Natural laminar-turbulent transition delay by dielectric barrier discharge

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Abstract. The use dielectric barrier discharge for the delay of laminar turbulent transition excited by natural flow disturbances in a quiet wind-tunnel was investigated experimentally. Optimal electrodes location and the operational regime of high-voltage impulse generator provided maximal downstream shift of transition location were found. It was demonstrated that the 10% increase of the laminar part of boundary layer can be obtained using barrier discharge with the cross-flow electrodes. This gives up to 20% friction drag reduction.

1. Introduction

Flow control by means of dielectric barrier discharge (DBD) actuators is studied extensively last years. Physics of this type of electric discharge and gas flow induced by it was investigated in (Enloe et al. 2004). Its action on the gas flow can be modeled by combination of steady body force and heat release (Kotsonis et al. 2010), (Duchmann et al. 2010). Usually DBD actuators were used for airfoil lift enhancement by means of stall prevention (Vorobiev et al. 2010 ). However, such lift control is suitable for low speed only because of weak flow velocity (<10m/sec) induced by DBD. DBD application to boundary layer laminarization seems to be more attractive because of minimal change of velocity profile can improve boundary layer stability. Computations by (Duchmann et al. 2010) showed that 2-3% increase of near-wall flow velocity leads to two-fold increase of laminar flow region. High efficiency of cross-flow dominated transition control by DBD for transonic speed was demonstrated in theoretical work of (Kuriachii & Manuilovich 2009). Experiments of (Duchmann et al. 2010) and (Grundmann & Tropea 2008) demonstrated reduction of growth rates of artificially introduced growth rates and transition delay using DBD. Grundmann & Tropea 2008 also demonstrated TS wave cancellation by means of generation of artificial disturbances of opposite phase by DBD modulated by low-frequency signal. Discharge-induced streamwise vortices were used in (Hanson et al. 2010) for by-pass transition control.

All previously mentioned experiments deal with transition caused by artificially introduced disturbances of relatively large amplitude. However, possibility of natural transition delay by DBD is not clear for discharge may become the main source of unstable disturbances in this case. The present work deals with experimental study of natural transition delay by DBD in low-turbulence wind tunnel. Drag reduction due to transition delay is studied also.
2. Experimental setup & conditions

Experiment was performed in the low-turbulence direct flow wind tunnel T36I of TsAGI. Its test section is 2.6 m long, 0.5 m wide and 0.35 m high, and is preceded by a 12:1 contraction. The free-stream turbulence level in the test section is 0.06% measured in the band 5-1500Hz for flow velocity 8-20 m/s. Measurements were made in the boundary layer on the floor of test section for flow velocity 8-15 m/s. Plasma actuator with three normal to flow direction electrodes was placed in the hatch located at the distance of 1100 mm from the beginning of the test section. Dielectric barrier discharge on any pair of electrodes may be turned on or off. It was powered by high-voltage-impulses generator which initiates rectangular impulses of duration $\tau = 20\mu s$. Four regimes of generator operation were used in experiment. Amplitude of impulses $V$ and its frequency $f$ for these regimes are listed in table 1. Outline of experimental facility and design of plasma actuator are shown in figure 1.

Table 1. Parameters of generator operation regimes

| regime | $f$, kHz | $V$, kV |
|--------|----------|---------|
| 1      | 6.25     | 4.4     |
| 2      | 3.57     | 4.4     |
| 3      | 12.5     | 4.4     |
| 4      | 12.5     | 3.3     |

Figure 1. Experimental set-up (a), and plasma actuator design (b).

Averaged value and pulsations of streamwise velocity in the boundary layer were measured by constant temperature hot-wire anemometer using single-wire probe made from 5 $\mu m$ diameter wire of 0.5mm length. To verify the proper operation of hot-wire anemometer in the neighborhood of the discharge part of velocity profiles measurements were repeated using the micro Pitot tube of 0.4 mm diameter. The accuracy of mean velocity measurements by hot-wire anemometer was 1%, whereas error of velocity measurements by Pitot tube varied from 0.5 to 1% in velocity range 8-15 m/s. All measurements were made in the vertical plane in the middle of the test section. Hot-wire probe or Pitot tube were traversed in streamwise and vertical directions by coordinate mechanism with steps 1 mm and 0.1 mm respectively. Coordinate system with origin on the trailing edge of the third electrode and $x$, $y$ axes directed along the flow and vertically will be used for description of the results.
3. Boundary layer and laminar-turbulent transition without discharge

At first the state of boundary layer on the floor of test section without discharge was investigated. Main boundary layer characteristics as functions of streamwise coordinate are shown in Figure 2. Outer flow velocity distribution measured in the mid-high of the test section \((y=175 \text{ mm})\) reveals slight adverse pressure gradient with velocity drops approximately to 1% over 1 meter. Relative velocity distributions measured for different flow velocity well coincide, so pressure distribution in the test section is not sensitive to laminar-turbulent transition location. R.m.s. velocity pulsations measured for different flow velocity reveals that transition moves upstream with increase of speed. This fact indirectly justifies that transition to turbulence on the floor of the test section is really natural. Most of subsequent results were obtained for flow velocity 10 m/s and this value of velocity will be assumed on default if another is not declared. For this value of flow velocity transition found from the maximum of pulsations is located at \(x=400 \text{ mm}\).

\[ u = 0.4u_\infty \]

In the laminar part the boundary layer is well described by the Blasius solution with virtual leading edge location \(x=-1490 \text{ mm}\). Its shape factor here is close to theoretical value for Blasius velocity profile \(H=2.59\). Near the transition point it drops to characteristic value \(H=1.3\) for turbulent boundary layer. Transition Reynolds number estimated from displacement thickness is \(R_\delta \approx 2000\) and corresponds to Reynolds number \(R_e = 1.3 \times 10^6\) based on the length of equivalent plate. This value is rather small compared with classical results of (Shubauer&Skramstad 1948). Such earlier transition on the floor of test section could not be caused by weak adverse pressure gradient and is probably initiated by disturbances coming from transitional boundary layer on the side walls of the test section.

\[ u = 10m / s \]
Profiles of mean velocity and pulsations in boundary layer are presented in figure 3. Velocity profiles measured before the transition fall on Blasius profile. Maxima of pulsations here are located at distance $0.7 \delta^*$ from the wall which is familiar for maximal pulsations in Tollmien-Schlichting wave. Last velocity profile measured at $x=800$ mm is fully turbulent. Velocity pulsations spectra (shown in Figure 9) show that subharmonic regime of transition take place on the floor of test section.

4. Effect of DBD on laminar-turbulent transition

Influence of regime of generator operation on the transition location was investigated initially. Results obtained in form of amplification curves of velocity pulsations for different discharge regimes are presented in Figure 4. It shows that transition is rather sensitive to the discharge parameters. Maximal downstream shift of transition ~150mm was obtained for regime #1. Regime #2 with two-fold lower frequency delays transition also, but the shift of transition point is two times smaller. High-frequency regimes of discharge #3 and #4 move transition upstream. These high-power regimes of discharge (the power of discharge is roughly proportional to a product of relative time of high voltage action and its amplitude) excite too large pulsations in the boundary layer near the electrode. Mechanism of these disturbances origination is not clear and they may be probably caused by inflexible instability of boundary layer velocity profile with a strong near-wall jet.

Figure 4. Influence of regime of discharge on laminar-turbulent transition for $u_{inj} = 10 m/s$

Figure 5. Flow produced by discharge in regimes #1 and 2 in a still air

Figure 5 shows flow induced by regimes #1 and #2 of discharge in a still air. Near the electrode the discharge produces a thin near-wall jet which becomes weaker and spreads as distance from electrode increases. Relatively high pulsations (of amplitude 9% and 5% from maximal velocity for regimes #1 and #2 respectively) are present in discharge-induced jet. Pulsations in the strong jet from regime #1 of discharge have two maxima in the regions of large velocity gradients at the sides of jet. Such behavior of pulsations testifies that they are initiated by the instability of the jet velocity profile. Large amplitude of pulsations in flow induced by regime #1 of discharge permit us to conclude that this flow is a pre-transitional. Jets induced by rather more powerful high-frequency regimes of discharge #3 and #4 should be entirely turbulent. This may be a reason for its negative influence on laminar-turbulent transition in boundary layer. In the weaker jet induced by regime #2 of discharge profile of pulsations is roughly the same as mean velocity profile. Such pulsations probably can be treated as quasi-steady variations of jet amplitude caused by variation of discharge induced force in time. Such relatively low-frequency variations of discharge luminescence are well seen by the non-aid eye.

Measured discharge-induced velocity profiles permit us to estimate the integral body force induced by discharge. It can be found from the momentum flux in the jet as
\[ F = \int_0^\infty \rho u_i^2 \, dy \approx \rho u_m^2 \, d \]  

where \( u_i \) is discharge-induced velocity, \( u_m \) is its maximal value and \( d \) is the characteristic thickness of the jet. Such estimate gives integral values of body forces \( F = 1.5 \times 10^{-3} \, n/m \) and \( 7 \times 10^{-5} \, n/m \) for regimes #1 and #2 respectively. Comparable value of body force was obtained in (Enloe&Tropea 2004) by direct measurement of thrust force of discharge. Force induced by regime #1 is approximately two times greater than this for regime #2. It means that the force action of discharge is roughly proportional to relation of impulse duration to the time between the impulses.

Figure 6. Influence of discharge (regime #1) location on laminar-turbulent transition for different flow velocity

The next topic of investigation was finding of optimal discharge location which gives maximal delay of transition. This was made by means of measurements of pulsations distribution along the boundary layer for discharge in regime #1 on different electrodes. Such results obtained for flow velocities 8, 10, 12 and 15 m/s are shown in Figure 6. Its analysis results in conclusion that optimal location of discharge is the place where natural pulsations amplitude is near to 1%. This can be illustrated by two ways. The first one is consideration of amplification curves for flow velocity 10 m/s. In these conditions the best results gives the discharge on electrode #2. Discharge on electrode #1 which is too far from transition point gives only minimum transition delay. Action of discharge on the electrode #3 located closer to transition point is also some weaker then effect of discharge on electrode #2. Another way to change the position of discharge with respect to transition point is to vary flow velocity for discharge on fixed electrode. Let’s consider the action on transition discharge on electrode #1 for different flow velocity. For small velocity 8 m/s, discharge on this electrode moves transition upstream. Increase of flow velocity moves transition point to discharge location and its action on transition becomes neutral for \( u_c = 10 \, m/s \). Further increase of velocity to 12 m/s results in transition delay by discharge on electrode 1. Its effect becomes the best (compared with action of discharge on other electrodes) for maximal flow velocity 15 m/s.

Existence of optimal discharge location may be explained as follows. When discharge is too far from transition point, discharge induced pulsations well exceed natural disturbances. So, negative effect of increase of pulsation level exceeds stabilizing effect of change of velocity.
profile. If the discharge is too close to transition, discharge-induced change of velocity profile can not prevent fast non-linear growth of disturbances. In optimal location discharge only slightly change the amplitude of pulsations but change of velocity profile is enough to reduce the growth rates of linearly developing perturbations.

Figure 7. Influence of discharge on profiles of mean velocity and its pulsations in the boundary layer for $u_{w} = 10 \text{ m/s}$

Figure 8. Difference of velocity profiles induced by discharge for $u_{w} = 10 \text{ m/s}$

Influence of discharge on electrode #2 on laminar-turbulent transition was studied in more details for near-optimal for this discharge location flow velocity 10m/s. Figure 7 shows its effect on profiles of mean velocity and pulsations in the boundary layer. Acceleration of velocity in the near-wall region by discharge is well seen in two nearest to discharge sections $x=-27$ and 170 mm. Profiles of discharge-induced difference of velocity in boundary layer are additionally plotted in figure 8. Maximal flow acceleration by discharge is approximately equal in both sections and is estimated as 5% from outer flow velocity. Theoretically it should be enough for two-fold transition delay in accordance of results of Duchmann et al. 2010. Further downstream location of maximal velocity difference moves from wall and stabilizing action of discharge become weaker.

Assuming that discharge has no influence on the velocity profile upstream the electrode, the volume force induced by it can be found from the change of the momentum flux in the boundary layer as

$$F = \int_{y_{0}}^{y} \rho (u_{d}^2 - u_{0}^2) dy \approx 2 \rho u_{0} \Delta u_{m} d$$

Here $u_{d}, u_{0}$ - are velocities measured in the boundary layer with discharge and without it, $\Delta u_{m}$ - maximal difference between them, $d$- characteristic thickness of discharge induced velocity difference profile. Integral body force values found from profiles measured at $x=-27$ mm and $x=170$ mm are $F = 2.1 \times 10^{-3} \text{n/m}$ and $7.2 \times 10^{-3} \text{n/m}$ respectively. Within the experimental error, integral body forces found in still air and in from change of velocity profile in the nearest section $x=-27$ mm well coincide. This finding verifies the hypothesis about independence of discharge induced force from flow velocity. However, this force found from profiles in more far from discharge section $x=170$ mm is approximately 4 times grater. This surprising result may be explained by the influence of high-amplitude pulsations on the velocity profile without discharge in this section. This profile can not be treated as entirely laminar one. This is clearly seen from the friction drag dependence from $x$ shown in figure 10 (see section 5).
Figure 7 also illustrated the influence of discharge on development of pulsations in the boundary layer. Near the electrode discharge drastically increases the pulsations amplitude, however discharge-induced pulsations are concentrated near the wall well below the maximum of natural disturbances. Further downstream, stabilization of the velocity profile by discharge leads to substantial reduction of pulsations. It leads to change of flow regime from turbulent to laminar in section $x=550$ mm.

![Figure 7](image1)

**Figure 9.** Influence of discharge on velocity pulsations spectra (a), and amplification rates of disturbances of fundamental and subharmonical frequency (b)

Influence of discharge on pulsations spectra shows figure 9. In the vicinity of electrode ($x=-30$ mm) discharge increases the pulsations of fundamental frequency. Its influence on subharmonic in this section is minimal. Further downstream discharge effectively reduces the amplitude of both main TS wave and subharmonic. Growth of fundamental frequency peak in the spectrum is fully suppressed on the interval from 120 to 210mm. However, discharge action on subharmonic is not so pronounced.

5. Friction drag reduction by DBD

Influence of discharge on the friction drag was evaluated using momentum method. Consideration of equation for integral momentum in incompressible boundary layer with zero pressure gradient gives the following equation for the friction stress on the wall $\tau_w$ (Schlichtig 1974)

$$\frac{d\delta^{**}}{dx} = \frac{\tau_w}{\rho u^2}$$

(3)

Using this equation, friction drag coefficient $c_f$ of the part of the wall between two sections $x_1$ and $x_2$ can be related with the difference of momentum loss thicknesses in these sections

$$c_f = \frac{2F_s}{\rho u_0^2 \Delta S} = 2 \frac{(\delta^{**}_2 - \delta^{**}_1)}{x_2 - x_1}$$

(4)
This drag coefficient of relatively short portion of the wall will be referred as local drag coefficient. Relative change of local drag coefficient due to discharge can be determined as

\[
\frac{\Delta c_f}{c_f} = \frac{c_{fd} - c_{f0}}{c_{f0}} = \frac{\delta_d^{**}(x_2) - \delta_0^{**}(x_2)}{\delta_0^{**}(x_2) - \delta_0^{**}(x_1)}
\] (5)

Here parameters measured with discharge and without it are denoted by subscripts “d” and “0”. Deriving (5) we assumed that initial section \(x_1\) is located before the electrode and discharge do not change velocity profile in it. Relative change of local drag by discharge in electrode #2 for fixed \(x_1 = -72\)mm as function of final section \(x_2\) is plotted in figure 10. It reaches maximum value of 60% for the final section coinciding with transition location in the boundary layer with discharge.

**Figure 10.** (a) - Relative local (equation (4)) and integral (equation (5)) drag reduction by DBD, (b) – influence of discharge on integral drag coefficient. Dashed lines – theory (8)

Total drag of the part of the equivalent plate \(C_{F2}\) before the section \(x_2\) can be found from (4) with \(x_1 = x_{\text{eff}} = -1360\)mm

\[
C_{F2} = 2 \frac{\delta_d^{**}(x_2)}{x_2 - x_{\text{eff}}}
\] (6)

Total friction drag coefficients found with discharge and without it as functions of \(x_2\) are plotted in figure 10, b. In pure laminar part of the boundary layer they well coincide with theoretical formular for Blasius flow

\[
C_{F2} = 1.328 \left( \frac{u_*L}{V} \right)^{1/2}; \quad L = x_2 - x_{\text{eff}}
\] (7)

Rapid growth of total drag coefficient begins after transition point \(x_*\). Without this point is located at \(x_* \approx 350\)mm and discharge moves it to \(x_* \approx 550\)mm. It should be mentioned that transition point found as the place of deviation of \(C_{F2}(x_2)\) curve from theoretical value (7) do not correspond to the location of maximum pulsations. Full drag coefficient of the plate with transitional boundary layer is related with transition location by the empiric relationship (Schlichting 1974)

\[
C_{F2} = C_{FT}(L) - \frac{L_*}{L} (C_{FT}(L_* - C_{F1}(L_*))
\] (8)
where $C_{\varphi L} = 0.074 \text{Re}^{-0.2}$ is a drag coefficient for the plate with turbulent boundary layer, $L = x_e - x_{\text{eff}}$. Relative values of total drag reduction found from momentum loss thickness measurements (6) and computed using (8) are plotted in figure 10, as functions of $x_2$. Maximal total drag reduction reaches 20% for length of plate equal to transition point in boundary layer with discharge. Theoretical curve (8) well approximates experimental results. It means that drag reduction due to discharge is entirely caused by laminar-turbulent transition delay.

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6. References

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