Evolution of artificial disturbances in a shear layer at M=1.43

O I Vishnyakov*, P A Polivanov and A A Sidorenko
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS
630090, 4/1 Institutskaya Street, Novosibirsk, RUSSIA

*E-mail: vis_ol@itam.nsc.ru

Abstract. The evolution of artificial disturbances in a laminar boundary layer on a flat plate model in the presence of an incident shock wave is considered. The flow is supersonic with the freestream Mach number M = 1.43. The study is carried out by hot-wire anemometry. A dielectric barrier discharge is used to generate disturbances. Data on the distribution in space of the average and non-stationary components of the mass flow are obtained. Disturbances created by the discharge and their evolution along the separation zone are recorded.

1. Introduction
At present the possibility of wider use of the natural laminar boundary layer on the surface of a future's aircraft to improve their efficiency is being considered. At the same time, a transonic flight is usually accompanied by the appearance of shock waves which can lead to separation of the boundary layer. In the case of a laminar boundary layer, interaction with a shock wave can generate significant flow instability, which provokes a shift in the position of the laminar-turbulent transition [1]. In this regard, the study of the development of disturbances in the zone of the laminar separation bubble and their influence on the separation zone, as well as the position of the laminar-turbulent transition, is important for the correct calculation of such flows. It is most convenient to investigate disturbances introduced at a selected frequency [2, 3] and an electric discharge can be used as a source of such disturbances [4]. Only high-pressure-resistant types of discharges such as spark discharge and dielectric barrier discharge (DBD) can be used in transonic flows. In addition to stable operation at high pressures, the advantages of the dielectric barrier discharge include a stable and controlled breakdown frequency, the possibility of creating a plasma region with a sufficiently high degree of uniformity. This allows for a quite uniform energy contribution along the span of the model, thereby simulating the conditions of the two-dimensional problem. Dielectric barrier discharge affects the flow by several methods: by weak shock waves caused by the formation of streamers - high temperature and high conductivity channels, by ionic wind existed as a result of field strength effect on charged particles in the discharge gap, and also temperature effect. However, according to, for example, [5], the ionic wind has low energy and its effect on the supersonic flow is being negligible, and the temperature effect is major. According to these considerations, the effect of the dielectric barrier discharge as a heat source on the laminar separated flow is modeled in [6]. The problem is investigated numerically in a two-dimensional setup and using the linear theory of stability. It is demonstrated that the dielectric barrier discharge may operate as the source of two-dimensional perturbations.

In the paper, an attempt is made to introduce disturbances using the dielectric barrier discharge into the laminar boundary layer in a wind tunnel experiment, followed by fixing these perturbations and their evolution along the separation zone by hot-wire anemometry technique.
2. Experiment setup

The experiments were carried out in the T325 wind tunnel of the ITAM SB RAS. The flow parameters were as follows: Mach number $M = 1.43$, stagnation pressure $P_0 = 70$ kPa, stagnation temperature $T_0 = 290$ K, and the unit Reynolds number $Re_1 = 10.6 \cdot 10^6$ 1/m. The schematic of the experiment is shown in figure 1. A model of a flat rectangular plate with a sharp nose was used; it was mounted on pylons at zero angle of attack. A laminar boundary layer developed from the leading edge. Above the plate was placed a shock wave generator - a wedge-shaped body with the ability to adjust the angle of attack. In this series of experiments, the angle of attack was $\beta = 4^\circ$. The shockwave from the wedge was crossing the plate at approximately $X=132$ mm. The result was a separation zone spreading upstream from the shock wave forming compression waves. In the shear layer above the separation region, near the incident shock wave, a laminar-turbulent transition process occurred. The incident shock wave was followed by a decompression wave and the flow attachment. Downstream, a reflected shockwave was generated and a turbulence wake was observed.

![Figure 1. Scheme of the experiment](image)

The measurements were carried out using a hot-wire anemometer sensor. The wire diameter was 10 $\mu$m and the length was 2 mm. The sensor was connected to a constant resistance hot-wire anemometer. To enable scanning measurements, the sensor was placed on a special coordinate device with a small mid-section was approximately 4% of the test section square at the narrowest point. In turn, the coordinate device was mounted on the rod of the standard coordinate mechanism of the T325 wind tunnel, located downstream of the test section, this allowed measuring different longitudinal sections. The measurements were carried out at overheating ratio $a_w=1.75$. To obtain quantitative data, the hot-wire anemometer was calibrated. During the calibration process the mass flow rate was varied by adjusting the stagnation pressure. At the same time, the stagnation temperature and the Mach number did not change, and the sensor was located in a free flow.

The dielectric barrier discharge used to introduce disturbances was located at 75 mm from the leading edge of the plate and had the following configuration: the length along the span of the model was 100 mm (0.5 span), the length along the flow was about 10-13 mm, and the height of the plasma region was about 0.3-0.5 mm, i.e., of the order of the boundary layer thickness. The electrical circuit of the discharge power supply was similar to that used in the study [5]. To excite the discharge, an alternating voltage with a frequency of 37.5 kHz was applied to electrodes in the burst mode, the burst repetition rate was 1 kHz, and the signal duty cycle was 0.5. The voltages on the electrodes were 4 kV. Figure 2 shows the example of oscillograms of driving signal (in Volts) and signal of current in dielectric barrier discharge power supply circuit. It can be seen from the oscillograms that after the control rectangle is applied to the high-voltage source of alternating voltage, the mode is reached during several periods. And after passage the last one in the driving pulse packet, a gradual decay of the current in the dielectric barrier discharge power circuit is observed.
3. Discussion of the results

To illustrate the flow under study, figure 3 shows the mass flow profiles in several longitudinal sections. Section X = 117 mm also shows the profile obtained in the case without energy deposition by dielectric barrier discharge (marked as no DBD). Comparison of the profiles, measured with dielectric barrier discharge turned on and off, shows that the power supply does not affect the average flow, as expected. The first measured cross section X = 110 mm was located at some distance from the plasma region to avoid damage to the sensor. This section was located at the beginning of the laminar separation region. The mass flow profiles show an increase in the thickness of the separation bubble up to a coordinate of 130 mm, which is located immediately in front of the place where the shock wave falls.

In order to select the disturbances introduced by the discharge, the pulsations of the mass flow rate were averaged using the burst period (T = 1 s), the averaging window, and also using the driving rectangle signal to determine the beginning and end of the averaging window. As a result of this averaging, only the disturbances associated in phase with disturbances introduced by the discharge remain. The data processed in this way are presented in the form of two-dimensional fields of mass flow pulsations versus time and vertical coordinates in figure 4. The time axis in figure 4 is in-phase with the driving signal to ensure in-phase averaging.
with the axis in figure 2. It can be seen that during the period under consideration, both the phase of the growth of pulsations (positive phase) and the phase of their decrease (negative phase) are observed. For all investigated sections in the range from \( X = 110 \text{ mm} \) to \( X = 122 \text{ mm} \), there are two peaks of pulsations along the vertical coordinate, both for the positive phase and for the negative phase. Comparison of the distribution fields of mass flow pulsations in Figure 4 and mass flow profiles in Figure 3 shows that for these three longitudinal sections the positions of the zones of maximum pulsations along the vertical coordinate correspond to the lower and upper boundaries of the shear layer. The lower boundary is between the shear layer and the separation zone, and the upper boundary is between the shear layer and free stream.

![Distribution fields of mass flow oscillations](image)

**Figure 4.** Fields of mass flow oscillations distribution in \( Y \) direction during the burst period
Downstream in the sections $X = 125$ mm and $X = 130$ mm, two zones with the highest amplitude pulsations, previously spaced apart along the vertical coordinate, merge into one, more evenly distributed over the entire height of the shear layer. This observation is correct for both positive and negative phases. The general regularity in the evolution of disturbances for all cross sections is the shift of the pulsation maxima in phase and vertical coordinate, as well as a change in the amplitude.

The maximum amplitude of pulsations is reached in section $X = 122$ mm; further downstream, it decreases. Nevertheless, due to a change in the size of the pulsation zone, the integral value still increases.

The high-frequency noise that can be observed in Figure 4 is associated with the operation of the discharge at a frequency of 37.5 kHz.

**Conclusions**

Hot-wire measurements have been carried out in the separation zone on a flat plate model in the presence of artificial disturbances introduced by DBD. The average and pulsation values of the mass flow rate across the shear layer in several longitudinal sections have been obtained. The perturbations introduced by the discharge are shown to develop in the shear layer, changing the amplitude and spatial distribution. The maximum pulsations are observed in the places of the maximum gradient of the profile of the average mass flow rate. In distant sections, the distribution of pulsations becomes more uniform, which is most likely associated with the onset of flow turbulization.

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