonic airflow with Mach number $M = 2$, at discharge initiation frequencies up to 2000 Hz and with an average energy input of less than 300 W. Earlier it was shown [9] that the initiation of a spark discharge on the surface of a body (airfoil model) can significantly change the flow pattern near the surface, including the displacement of the separation point downstream.
At high values of the angle of attack, near the trailing edge of the airfoil, a separated flow can be formed, and it characterizes by the presence of reversal or chaotic flow with respect to the main airflow. At the same time, in the separation region near the surface, the pressure is greater than it would be without flow separation. In order to act on the separation region it is proposed to initiate a long spark discharge near the surface of the airfoil upstream. This creates a gas-dynamic perturbation with increased pressure relative to the static pressure of the main flow, which moves downstream and interacts with the separation zone.

Upon initiation of a long spark discharge of submicrosecond duration on the surface a cylindrical shock wave is formed in the oncoming stream. Depending on the energy released in the discharge the propagation speed of the front of this wave can be different. At present work the energy in the discharge is less than 0.1 J for a spark discharge length of 10 cm. In this case the Mach number of the front of the cylindrical shock wave is slightly higher than 1, and the main airflow blows downstream the shock wave and the gas-dynamic perturbation (hot gas and high pressure region). When this perturbation interacts with the separation zone the separation point shifts downstream.

2. Experimental setup

A quasi-two-dimensional airflow around an aerodynamic body (NACA airfoil) with a pulsed-periodic instantaneous energy release near the surface in front of the separation zone near the trailing edge is experimentally simulated. The energy is released when a spark discharge of submicrosecond duration is initiated near the airfoil surface.

To initiate a spark discharge in a supersonic airflow, an electric discharger of a special design was used (see figure 1), so called segmented discharger [9]. To create long spark discharge, a set of several conducting segments 9, that are installed in the streamlined surface of the aerodynamic body (NACA airfoil), of the characteristic size of 3 mm are used, separated from each other by a thin dielectric film 10 of 0.1 mm thickness. In such a design, it becomes possible to create a discharge on a significant gap between the outer electrodes, i.e. the discharge is localized near the surface of the conducting segments, and the oncoming airflow does not lead to the blowing of the spark downstream. This is due to the redistribution of the electric field and the increase in its local strength near the surface of the conducting segments. It should be noted that the dielectric film 10 can be removed between segments located at the ends of the discharger 11. Since the number of segments 11 can be changed, in the experiment it is possible to set the length of the discharge gap, i.e. the length of the spark and the length of the region near the surface of the body, in which a rapid release of energy occurs.

The aerodynamic body with a flush-mounted discharger on its upper surface is an asymmetric NACA64a212 airfoil with a chord length of 10 cm and a span of 15 cm. The conducting segments of the discharger are 38 mm from the trailing edge of the airfoil. Fused silica is the material of airfoil, and it is characterized by good resistance to discharge plasma action (heat, chemical reactions). The airfoil was placed in a supersonic jet with Mach number $M = 2$, formed in an atmospheric-vacuum wind tunnel (see figure 1). The supersonic flow is formed when air 1 passes from the atmosphere to the vacuum system of the installation through de Laval nozzle 2 with a diameter of the output section of 11 cm. The supersonic jet of air forms and it has a static pressure approximately equal to $p_{st} = 0.15$ atm, and the flow velocity is close to 500 m/s. When the wind tunnel is operating, three modes of supersonic flow can be outlined: underexpansion, overexpansion, the matched regime when the pressure surrounding the jet $p_a$ is less than $p_{st}$, $p_a > p_{st}$, $p_a = p_{st}$ respectively. The pressure $p_a$ constantly increases as air from the atmosphere fills the vacuum system, and the filling rate is $Q = 1$ kg/s. At the same time as long as supersonic regime exists, the static pressure $p_{st}$ remains constant. The underexpanded mode is characterized by the presence of rarefaction waves in a supersonic jet, which leads to a nonuniform distribution of the components of the flow velocity vector. The case of overexpansion is characterized by the presence of shock waves, which also disrupt the uniformity of the flow parameters, and when an aerodynamic body is placed in such a jet, flow separation may occur due to the interaction of the shock wave and the boundary layer. Because of the relatively large volume of the vacuum system ($V_0 = 240$ m$^3$), the time for supersonic flow maintaining is about 60 seconds, however, to measure the flow
parameters of the aerodynamic models it is necessary to work on a much narrower time interval containing the time moment when \( p_a = p_{st} \). This moment of time is characterized by uniform distribution of the velocity vector components in the volume of the jet (at a distance from nozzle out section of the order of the nozzle diameter). Thus in presented experiments on the airflow around the airfoil were carried out near the matched regime and no longer than 10 seconds.

![Figure 1 Schematic representation of the experimental setup.](image)

The high voltage from the capacitor \( C \) (capacitance \( C = 4.1 \) nF), which is charged from a high voltage power supply HV (Spellman SL15P2000) through the ballast resistor \( R \) (resistance \( R = 90 \) kΩ) is applied to the electrodes of the discharger. When the charge voltage of the capacitor \( C \) exceeds the breakdown voltage, a discharge occurs on the surface of the NACA airfoil. With the help of a 12-bit high-resolution oscilloscope LeCroy 66Zi, the voltage across the capacitor \( C \) is recorded for 10 seconds, which allows tracing the stability of the spark discharge parameters: breakdown voltage, discharge energy, discharge duration.

To visualize the separated flow near the trailing edge of the NACA airfoil the Particle Image Velocimetry (PIV) technique is used, see figure 1. Air 1 together with oil droplets of submicron diameter from the atmosphere enters the de Laval nozzle 2 where it accelerates to supersonic speed and a supersonic jet in the working chamber 3 flows around the NACA airfoil with the spark discharger 4. Then the air jet flows to the vacuum system 5. The oil aerosol is formed using a generator based on the Laskin nozzle [10], and the used liquid is vegetable oil. The working chamber 3 has several transparent windows of optical glass, so it is possible to perform visualization. The laser beam 6 passes through the laser sheet optics 7, then through the transparent window gets inside the working chamber 3. The laser sheet (in figure 1 is shown in dashed lines) illuminates droplets of oil aerosol in the flow area above the upper surface near the trailing edge. The plane of the laser sheet contains the axis of the nozzle 2. The laser radiation is scattered on the oil droplets and scattered light is recorded by the Imager Pro X 2M double exposure video camera. Laser system consists of two Nd:YAG lasers, so the PIV system allows getting two photographs with a resolution of 1600x1200 pixels and with a frequency of up to 14 Hz. The delay between the pulses of lasers in the experiment was 0.8 μs. Operation of the laser and video camera is controlled by the internal generator of the PIV system, and the process of initiating the discharge occurs at a random time. To compare each time moment of PIV-photograph of the laser radiation scattered on the drops and the time moment of discharge the SYNC OUT output of the camera is connected to the second channel of the oscilloscope. Also in the experiment, the pressure values \( p_a \) and \( p_{st} \) are recorded in order to compare the frames to the flow regime from the nozzle. The typical size of the visible video camera area is 10 cm.
3. Experimental results
The main problem in visualizing of interaction between separated flow near the trailing edge and the gas-dynamic perturbation that occurs when a spark is discharged on the surface of a NACA airfoil is the unsteadiness of the detached flow. One of the methods of obtaining data that allows evaluating the effect of this disturbance on the position of the separation point position is to keep constant all parameters and make multiple photographs (PIV measurements). If the energy released in the discharge, the place where the discharge was initiated, the time $t$ between the discharge time moment and the time moment of photograph taken for PIV measurements are fixed, then flow patterns can be averaged and a picture of the interaction between the gas-dynamic perturbation and the separation zone at time $t$ is obtained.

The place of initiation of the discharge, as already mentioned above, is fixed due to the design of the discharger. It should also be noted that the surface is not destroyed by the discharge plasma due to the selected airfoil material. Figure 2 shows a photograph of the spark discharge in a supersonic air flow on the surface of the airfoil made by a video camera with an exposure of 100 microseconds (which is much longer than the flying time). It can be seen that a plasma spark 10 cm long has sharp contours and is directly above the spark discharger.

By the measurements taken using a high-resolution oscilloscope, it is shown that the breakdown voltage, energy, discharge initiation period, discharge duration have sufficient stability during the experiment time (10 seconds). Figure 3 shows the histogram of the breakdown voltage obtained by processing the voltage waveform on the high-voltage capacitor $C$ for the case of the airfoil angle to the oncoming flow of 14 degrees (RF is the relative frequency of occurrence of the breakdown voltage value).

![Figure 2 Typical photograph (top view) of a spark discharge in a supersonic airflow with Mach number $M = 2$. On presented photograph flow is from top to down.](image)

![Figure 3 Typical histogram of voltage $V$ on capacitor $C$ at the moment of breakdown of the discharger.](image)

Similar histograms can be obtained for the energy $E$ stored in the capacitor at the time moment of discharge, both for the discharge duration $\tau$, and for the discharge frequency $f$ (or period $T$). The discharge duration $\tau$ is defined as the time during which the voltage drops from 0.9 to 0.1 of the voltage across the capacitor at the time moment of breakdown. The energy $E$ is defined as the difference between the energy in the capacitor at the moment of breakdown minus the energy in the capacitor after the
breakdown of the discharge gap. In reality, the second value (the residual energy in capacitor $C$) is much less than $E$ (by two orders of magnitude). It should be noted that, under the experimental conditions, the discharge initiation frequency was about 2 kHz. This means that the histograms are built with a significant number of measurements (of the order of 20,000).

Such histograms are characterized by the value of the parameter that is most often encountered in this experiment, as well as the width of the histogram measured at its half-height. For example, it follows from figure 3 that a breakdown voltage of about 8.5 kV is most often encountered (in 10% of the total number of discharges), and the width of the histogram at a height of 50% is about 0.2 kV. Figure 4 shows the results, the most frequent values of the energy $E$ in various experimental launches. The vertical error corresponds to the half-width of the histogram, and the dashed line represents the average value of $E$ for the histogram maxima in experiments No. 1–10.

![Figure 4](image)

**Figure 4** The maxima of the histograms $E$ obtained in different experimental launches

For the PIV measurements of the process of interaction between the gas-dynamic perturbation caused by the discharge and the separation zone, the following parameters were chosen: the length of the discharge gap is 10 cm, the capacitor $C = 4.1$ nF, the angle of attack is 14 degrees, the resistance of the ballast resistor is $R = 90$ kΩ. A number of experiments were performed (10), at each voltage oscillograms on the capacitor were recorded, and then histograms of the discharge parameters were plotted for: energy stored in capacitor $E$, breakdown voltage $V$, discharge duration $\tau$, period between serial discharges $T$, repetition frequency $f$. For each of the 10 histograms a conclusion was made about the stability (repeatability) of the initiation parameters of the discharge $V, E, \tau, T, f$. Also from the obtained data the average value of these parameters was calculated and the ranges of variation were determined. The data obtained are as follows: $V = 8.4$ kV (+/- 5%), $E = 0.14$ J (+/- 10%), $\tau = 0.3$ µs (+/- 10%), $T = 450$ µs (+/- 20%), $f = 2.2$ kHz (+/- 20%). Thus, the energy $E$ and the duration of the release of energy in the flow $\tau$ vary within ±10%. This gives reason for averaging the resulting spatial flow patterns corresponding to a certain delay range $t$ from the moment of discharge to the moment of PIV measurement. Due to the low speed of the PIV system, and also to increase the number of spatial distributions of the velocity vector for averaging, the value of $t$ is selected from 0 µs to 150 µs with step of $\Delta t = 10$ µs. These spatial flow patterns are grouped if they correspond to the delay in the range from $t$ to $t + \Delta t$. The spatial flow patterns corresponding to the time delay between the discharge and shooting moments lying in the range from $t$ to $t + \Delta t$ are averaged, and the delay of $t + \Delta t/2$ is assigned to obtained average picture. Figure 5 shows the spatial distributions of the flow velocity vector over the upper surface of the airfoil near its trailing edge and at different time moments. For clarity the color indicates the region in which the flow velocity is subsonic (i.e. the separation zone), the white region is
the region of supersonic main flow, the green area corresponds to the position of the airfoil in space. The place of initiation of the discharge is not shown, because it is located upstream (at a distance of 38 mm from the trailing edge). The flow patterns presented are obtained by averaging 15 PIV measurements.

![Figure 5](image)

**Figure 5** Averaged distributions of the flow velocity vector field near the trailing edge of the airfoil: a — time moments \( t \) in the range from 0 to 10 μs after the discharge, b — 60–70 μs, c — 90–100 μs, d — 140–150 μs. Values on the color scale are in m/s.

For a different time value \( t \) after the moment of the discharge similar pictures of the distribution of the velocity vector in the space above the airfoil are obtained. According to the average flow patterns the separation point position relative to the trailing edge (average distance from the separation point to trailing edge) is obtained and the root mean square deviation of the separation point position from the mean value is obtained from individual frames from the time range from \( t \) to \( t + \Delta t \). Figure 6 shows the results of processing spatial patterns, where the width of the point corresponds to the width of the time range \( \Delta t = 10 \) μs, and the height is the root mean square of deviation in the position of the separation point for the selected time interval. It can be seen that for some time after the moment of discharge, the position of the separation point is displaced downstream, but then the position of the separation point returns to a position that is slightly upstream from the initial position.

![Figure 6](image)

**Figure 6** Change of distance from the point of flow separation to the trailing edge (SPP, separation point position) vs. a time after the moment of discharge \( t \).
4. Conclusions
The visualization and measurement of the spatial distribution of the flow velocity over the upper surface of the airfoil, which is streamlined by the supersonic airflow, was carried out with initiating a rapid heat release and in the presence of a flow separation near the trailing edge. With the help of a special design of discharger a heat release occurs by initiating long spark discharge, which occurs when a voltage is applied to a discharger of a certain value. This generates a cylindrical shock wave and a long spanwise gas-dynamic perturbation that interacts with the separation zone. These circumstances allow concluding that a quasi-two-dimensional case is modeled in presented experiment.

The discharge initiation parameters were measured experimentally and it is shown that the self-initiation of the spark discharge occurs with relatively constant parameters, in particular the energy and duration of the discharge. These parameters vary from discharge to discharge, from experiment to experiment no more than in a range of +/- 10% of the average value.

The relative constancy of the discharge parameters made it possible to perform a detailed flow visualization using the PIV method, which unambiguously shows the position of the subsonic separated flow region. The position of the point on the upper surface of the airfoil is shifted to the trailing edge of the airfoil as the gas-dynamic perturbation from the discharge moves downstream. Then the separation point returns to its initial position and even upstream. This circumstance may be due to the fact that the leading front of a cylindrical shock wave propagating along the boundary layer can cause its detachment. The front of the cylindrical shock wave propagates along the flow, which moves with supersonic speed (Mach number is $M > 2$, flow speed is about 600 m/s), both upstream and downstream. The front of the shock wave leads to the appearance of a positive pressure gradient in the boundary layer upstream, which can lead to an earlier formation of separation than it was before the discharge was initiated. This circumstance should impose certain limitations on the energy to be released with discharge into the stream.

The obtained instantaneous PIV flow patterns with the delay $t$ in range from 0 $\mu$s to 150 $\mu$s show that the interaction of the gas-dynamic perturbation caused by the spark discharge, characterized by the presence of an area of increased pressure relative to the static pressure of the main supersonic flow, leads to deformation of the separation zone and to the displacement of the separation point downstream. Apparently, the initiation of a spark discharge within the separation zone is not advisable, because will lead to even greater increase of pressure in the separation region and to the appearance of a positive pressure gradient in the boundary layer upstream.

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References

References
[1] Moreau E 2007 *J. Phys. D: Appl. Phys.* 40 605–36
[2] Bletzinger P, Ganguly B N, Van Wie D and Garascadden A 2005 *J. Phys. D: Appl. Phys.* 38 R33
[3] Bityurin V A, Efimov A V, Kazanskiy P N, Klimov A I and Moralev I A 2014 *High Temp.* 52 483–89
[4] Correale G, Popov I B, Ratikin A E, Starikovskii A Y, Hulshoff S J and Veldhuis L L M 2011 *Proc. 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition (Orlando FL, January 2007)* AIAA 2011-1079
[5] Leonov S B, Houpt A W and Hedlund B E 2017 *Proc. 48th AIAA Plasmadynamics and Lasers Conf. AIAA AVIATION Forum (Denver CO)* AIAA 2017-3673
[6] Moralev I, Sherbakova V, Selivonin I, Bityurin V and Ustinov M 2018 *Int. J. Heat Mass Transfer* 116 1326–40
[7] Kopiev V F, Kazansky P N, Kopiev V A, Moralev I A and Zaytsev M Yu 2017 *J. Phys. D: Appl. Phys.* 50 475204
[8] Elias P Q and Castera P 2013 J. Phys. D: Appl. Phys. 46 365204
[9] Golub V V, Saveliev A S, Sechenov V A, Son E E and Tereshonok D V 2010 High Temp. 48 6 903–9
[10] Raffel M, Willert C E, Wereley S and Kompenhans J 2007 Particle Image Velocimetry. A Practical Guide (Berlin: Springer)