Influence of the position and energy of local rapid heating of the supersonic gas flow on the position of the separation point on the surface of airfoil

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Abstract. Using numerical simulation, the study of the process of rapid local energy release in supersonic flow in a two-dimensional unsteady case and the process of separation point shift by a gas-dynamic perturbation caused by the energy input into the flow were carried out. The flow around the airfoil was modeled as laminar, and local heat release as instantaneous isochoric process without changing the gas density. The value of energy input and the place of gas heating on the surface of the airfoil were varied. The cases of initiation of energy input at a certain distance before and after the initial position of the separation point, as well as immediately before the separation point, were considered. During obtained flow patterns processing, the displacement of the separation point position downstream, the time of this displacement, the position and size of the separation region with reattachment and the lifetime of this flow zone were determined. The obtained data can help to choose a strategy for initiating energy input in a repetitively pulsed regime, as well as in a regime of a variable position of energy release on the surface of a body, streamlined by compressible gas flow.

1. Introduction

Over the past decades and now there is an interest in applied and fundamental work related to the control of gas flow regimes using an energy release. In particular, with the help of numerical simulation, studies of pulsed or constant energy input (heating) into the flow were carried out ([1–5, 8]). In [1], the process of reducing the wave drag in the transonic regime of the flow around airfoil was investigated. It is shown that there is a certain limit of parameters (Mach number, shock position, etc.) at which a significant decrease in drag is possible (25%). In work [2], the effect of local surface and volumetric continuous heating on local frictional force (drag decrease) in a turbulent flow (Mach number $M=2$) near surface of plate is qualitatively shown. In [3], the effect of continuous heating on the parameters of a $\lambda$-shock was investigated when a transonic flow is flowing around an airfoil; it is shown that with the help of an energy input it is possible to significantly change the value of the pressure gradient in the boundary layer and to increase its resistance to separation. The effect of energy release by means of an electric discharge of specified parameters on the process of separation of the boundary layer in front of a flat step in supersonic flow regimes has been investigated. The cases of adiabatic and isothermal streamlined surfaces are considered. It was shown that with the help of continuous heat input, it is possible to control the position of the flow separation point in front of the step. In [5], the process of pulse-periodic energy input into the flow in the transonic flow regime
was considered. A significant change in the wave drag was shown, and a further increase in the frequency of initiation of energy release does not lead to a further decrease in drag, which made it possible to estimate the energy consumption (30% of the engine power) and suggest the possibility of practical use of the method in the cruise flight of the aircraft.

Earlier, it was experimentally demonstrated the possibility of using long spark discharge to influence the separation region, which is formed near the trailing edge of the aerodynamic body [6]. In that work, an original method of initiating long spark discharge on the surface of an aerodynamic body (NACA airfoil) across the flow was used, and its duration (submicrosecond duration) was much less than the flight time. That work was carried out on an atmospheric-vacuum wind tunnel ST-4 [7], which makes it possible to obtain a stationary supersonic flow with a Mach number \( M = 2 \) for one minute. Using the developed technique of high-speed digital photography by the shadow (schlieren) method, it was shown that as a result of rapid heat release, a gasdynamic disturbance (quasi-cylindrical shock wave) is formed and it propagates in moving supersonic flow, interacts with the separation region near the trailing edge and shifts the separation point position downstream. After a few tens of microseconds the resulting schlieren pictures show that the separation point returns almost to its initial position upstream. In [8] it was shown by the method of two-dimensional non-stationary modeling that the interaction of a gasdynamic disturbance with the separation region leads to the fragmentation of the last one. This partially explained the experimentally observed rapid return of the separation point at almost initial upstream position.

A further continuation of the work on studying the effect on the separation point by initiating long spark discharge of submicrosecond duration was the use of Particle Image Velocimetry (PIV) diagnostics on the ST-4 wind tunnel [9, 10]. A PIV system of low acquisition rate was used, so synchronization of the process with the system was necessary for flow diagnostics. For this, a new electrical circuit for the initiation of the discharge was developed, in which long spark discharge could be initiated by a low-voltage input signal. As a result of performed work the same effect of a short-term displacement of the separation point downstream was demonstrated using a technique that clearly indicates region of reverse direction of flow (i.e. separation region).

As a result of the experimental study it became clear that to extend knowledge about the process it is necessary to use numerical simulation. In the experiment there were restrictions on the position gas heating, on the transverse length of the region of energy release, on the electric energy of one discharge and the repetition rate of the discharge. The last mentioned circumstance was obviously associated with the limitation of the power of the high voltage source. The use of a quasi-two-dimensional aerodynamic model in the experiment (in the form of airfoil with a constant chord length of 98 mm) made it possible to carry out 2D modeling. The relatively short duration of the electric discharge made it possible to simulate the process as quasi-instantaneous. In this case, the energy input region was determined by photographing the plasma glow in the experiment. An important parameter that had to be determined before carrying out a numerical simulation of the process was the fraction of the stored electrical energy (this value was registered in the experiment) turned into local heating of the gas. To determine this value in [11, 12] a numerical simulation of the process of a single energy release using a long spark discharge was carried out. By comparing the experimentally obtained instantaneous shadow patterns of flow and the velocity vector fields at different times after the initiation of the discharge, the values of fraction of electrical energy were obtained for two ways of initiating the discharge: for an uncontrolled method (self-breakdown), this fraction was 20% [12], and for a controlled one, about 7% [11].

In [13] the case of pulse-periodic initiation of local heating was considered. As in the experiment, the energy input region was located directly in front of the separation region. The discharge energy also corresponded to one of the values of the electric discharge energy in experiment. It was shown that the repetition rate of the energy input significantly affects the position of the separation point on average over time. Correctly selected frequency allows a significant shift in the position of the separation point downstream, but an incorrectly selected repetition rate can lead to deterioration in the flow pattern when the separation point shifts upstream. In addition, it was shown that the initiation of
an additional random energy input leads to a deterioration in the flow pattern. The paper gives recommendations on the selection of the value of the repetition period of the energy input for a fixed value of the energy value.

In this paper, the question of the optimal parameters for the initiation of local heating of a supersonic flow is considered: energy, place of initiation. The data obtained in this work should help to choose a strategy for the optimal pulse-periodic heating of the gas with a change in the position of local heating on the surface of the model.

2. Numerical simulation

The papers [11, 12, 13] mentioned in the Introduction give a detailed description of previously used numerical simulation method. Since this work is a continuation of the previously carried out numerical simulation, only a brief description of the applied numerical technique will be given here. For a more detailed description of numerical technique, one should refer to the works mentioned above.

The sonicFoam solver (OpenFOAM package [14]) was chosen as a solver for the numerical simulation. The process parameters, such as the energy of one discharge, geometry, parameters of the incident flow and the amount of energy input were set the same as they were in the experiment, since one of the important tasks of the work is the constant comparison of the experimental data and the results obtained in the simulation. So, the airfoil, the geometry of which is known, with a chord length of 98 mm, was placed in the oncoming supersonic airflow with the Mach number $M=2$, total temperature $T_0=300$ K and total pressure $p_0=1$ atm. The gas viscosity was calculated using the Sutherland formula. The entire computational domain had a characteristic size of about 1 m, which was an order of magnitude larger than the chord length. The two-dimensional mesh was developed in such a way that the leading edge had the coordinate $(x, y)=(0, 0)$ mm, and the trailing edge had the coordinates $(x, y)=(98, 0)$ mm. In this case when the airfoil was rotated to an arbitrary angle of attack, these coordinates did not change, i.e. the incoming air stream was turning instead. The number of cells in the computational mesh was chosen equal to 240,000, because upon further refinement of the mesh, the flow pattern obtained in the simulation and the values of the aerodynamic coefficients changed insignificantly (the results of the study on mesh convergence can be found in [12–13]).

The first step in the numerical simulation was to determine the dependence of the position of the separation point depending on the angle of attack, as well as other parameters, such as the position of the bow shock wave and the velocity of the external flow near the place of initiation of energy release. This stage of investigation was performed over a wide range of angles of attack. Comparison of the experimental curve with the one obtained in the calculation indicates a good agreement between the data, and the laminar nature of the flow around the airfoil in the experiment was proven [13]. It should be noted that at this stage of numerical simulation, a study was carried out on the steadiness of the separated flow. This was done using a long-term calculation, the time of which was more than one order of magnitude greater than the time of flight over the airfoil. As a result, it turned out that about 500 $\mu$s after the start of simulation, a stationary separation was formed, and the position of the separation point became stationary. Continuation of the simulation (up to 5 ms) did not change the position of the separation point or the magnitude of the aerodynamic coefficients of lift and drag.

In this work the angle of attack (AoA) of 14° was used, because the largest set of experimental data is available for this AoA. This is due to the fact that in the experiment the position of the initiation of long spark discharge is fixed and it is located on the upper surface of the profile in the vicinity of the position of the separation point at 14° of the angle of attack. Figure 1a shows an example of the obtained pattern of stationary flow around the airfoil without energy release into the flow at an angle of attack of 14°.

The study of the unsteady process (with energy input) was carried out by superimposing the fields of increased values of temperature and pressure on the previously obtained stationary flow pattern, while the place of this superimposing corresponded to the place of initiation of the electric discharge in the experiment. The calculation of the pressure and temperature values in this area was carried out in accordance with the isochoric process (instantaneous energy input without changing the gas...
density), taking into account the partial transition of electrical energy to thermal energy. In this work it was assumed that only $\eta=10\%$ of the electrical energy is converted into thermal energy, the energy input region has the shape of a half-circle with a radius of 1 mm, the length of the energy input region across the flow is $L=0.1$ m. The value of electrical energy $E$ varied in the range from 0.1 J to 20 J, so that the value the heat input $\eta E/L$ varied in the range 0.1–20 J/m. The time between the instantaneous heating (time $t=0$ s) to the termination of the simulation was 200 $\mu$s, since by this time, at various parameters of the process, the flow separation began to form close to its initial position.

Figure 1. An example of stationary (a) and non-stationary (with rapid local heat release) (b) patterns of flow around airfoil at angle of attack of 14°. The arrows show the direction of the incoming supersonic flow, and the red half-circle shows the place of air heating. The color palette corresponds to the length of the velocity vector in m/s.

The instantaneous velocity fields obtained in the calculation are in qualitative agreement with the flow patterns observed in the experiment. After the initiation of the local energy input in the flow, a quasi-cylindrical shock wave is formed near the model surface. Behind the shock front, the gas acquires additional velocity and pressure, which makes it possible to exceed the pressure in the separation region and to shift the separation point downstream. Figure 1b shows an example of an instantaneous flow pattern at a time instant of 20 $\mu$s after pulsed heating of a flow with a specific energy of 10 J/m. The magnitude of the displacement of the position of the separation point depends on the energy deposited in the gas. Since the shock front moves both up- and downstream, a new separation is formed upstream of the gas heating initiation place, which, nevertheless, then attaches the surface (see figure 1b). As the shock wave decays in time on the upper surface of the airfoil, the separation region with reattachment disappears, and a new separation is formed, the position of which almost completely coincides with the initial position of the separation point (before the initiation of local gas heating). After some time of the order of several hundred microseconds, the flow pattern returns to the initial one obtained in the stationary case without energy release.

In [13] the method of processing the obtained flow patterns is described, which consists in the fact that after the completion of the calculation with the help of the appropriate utility it is possible to obtain the distribution of flow parameters (pressure, temperature, velocity vector components) in the vicinity of the model surface (in the first computational cell in contact with this surface). When analyzing the $x$-component of the velocity vector $u_x$ near the surface of the model (in the boundary layer), it is possible to distinguish regions with a positive value $u_x$ (region without separation) and with
a negative value \( u_x \) (region of return flow, region of separation). When analyzing the dependences \( u_x(x) \) near the upper surface of the model at different times, it is possible to obtain the time dependence of the position of the separation point after local heating of the gas and the position of the separation region with reattachment. Figure 2a shows the typical time dependence of \( x_{SPP}(t) \) of the separation point position for a heating energy of 20 J/m deposited into the gas. On the graph the initial coordinate of the position of the separation point \( x_{SPP0} \) (dashed red line), as well as the area of separation with reattachment (filled area) are shown. The red point indicates the location \( x_{disch} \) and the time (0 \( \mu s \)) of rapid gas heating. It can be seen that the place of heating is in the vicinity of the separation point.

Figure 2b shows typical pictures at different time moments after heat release. It should be clarified that although the profile is horizontal in the picture, its angle of attack is not zero. In the simulation, as mentioned earlier, it was not the wing profile that rotated, but the computational grid, while the vector of the incoming air flow also experienced a rotation. In addition, the figure shows the field of the \( x \)-component of the velocity \( u_x \) (in m/s), but the color palette is limited to values \((-200, 0) \) m/s so that the areas of the return flow are clearly visible: the red area is the area of flow that is co-directional with the main flow (i.e. without separation), the area of cold shade is the area with separation (reverse flow).

It can be seen that by the time moment 20 \( \mu s \) the main separated flow is displaced to the trailing edge, while upstream a separation with reattachment is formed. At about 30 \( \mu s \) after heating, the main separation region is shifted almost to the trailing edge of the model. In the time range from 60 \( \mu s \) to 100 \( \mu s \), the separation region is not observed on the upper surface of airfoil, and the separation region with reattachment is absent. Then, the main flow region begins to form again and at the time moment 120 \( \mu s \) is clearly visible in the flow pattern. At a time moment of 200 \( \mu s \), the flow pattern resembles the initial one (0 \( \mu s \)). The presented case can be characterized as a case with a relatively large value of the gas heating energy (20 J/m). As will be seen below, at relatively low energy values, the cases when the position of the main separation point is displaced not to the trailing edge, but is displaced by relatively small distance are possible. Cases are also possible when the separation region with reattachment exists at the moment in time when the main separated flow returns to its initial position.

To describe these processes quantitatively, it is convenient to mark the main quantities on the obtained \( t-x \) diagrams (as in figure 2a). The time after which the main separated flow returns to its initial position (a sharp downward movement on the \( x_{SPP}(t) \) plot) is called \( t_p \), which denotes the positive effect of the local heating on the flow pattern. The time during which the separation region with reattachment exists is called \( t_n \), i.e. the time during which the negative effect of rapid local gas heating exists. The values max(\( x_{SR} \)) and min(\( x_{SR} \)) are the maximum and minimum positions of the separation region with reattachment respectively. The difference between these values will give an
idea of the width of this area, and the values themselves will give an idea of how far upstream they extend. The maximum position of the separation point will be called $\text{max}(x_{\text{SPP}})$, and if this value coincides with the position of the trailing edge, then we will assume that the main separation has disappeared under the action of a gasdynamic disturbance created by the rapid local heating of the gas.

In the numerical simulation not only the heating energy was varied, but also the method of energy input into the flow. Table 1 summarizes the parameters of the fast local heating process, which was simulated in this work.

### Table 1. The cases of local heating considered in this work.

| Case # | 1   | 2   | 3   | 4   |
|--------|-----|-----|-----|-----|
| $\eta E/L, J/m$ |    | 0.1–20 |     |     |
| $\text{AoA}/x_{\text{SPP}0}$ |    | 14°/61.3 mm |     |     |
| $x_{\text{disch}}, \text{mm}$ | 60 | 50 | 70 | 60 |
| $T_{\text{disch}}$ | Isochoric process |     |     |     |
| $\rho_{\text{disch}}$ | Isochoric process |     |     |     |

It follows from the presented table that the simulation was carried out at one angle of attack of the wing model (14°), which corresponds to the coordinate of the initial position of the separation point $x_{\text{SPP}0}=61.3$ mm. The local heating energy was varied in the range 0.1–20 J/m, with the discharge initiation site located immediately before the separation point (cases 1 and 4), upstream (case 2), and inside the main separation (3). As noted above, the nonstationary simulation was carried out by superimposing the fields of increased values of pressure $p_{\text{disch}}$ and temperature $T_{\text{disch}}$ at the place of energy input, and these values were calculated by the isochoric process (at a constant density). For case 4, a different method is used, when the pressure $p_{\text{disch}}$ is calculated in the same way as in cases 1–3, and $T_{\text{disch}}$ does not change and remains equal to the local static gas temperature. This phenomenon can be represented as the rapid placement of additional gas particles in the volume of energy input, so that the pressure increases not due to an increase in temperature, but due to a local increase in the gas density.

### 3. Obtained results and discussion

Figure 3 shows the dependences of the maximum displacement of the position of the separation point $\text{max}(x_{\text{SPP}})$ on the gas heating energy in various cases of discharge initiation. The numbering of the columns of the histogram in the figure corresponds to the numbering of the cases in Table 1. It can be seen that at heating energy of 5 J/m, it is possible to shift the position of the separation point almost to the trailing edge. But it should be kept in mind that the time of finding the position of the separation point at this edge is short. If we compare the first and second cases, then when initiating the energy input upstream, all other things being equal, it turns out to be less effective than when initiating in vicinity (case 1). On the other hand, the initiation of the energy input inside the separation region turns out to be more efficient from the point of view of the downstream shift of the separation point. This is due to the fact that the closer the place of heating initiation is to the trailing edge, the further along the flow the intensity of the cylindrical shock wave caused by heating decays. Case 4, characterized by a low temperature of the region of local pressure growth, is the most effective and shows the maximum displacement of the separation point. Apparently, this circumstance is associated with the fact that the static temperature of the gas decreases with the expansion of the region of increased pressure, thereby causing a decrease in viscosity [15], which leads to the stability of the flow against flow separation.

Figure 4 shows the dependences of the time of the displacement of the separation point downstream $t_p$, as well as the time of existence of the separation region with reattachment $t_n$. It can be seen that, in the first case of discharge initiation, the time of the displacement of the separation point downstream increases monotonically with increasing heating energy. However, it should be kept in mind that this growth is much slower than linear growth. Apparently, this is one of the circumstances indicating that there is an optimal value of the local heating energy, which corresponds to the time $t_p$ of
the separation point displacement, so that the time-average power applied in the local heating of the flow turns out to be minimal.

Figure 3. Dependence of the maximum displacement of the separation point on the gas heating energy for different heating methods. The numbering of the columns of the histogram corresponds to the numbering in table 1.

Figure 5 shows the dependences of the minimum \( \min(x_{SR}) \) and maximum \( \max(x_{SR}) \) of the positions of the boundaries of the separation region with reattachment. First of all, it should be noted that the dependence of the maximum position of the right (relative to main flow moving from left to right, as on figure 2b) boundary \( \max(x_{SR}) \) weakly depends on the heating energy. This value is maximum in the third case for an obvious reason, since the place of heating lies downstream than in other cases. For the same reason, in the second case, this boundary lies upstream in comparison with other cases, all other things being equal. If we compare cases 1 and 4, where the heating places coincide, then the difference is relatively small.

Figure 4. Dependences of the time of displacement of the separation point downstream \( t_p \) and the time of existence of the separation region with reattachment \( t_n \).

As for the other boundary of the separation region with reattachment, in this case one can reason the same way. In the second case, this region extends much higher upstream than in other cases, and
this is also related to the place of gas heating. If we compare cases 1 and 4, then the upstream displacement of this separation region turns out to be almost the same. In the third case, the intensity of the shock wave decays faster, because it begins to spread significantly downstream than in other cases.

Figure 5. Dependences of the minimum $\min(x_{SR})$ and maximum $\max(x_{SR})$ of the positions of the boundaries of the separation region with reattachment.

In general, the presented dependences in the form of histograms make it possible to talk about the heating parameters, which gives grounds for choosing the frequency and heating energy in the process of repetitively pulsed action on the separation region (the process considered earlier in [13]). On the one hand, it turns out that an increase in the energy of a single heating leads to an increase in the displacement of the separation point up to the trailing edge of the model. On the other hand, the dependence between this shift and energy is much slower than linear. The time after which the formation of a new separated flow begins also slightly increases with increasing energy. From the point of view of energy efficiency of action (i.e. achieving the required effect with the minimum required power), there is the most effective pair of values for heating energy and heating period. For case 1, this power turns out to be the smallest at the minimum heating energy $\eta E/L=0.1$ J/m; however, it should be taken into account that for this energy value $t_H>t_p$, that is, the separation region with reattachment does not have time to disappear. In other words, the cylindrical shock wave, which creates a positive pressure gradient in the boundary layer upstream, does not have time to decay. If we talk about the optimal place for the initiation of heating, then, most likely, this place corresponds to case number 1, when the place of heating lies directly in front of the region of separation. In this case, the region of the main separation meets a gasdynamic perturbation with the maximum gas pressure and velocity. When heating is initiated inside the main separation region (case 3), it seems to be more effective because of the proximity to the trailing edge. However, numerical modeling shows that in this case the main separation region is divided by the gasdynamic perturbation into two regions, one of which is the separation region with reattachment. The lifetime of this region is much longer than in other cases, which is a negative phenomenon.

4. Conclusions
The paper presents a numerical simulation of the process of a supersonic airflow around an airfoil at a positive angle of attack of 14° in the presence of a separation region and with rapid local heating of the gas, which represents long spark discharge across the flow. In the study the energy and place of gas
heating were varied near the upper surface of the model, where a separated flow exists. On the one hand, one should point out the existence of an optimal heating energy value. The search for this value is associated with the maximum displacement of the separation point, the maximum duration of this displacement, the minimum lifetime of the induced separation with reattachment, and, finally, the minimum value of the time-average power. The data obtained in this work will be useful for the continuation of studies using numerical modeling, in which it will be necessary to choose a strategy for initiating local gas heating in a pulse-periodic mode. In numerical simulation it is possible to change the position and value of the energy of local heating of the gas from pulse to pulse. In this case it is necessary to maximize the value of the displacement of the separation point downstream and to minimize the time-average value of the input power.

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