Influence on separation point position by rapid local gas heating with spark discharge on the surface of airfoil streamlined by supersonic airflow

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Abstract. Experimental investigation of interaction between gas-dynamic perturbations caused by long spark discharge and separation region on the surface of an aerodynamic model, streamlined by supersonic airflow with Mach number $M = 2$, is presented in this paper. A NACA-airfoil with a relative thickness of 12% of the chord length was used as an aerodynamic model. With the help of the Particle Image Velocimetry method airflow was visualized at various angles of attack, delays 0–100 μs relative to the moment of discharge initiation and at various values of stored electric energy 0.1–10 J, that was spent for discharge creation. It was found that the flow disturbance caused by the discharge leads to a short-term displacement of separation point downstream.

1. Introduction

The question of improving the aerodynamic characteristics and the pattern of flow around the surface of the vehicles is relevant today. When aircrafts move in the atmosphere, such regimes can be realized in which the possibility of flight or its control is threatened, for example, when an airplane is flying at supercritical angles of attack. One of the negative phenomena in the flow pattern is the emergence of separation region on the surface of the aircraft, which is characterized by nonstationarity and altered parameters, for example, increased pressure value, temperature inside the flow separation region, as well as increased drag. Currently there are passive or mechanical methods of controlling separation on the surface of aircraft and they are being used, and methods of active influence on the flow by initiating electrical discharges of various types near the streamlined surface are being investigated and developed. The main advantages of using electrical discharge are low response time, high peak power, the ability to use it only when it is necessary, and not during the entire flight at all altitudes. The rapid development of the high-voltage semiconductor industry past years makes it possible to speak of a lower specific weight of high-voltage equipment (per unit of power) compared with mechanical and pneumatic devices acting on the flow. However, there are also disadvantages of using an electrical discharge, primarily due to the need to use dielectric materials, because a discharge is initiated at a high electric field strength, as well as with the complexity of computer simulation of physical processes.
processes in plasma and gasdynamic processes occurring simultaneously near the surface of the aircraft, due to significantly different values of time parameters of these processes. Therefore, discharge plasma occurrence process is often considered simplistic, for example, as heating of the flow at the volume of discharge initiation. In this paper the investigation of initiation of long spark discharge of submicrosecond duration on the surface of a two-dimensional model of a wing across a supersonic airflow around this model at a positive angle of attack is presented.

With such duration of discharge it turns out that the transit time is much longer, and the discharge effect can be simulated as almost instantaneous local heating of the incoming airflow. After the rapid release of energy for local gas heating, a quasi-cylindrical shock wave is formed in the oncoming airflow, which propagates relative to this flow. Behind the shock wave front there is airflow, which has a certain speed relative to the main flow. This speed can be both subsonic at a relatively low intensity of the shock wave, and supersonic at high intensity. In this work using a spark discharge, a shock wave is generated, the recorded propagation velocity of which corresponds to a Mach number less than 2, and the air velocity behind its front has a velocity of the order of several tens of meters per second. The purpose of this study is to visualize with Particle Image Velocimetry method (PIV) the propagation of a gasdynamic perturbation caused by long spark discharge across a supersonic flow, and its interaction with the separation region at various angles of attack of airfoil and discharge energy.

2. Experimental setup

The experiments were carried out on the ST-4 supersonic wind tunnel of atmospheric-vacuum type, a detailed description of which can be found in [1]. At this facility aerodynamic models are tested in supersonic airflow. In this work the free-stream Mach number was $M=2$, the static pressure of the flow was $p_0=0.15$ bar, the mass flow rate through the nozzle was about $1 \text{ kg/s}$, and the time for maintaining a supersonic flow was one minute. The unit Reynolds number in the experiment is $Re_l \approx 10^7 \text{ m}^{-1}$. An aerodynamic model was placed in a supersonic airflow, which was the NACA64a212 profile with a chord length of 98 mm and a span of 150 mm, made of fused silica material and with a discharge device mounted at 38 mm from the trailing edge. A more detailed description of used aerodynamic model can be found in [2]. It is important to note that, due to its design, the discharger made it possible to obtain long spark discharge of 7 cm in length in a supersonic air flow with a Mach number $M=2$, while the heat release using a discharge occurred across the flow. The design of the working chamber ST-4 provides a mechanism by which it was possible to set the desired angle of attack of the wing model.

During test run the flow around a wing model was diagnosed using a Particle Image Velocimetry laser system. The working chamber of the supersonic wind tunnel is equipped with several transparent windows, which made it possible to introduce a laser sheet for visualizing the flow above the airfoil, as well as to photograph from above long spark discharge in the airflow. For measurements, the LaVision FlowMaster 2D PIV system was used, as well as an oil aerosol generator based on Laskin nozzle [3], which provides a productive airflow seeding by droplets of oil with a diameter close to 1 μm. The area visible by the PIV-videocamera was 48x35 mm$^2$ and it was located near the trailing edge of the profile, so that particles moving in the flow above the upper surface of the profile and the place of initiation of the discharge (discharger) were in PIV-photos. The spatial resolution of the PIV system was 0.5 mm.

High free-stream velocity, the presence of shock waves and the separation region require the usage of tracer particles with a relatively small diameter and, accordingly, high-energy lasers in a single pulse. Since the PIV system used an Nd:YAG laser pumped by a gas-discharge lamp with a pumping time of about 100 μs, which is close to the time of flight in experiments, and operational frequency less than 14 Hz, a high-voltage pulse generator was used to control the initiation of the spark discharge. A generator is an electrical circuit based on a Marx two-stage circuit. Switching in the generator took place with the help of two air spark dischargers, one of which is controlled. In [2, 4] another discharge initiation scheme was used, where the initiation of a spark discharge occurred in an
uncontrolled manner, and the non-stationary flow caused by the discharge was recorded independently of this process.

Simply the high-voltage generator circuit can be characterized by a net capacitance $C_0$, which at the time of discharge is charged up to doubled value of the charge voltage $U_0$. The capacitance $C_0$ was set by the generator circuit ($C_0$ was varied from 4 nF to 50 nF) with the help of several high-voltage capacitors, and $U_0$ was varied in accordance with the breakdown voltage for a controlled discharger and was set with the help of a high-voltage power supply. The amplitude of the high-voltage pulse when applied to the discharger mounted in the wing model corresponded to a voltage that exceeds a breakdown value of 1 kV/cm, which was previously determined under the same experimental conditions [2].

In experiments LeCroy WaveRunner 66Zi digital storage oscilloscope was used, the first input channel of which was supplied with voltage from a high-voltage 1:1000 LeCroy PPE20KV probe connected to a high-voltage generator, and to the second input channel a sync pulse from a PIV system was applied, which was a positive TTL-pulse, the rise edge of which corresponds to the moment of PIV-measurement. Oscillograms were recorded during the entire experimental run (10 s) with a discretization time 100 ns. The oscillogram of the voltage on the capacitors of a high-voltage generator can be characterized by a periodic process of slow charging to a voltage $U_0$ (~10 ms) and fast discharging to a voltage $U_1$ due to the occurrence of a spark discharge and the release of energy into the airflow (~0.1 μs). Due to this form of oscillograms of the voltage across the capacitor of the generator and the sync pulse of the PIV system, they can be processed with computer algorithm. Thus, by recording the oscillograms and their subsequent processing using a computer program, one can determine the voltage $U_0$, the residual voltage $U_1$ after the discharge, the moments of the occurrence of the discharge and the PIV measurements. With simultaneous processing of the oscillograms and PIV photographs of single test run, the average spatial distribution flow velocity vector at the time $\Delta t$ after the discharge, the average value of the electric energy $E$ that was consumed per discharge, the average duration of the discharge $\tau$ were obtained. The amount of electrical energy was determined by the formula:

$$E = 2C_0(U_0^2 - U_1^2)$$

In addition, the static pressure of the flow $p_{st}$ and pressure $p_a$ of air which surrounds the supersonic jet in the working chamber were recorded synchronously with the PIV measurements, so that each frame could be assigned a flow regime beyond the nozzle exit section. As stated above, one experiment lasted 10 seconds, 5 seconds before the onset of the ideally expanded flow regime on the ST-4 facility and 5 seconds after. At the same time, the pressure ratio $p_s/p_a$ varied in the range from 0.85 to 1.15. The number of PIV frames registered with a frequency of 14 Hz was 140.

Thus, in each experimental test run the following parameters were set: electrical energy $E$, which was spent on long spark discharge creation, the delay $\Delta t$ between the start of the discharge and the time of the PIV measurement, the angle of attack of the airfoil. The place of initiation of the discharge (i.e. the place of energy release) was fixed on the surface of the airfoil and was specified by the position of the discharger. By varying the value of $\Delta t$ in the range from 0 μs to 100 μs (the characteristic value of the transit time) with a step of 10 μs or 20 μs, it was possible to reconstruct the dynamics of the propagation of gasdynamic perturbations that occur after the initiation of the discharge. To do this, the PIV frames obtained in single test run were tested (by oscillogram processing) for compliance with the delay relative to the set value and for the occurrence of a discharge (by the frames taken from the top view of the airfoil). The frames that passed tests were averaged, and the flow pattern was obtained in the form of fields of velocity vectors for a given delay $\Delta t$.

3. Obtained results

In order to average the passed PIV frames, obtained with fixed $E, \Delta t$, it is necessary to check how wide the dispersions of these parameters from discharge to discharge in single test run are. It is also necessary to check that the discharge duration $\tau$ has a constant value, and the place of discharge
initiation coincides with the location of the discharger on the surface of the wing model. To do this, the oscillograms and recorded images of a spark discharge, obtained in each test run, were processed. After such processing statistics of the energy $E$, the duration $\tau$, the delay from the PIV-frame moment relative to the moment of initiation of the discharge $\Delta t$ were obtained of an each individual discharge. The processing was carried out with the help of the developed computer program, which takes on its input the oscillograms of the voltage on the capacitor of the high-voltage generator and the PIV system sync pulse. To reconstruct the nonstationary flow pattern, i.e. to obtain PIV measurements at different $\Delta t$ values, it is necessary to show that from one test run to another the value of $E$ does not change significantly.

Figure 1 shows the typical histograms of the distribution of delay $\Delta t$ and energy $E$, obtained after processing the oscillograms of one experimental test run. On the presented histograms one can select the maximum and its width. Figure 2 shows the variation of the parameters $\Delta t, E$ and $\tau$ in different experimental series depending on the number of the experimental launch. Table 1 presents the parameters of each run. In table 1 and in figure 2, the values with the ‘av’ index is the mean values for the corresponding experimental series. The nonmonotonic dependence between discharge time $\tau$ and the net capacitance $C_0$ of the generator is associated with the usage of various ceramic capacitors in various experimental series. These sets of capacitors differ in their nominal capacitance (1 nF, 4.7 nF or 10 nF), in size, manufacturers. Thus, in the experimental series, not only the magnitude of the net capacitance $C_0$ changed, but also the inductance of the discharge circuit.

The following conclusions can be drawn from the presented statistics of the properties of discharges. The duration of any discharge $\tau$ did not exceed 1 $\mu$s in any experiment, while the average discharge duration $\tau_{av}$ did not exceed 0.5 $\mu$s. During this period, the main flow over the airfoil travels no more than 0.6 mm, which is two orders of magnitude less than the length of the wing profile chord. At the same time, the obtained photographs of the discharge from top view with an exposure of about 10 $\mu$s do not show a ‘blurred’ image of the spark channel. These two circumstances make it possible to consider the process of energy release into the oncoming air stream almost instantaneously.

The scatter of the magnitude of the energy $E$ of all discharges mainly (except series 4) did not exceed $\pm$5% of the average value of the electric energy $E_{av}$. In the theory of a very strong explosion [5] the velocity of a generated shock wave with a two-dimensional fast release of energy has a power dependence on $E$ with an exponent of 0.25. The length of the energy release is fixed and coincides with the distance between the outer segments of the spark gap (this distance is 7 cm). These circumstances make it possible to assume that the intensity of the shock waves generated by the discharge in each experimental test run has a relatively stable value. At the same time, this intensity is relatively stable throughout the entire experimental series.

![Figure 1. Typical histograms of the distribution of the delay $\Delta t$ (a) and energy $E$ (b). ‘RF’ is the relative frequency of the discharge occurrence with a given parameter value.](image-url)
The change of the $\Delta t$ value is from $-10 \mu s$ to $+20 \mu s$ relative to that set in the experiment test run, and this dispersion increases with increasing energy of the discharge. But it should be noted that the maxima in the $\Delta t$ histograms lie in the range of $\pm 5 \mu s$ relative to the average value, i.e. most discharges occur with $10 \mu s$ jitter.

Figure 2. The dispersions of delay $\Delta t$ (a), energy $E$ (b), and discharge duration $\tau$ (c) in various experiments with different parameters. The number denotes the experimental series, the parameters of which are presented in the table 1.

Table 1. The parameters of experimental series. ‘AoA’—angle of attack.

| Ser. No | Exp. No | AoA, $^\circ$ | $U_0$, kV | $C_0$, nF | $E_{av}$, J | $\tau_{av}$, $\mu s$ |
|---------|---------|--------------|-----------|------------|-------------|-----------------|
| 1       | 1–24    | 12           | 7.32      | 1.8        | 0.17        | 0.20            |
| 2       | 25–39   | 12           | 8.80      | 3.9        | 0.56        | 0.25            |
| 3       | 40–45   | 14           | 8.80      | 3.9        | 0.55        | 0.25            |
| 4       | 46–60   | 12           | 9.50      | 8.4        | 1.26        | 0.22            |
| 5       | 61–75   | 14           | 9.00      | 19.5       | 2.95        | 0.24            |
| 6       | 76–90   | 14           | 9.00      | 8.4        | 1.23        | 0.20            |
| 7       | 91–98   | 14           | 9.50      | 38.9       | 6.08        | 0.39            |
| 8       | 99–105  | 16           | 9.50      | 44.0       | 6.86        | 0.43            |

Figure shows the typical averaged fields of the flow velocity vector (the $V_y$ component of the velocity vector is shown in color map) when initiating long spark discharge on the surface of the wing profile model for two experimental series (see experimental series 4 and 7 in table 1). In this case, averaging is made over approximately 100 PIV measurements. The red line shows the place of initiation of the spark discharge, the gray area is the schematically indicated airfoil, and the black area below is the shadow from this airfoil. The white area in the flow patterns actually corresponds to the
separated airflow. Oncoming supersonic airflow is from left to right. The $x$ axis is directed horizontally from left to right, and the $y$ axis is directed vertically from bottom to top.

On the presented unsteady flow patterns for the fourth series at the time $\Delta t=12 \, \mu s$, it can be seen that a shock wave is formed after the discharge, which adds velocity to the incident flow in the direction of the $y$ axis. At the time $\Delta t=91 \, \mu s$ the separation area has the smallest size, and the distance from the separation point to the trailing edge (coincides with the right edge of the shadow from the airfoil) has the smallest value at this time point. At the time $\Delta t=131 \, \mu s$, the front of the shock wave is not registered in the flow pattern, because on the one hand the intensity of the shock wave has significantly decreased by this time, and on the other hand, the shock wave partially left the area visible by the video camera due to blow-off by the incident airflow. At this time moment the position of the separation point has almost returned to the initial one.

The flow pattern for the seventh series (figure b) shows that at the initial moment of time after discharge ($\Delta t=2 \, \mu s$), the separation region is closer to the place of initiation of the discharge (because angle of attack is greater than in fourth series of experiments), but still energy release occurs upstream relative to the separation point. After initiating discharge, a quasi-cylindrical shock wave briefly arises in the flow, which propagates downstream and interacts with the separation region. It is seen that at a certain point in time ($\Delta t=83 \, \mu s$) this interaction leads to a shift of the separation point downstream. In the middle frame ($\Delta t=83 \, \mu s$), the shock wave is still visible in the form of a relatively high value of $V_y$ in the upper part of the flow pattern. The position of the separation point returns to its original value as the shock wave is blown off by an external supersonic and flow and its intensity decays ($\Delta t=122 \, \mu s$).

**Figure 3.** The averaged fields of the $V_y$ component (in m/s) of the velocity vector at different times (indicated in the frames) after the start of the discharge for the fourth (a) and seventh (b) experimental series. Arrows indicate airflow direction. Dashed curves indicates schematically shock waves front detected by increased value of $V_y$.

Interaction of flow separation region and gasdynamic perturbation caused by discharge can also be shown by a set of velocity profiles along the interval perpendicular to the airfoil surface. On figure 4a and 4b $V_x$ component (normalized on oncoming airflow speed $V_\infty=500$ m/s) profiles along the
corresponding intervals are presented. For experimental series 4 (see table 1) this interval starts on the distance 10 mm from trailing edge, for experimental series 7 this distance is 11 mm. These values were chosen to demonstrate clearly the effect of interaction between gasdynamic perturbation and flow separation region. If interval is not in flow separation region then $V_x$ is always greater than 0 m/s (see red curves), but if $V_x<0$ m/s then there are separation region (see black and blue curves). Velocity vector is directed almost parallel to the airfoil surface (in vicinity to it) and $V_y$ is also can indicate separation region and separation point position. The practice shows that spatial distribution of $V_x$ component (that is presented at figure ) more clear shows separation point position at the surface of airfoil. It should be noted that on presented profiles $V_x$ is not equal 0 m/s at $l$ =0 mm, because start points of intervals lay slightly higher than airfoil upper surface. In experiment PIV-measurements cannot be performed in closer vicinity of this surface due to light scattering on it and spatial resolution of optical system.

Figure 4. $V_x$ component (normalized on incoming airflow velocity $V_{∞}=500$ m/s) profiles along intervals shown on figure . ‘l’ is a distance from airfoil surface.

The experimentally observed effect can be represented as graphs of the dependence of the separation point position $x_{SP}$ relative to the trailing edge versus time $Δt$ after the discharge initiation. Figure 5 presents the dependences of $x_{SP}(Δt)$ for some experimental series 4, 5, 7, 8 (see table 1). From the presented dependencies one can conclude that in the range of electrical energy from 0.18 J/cm to 0.98 J/cm, which is spent for spark discharge initiation on the surface of the airfoil, a short-term displacement of the separation point is less than 1 cm. When the discharge energy changes by 5 times, this shift turns out to be almost the same. If one compares all the experimental series presented in the figure, it turns out that the displacement of the separation point downstream begins earlier at a larger value of angle of attack. This circumstance is due to the fact that at a larger angle of attack the position of the separation point is closer to the place of initiation of the discharge. If we compare the experimental series 5 and 7, it turns out that with an increase in the discharge energy by a factor of two, a short-term effect of early separation may occur due to an excessively strong shock wave caused by the discharge. On the graph this is expressed by a short-term increase in the $x_{SP}$ position of the separation point.

The separation of the flow from the upper surface of the airfoil has unsteady nature, and the position of the separation point is not constant in time. Figure 5 shows the average values of separation point position, which was determined by the average velocity field. In addition to the averaged field, the fields of root mean square (RMS) of the components and the length of the velocity vector from the average were calculated in order to determine the boundaries of the separation point position. Figure 6 shows the fields of the RMS value for the length of the velocity vector for experiments corresponding to figure. To determine the magnitude of the fluctuations in the position of the separation point, a threshold of 250 m/s was selected, which corresponds to half the free-stream velocity $V_{∞}=500$ m/s. In the presented RMS fields regions with maximum values that are close to this threshold are visible. The projection of these regions onto the upper surface of airfoil determined the magnitude of the
fluctuations in separation point position. It should be noted that as a result of this approach, it was found that at angles of attack 12°–16° the region of fluctuations of separation point position on the upper surface has a length of about 1 cm, and at the time when the gasdynamic disturbance interacts with the separation zone, this length is reduced to 3–5 mm.

![Figure 5](image1.png)

**Figure 5.** Distance $x_{SP}$ between separation point and trailing edge at various time moments after discharge $\Delta t$.

![Figure 6](image2.png)

**Figure 6.** The RMS fields of the velocity vector length (in m/s) at different times (indicated in the frames) after the start of the discharge for the fourth (a) and seventh (b) experimental series.

4. Discussion

The main parameters of energy and time of the discharge are experimentally investigated. With the help of high speed video photography of the discharge and oscillograms of voltage of high-voltage generator, it was shown that the energy release occurs almost instantly in less than 1 $\mu$s, which is much less than the transit time. The mentioned properties of the object of investigation give reason to believe that the process of heat release is fast (instantaneous), and the unsteady flow is quasi-two-
dimensional. These properties are important because they allow computer simulation of this process in a two-dimensional formulation without the use of significant computational resources. And in this case the initial local heating of the flow can be simulated as an area of increased pressure and temperature. The calculation of these values of pressure and temperature should take into account that as a result of a spark discharge only a part of the electric energy $E$ is transferred to gas heat. The fraction of this energy is usually determined by comparing the experimentally obtained flow patterns with flow patterns obtained in numerical simulation. For long spark discharges, this value may be different depending on the type of discharge initiation and external conditions (flow parameters). From the literature values of this fraction differ several times from 10% [6] to 40% [7].

As a result of processing the PIV data, averaged patterns of unsteady flow were obtained at various time moments after discharge. The pictures show that as a result of rapid local heating of the incident flow with discharge, a nonstationary gas-dynamic perturbation occurs, which is an expanding hot gas region heated by a spark discharge, and a quasi-cylindrical shock wave, behind the front of which the gas has an additional velocity.

The averaged flow patterns obtained by the PIV method showed that the propagation of a gas-dynamic perturbation leads to a short-term displacement of the separation point downstream. The experimental data show that an increase in the input electrical energy by a factor of two from 0.42 J/cm to 0.87 J/cm does not lead to a significant change in the magnitude of this displacement, but at the initial moment of time the position of the separation point may shift upstream when energy value is large enough. The maximum displacement of the position of the separation point is about 1 cm in about 40 μs at angles of attack 12°–16°, which corresponds to the result obtained earlier at an angle of attack of 14° [2]. According to the data of the present and previous experiments [2, 4], carried out under the same experimental conditions, the velocity of the separation point downstream has a value (0.2–0.3 km/s) that is less than the velocity of external air flow (depends on the angle of attack, about 0.6 km/s). This circumstance suggests that the left-hand side of the gasdynamic perturbation, which moves against the oncoming airflow, has an influence on the position of the separation point. The influence mechanism can be the turbulization of the boundary layer, the generation of additional vorticity due to the presence of pressure and temperature gradients in the energy release region, the transfer of an additional impulse to the boundary layer due to the expansion of the heated region.

Relative energy deposition $\eta$ can be estimated as the ratio between the consumed electrical energy to create a discharge and the enthalpy of the incident flow:

$$\eta = \frac{\gamma - 1}{\gamma} \frac{E}{a_0^2 Q T}$$

where $a_0$ is the speed of sound of atmospheric air (~320 m/s), $\gamma$ is heat capacity ratio for air (1.4), $Q$ is airflow mass rate through the relative (planform) area $A_{rel}$ of airfoil ($Q=A_{rel} \rho \gamma V_c=1$ kg/s), $T$ is discharge initiation period, $E$ is electrical energy consumed by initiation of one discharge. The value of $T$ can be estimated from the data obtained in the experiment, if we assume that the restoration of the original flow pattern occurs after about 50 μs (figure 5). Then in the range of $E$ from 1.26 J to 6.86 J, the value of $\eta$ will be from 0.1 to 0.5. This value can be reduced by initiating the discharge with the smallest necessary energy, as well as by increasing the efficiency of converting electrical energy to local rapid heating of the gas.

5. Conclusions

An experimental study was carried out about the interaction between a separated flow and a gasdynamic perturbation generated by rapid local heating of the oncoming supersonic airflow near the upper surface of the airfoil at positive angles of attack of 12°–16°. For this a method for initiating long spark discharge of 7 cm length and an electrical circuit for it initiating in a pulse-periodic mode are proposed. A study of the parameters (energy, duration, delay) of the electric discharge was made, which showed their sufficient stability from experiment to experiment with average energy input, that was varied in range 2.4–98 J/m. This circumstance made it possible to measure the velocity vector field of airflow over the upper surface of the profile using the PIV method. The obtained instantaneous
(averaged) fields of the flow velocity vector at various time moments after the initiation of the discharge show that the gasdynamic perturbation, which is a quasi-cylindrical shock wave and a region of increased pressure that moves downstream, affects the separation region. This effect leads to a shift in the position of the separation point (up to about 1 cm) downstream to the trailing edge. Fields of root mean square for the velocity vector are also obtained, from which the boundaries of the position of the separation point on the upper surface of the profile are determined. At the specified angles of attack, the oscillations of separation point position were ±5 mm from average value. The experiment showed that the fluctuations in the position of the separation point decrease by 2–3 times during interaction of the gasdynamic perturbation with separation region. Thus, the region of increased pressure that caused by the discharge and propagating downstream limits the oscillation range of the separation point position, and this on average leads to its displacement to the trailing edge.

**Acknowledgments**
The reported study was funded by RFBR according to the research project № 18-38-00803.

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