The shape of DBD plasma jet striking into the static and quickly moving dielectric and metallic substrate

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Abstract. In the case of motionless ambient air, the quickly moving surface involves in the movement the gas adjoining to a surface. This gas-dynamic wall effect can influence both the shape of plasma jet interacting with the moving substrate and the efficiency of plasma modification of the surface to be treated. The issue mentioned above has been studied by an example of the DBD plasma jet striking into the static and fast moving dielectric and metallic substrate. The discs of acrylic plastic and aluminum were used as the static and quickly rotating substrates. The experiments were performed with He and Ar plasma jets generated by sinusoidal DBD operating at atmospheric pressure. It is proved that the change of the shape of plasma jet at the place of its striking into a moving dielectric and metal substrate happens due to the dragging of air by the fast moving surface.

1. Introduction
Non-thermal plasma jets at atmospheric pressure generated by dielectric barrier discharge (DBD) in He and Ar flow are the popular objects to investigation in many publications [1,2]. Such plasma jets are widely used for different applications, in particular, for plasma modification of thermally non-resistant materials. The plasma-chemical modification happens due to interaction of reactive plasma species with the surface. These species are generated in the discharge zone of DBD and transferred to the surface by plasma jet of a small diameter. The reactive plasma species are neutral and charged particles. At atmospheric pressure, the neutral particles are "frozen" into the gas stream forming the plasma jet. The charged particles are ruled predominantly by the electric field in the plasma. The total efficiency of plasma modification is determined by many factors among the most important of them one can note the efficiency in generation of primary reactive species in the discharge zone, their decay and partial transformation into secondary reactive species in the course of transport of reactive species by thin plasma jet to the surface and finally the spreading of primary and secondary reactive species over large area on the surface to be treated. The latter process depends mainly on gas-dynamic and electrodynamic phenomena related to interaction of gas stream with a solid surface and propagation of plasma on the substrate. The pointed above phenomena depend not only on the velocity of jet striking the substrate but on the stray capacitance of the substrate and its state (mobile or motionless) as well. The issues mentioned above have been studied by an example of the DBD plasma jet striking into the static and fast moving dielectric and metallic substrate. The discs of acrylic plastic and aluminum were used as the static and quickly rotating substrates. Additionally, polyethylene film, quartz and ceramic plates were used as the static substrates. The experiments were performed with He and Ar plasma jets generated by sinusoidal DBD operating at atmospheric pressure.
2. Experimental setup
In order to generate a long non-thermal plasma jet at atmospheric pressure we used a sinusoidal DBD in thin quartz tube blown with He and Ar flow. Sketch of the experimental setup is shown in figures 1a and 1c. Inner and outer diameters of the discharge tube were 2.5 and 4.5 mm. Frequency of the powering voltage was fixed and equal to 100 kHz; the amplitude was varied up to 4 kV. In some experiments the inner electrode (thin wire) was grounded and the powering voltage was applied to the outer electrode. Gas flow velocity at the DBD exit is equal to 25-30 m/s. Plasma jet enters the ambient air and strikes the substrate. Dielectric substrates were quartz, acrylic plastic, ceramic and polyethylene. The substrates to be treated were placed on the static or rotating aluminum of 160 mm in diameter, which can be grounded, if it was necessary. A distance from the DBD exit to the disc was 20 mm and 7-10 mm for the case of He and Ar as the plasma forming gases. In the case of rotating disk, plasma jet was directed to the point located of 70 mm away from its center. The disc rotation frequency was varied up to 170 turns per second. Maximum frequency corresponds to the linear velocity of 75 m/s of the disc at the point of the plasma jet striking. Fast rotation of the disc leads to dragging of a thin layer of ambient air adjoining the surface of the disc. Maximum averaged velocity of air measured by Pitot tube located at 0.5 mm from the surface of rotating disc is equal to 25 m/s.

![Sketch of the experimental setup](image)

**Figure 1.** Sketch of the experimental setup used for generation of a plasma jet by DBD in He and Ar flow and investigation of its colliding with the static (a) and quickly moving (c) dielectric and metallic substrate. The sketch illustrating the difference in radial distribution of plasma, reactive species and neutral gas over surface for the case of plasma jet normal striking the static dielectric substrate (b).

Figure 1b illustrates schematically the difference in the radial distribution of plasma, reactive species and neutral gas on the surface for the case of plasma jet normal striking the static dielectric substrate. This figure shows that the reactive species can be transported by a gas stream to a longer distance compared to the plasma. A reason of that is caused by relatively long time of their life.

3. Experimental results and discussions

3.1. Interaction of plasma jet with the motionless dielectric substrates
Figure 2 demonstrates influence of the electric parameters of DBD on brightness of plasma jet and its spreading on the motionless dielectric substrates. It was found out that the grounding of the inner electrode diminishes appreciably both the length and brightness of plasma jet independently on sort of plasma forming gas. Note that helium as plasma forming gas increases the length of free plasma jet compared to argon in both regimes when the inner or outer electrode is grounded. The dependence of visual diameter of plasma spot on the treated substrate vs the applied voltage is shown in figure 2c.
a) P=6.3 W, the inner electrode is grounded, the jet brightness is low, the exposure time τ=0.1 s. 
b) P=5 W, the outer electrode is grounded, the jet brightness is high, the exposure time τ=1 ms. 
c) The dependence of visual diameter of plasma jet on quartz vs applied voltage. He, V=28 m/s, h=20 mm, the outer electrode is grounded, the jet brightness is high, the exposure time τ=5 ms. Two photos in plot (c) show a large difference between visual diameter of plasma spot on the quartz (top image) and the diameter of the area treated by plasma jet (the circle with the strongly spread water droplets).

Figure 2. The images of plasma jet striking the polyethylene film (a, b). Ar, V=25 m/s, U=4 kV, h=7.5 mm.

Figure 3. The radial distribution of the contact angle of small water droplets deposited on polyethylene film treated by Ar plasma jet. The images of plasma jet striking the substrate are inserted with the same scale into some plots. The substrate is placed at a distance of 7.5 mm (a)-(c) and 15 mm (d)-(f) from the DBD exit. The inner electrode is grounded (a), (d); the outer electrode is grounded (b, c, e, f). The electric power of DBD: P=6.3 W (a,d); P=4 W (b,e); P=8.5 W (c,f). Treatment time is 2 s.

Figure 3 shows in detail the radial distribution of the contact angle of small water droplets deposited on polyethylene film treated by Ar plasma jet at different experimental conditions. This figure demonstrates the dependence of the treatment effect on a distance from the DBD exit, electric power of DBD and which electrode is grounded. One can see also in this figure that visual diameter of plasma spot is always smaller compared to the diameter of the area treated by plasma jet.
3.2. Interaction of plasma jet with quickly moving the dielectric and metallic substrates

The results on deformation of helium plasma jet on and in vicinity of the moving substrate are presented in figure 4. Note that the shape of plasma spot on a motionless dielectric and metallic surface is not the same - plasma widely spreads on a dielectric surface but concentrates into a small spot on the metallic substrate. Increase in a rotating velocity of the substrate (disc) leads to the dragging of ambient air in the vicinity of the disc surface that in its turn influences the interaction of plasma jet with the surface - the wind induced by the rotation separates the jet from the surface to be treated. This effect is the same for dielectric and metallic substrate and can lead to lowering the efficiency of plasma jet treatment. A positive effect of the wind is the destroying of current spot figure 4 (4c).

![Image of plasma jet interaction with moving substrates](image)

**Figure 4.** Set of images of He plasma jet striking the substrate of acrylic plastic (a, b) and aluminum (c) rotating with different frequencies F (revolutions per second). Set (b) shows the enlarged image of plasma jet deformation on the substrate and its separation from the surface with increase in F. Dashed line in photos marks the substrate surface. Jet velocity V=28 m/s; P=3.6 ±0.2 W; F=0 (1a, 1c, 2c); F=9 rps (2a, 3c, 4c); F=58 rps (3a, 5c); F=102 rps (4a, 6c); F=139 rps (5a, 7c); F=168 rps (6a, 8c).

Figure 5 presents the results on interaction of argon plasma jet with the rotating substrate. There is a great difference in the behavior of Ar plasma jet interacting with the dielectric and metallic substrate. According to figures 5a, 5b, deformation of argon plasma jet in vicinity of the dielectric substrate grows with increase in rotation frequency but there is no its separation. Ar plasma jet striking the metallic substrate exhibits unexpected behavior. At low electric power P < 8 W, plasma jet is diffusive (figure 5d) and interacts with metallic disc like He plasma jet. At higher electric power P > 8 W, DBD transits to the regime with alternation of low-current and high-current modes of 8.5 and 27 W respectively (figure 5e), which correspond to diffusive and filamentary plasma jet (figures 5d, 5e, 5f). This phenomenon is attributed to ability of the grounded disc to pass high current to the ground through plasma jet that leads to the development of the ionization instability in plasma jet and its transition into filamentary mode. The wind induced by the disc rotation influences the high-conductive
current filaments, which change the angle of their striking the surface (figure 5e, 5f). Note the filaments are strongly twisted. A reason of that is the necessity to increase their total length in order to be able to keep for short time a high voltage drop between the HV electrode and the ground.

![Current Filaments](image)

**Figure 5.** Set of images of Ar plasma jet striking the substrate of acrylic plastic (a, b) and the grounded aluminum disc (d, e, f) rotating with different frequencies F. Set (b) shows the enlarged image of the jet deformation with increase in F. Plot (c) presents the current-voltage waveform of DBD at the alternating regime. Dashed line in photos marks the substrate surface. Jet velocity V=28 m/s; F=0 (1a, 1b, d, e); F=58 rps (2a, 2b); F=102 rps (3a, 3b); F=139 rps (4a, 4b); F=168 rps (5a, 5b, f).

4. Conclusion
It is proved that fast movement of the dielectric and metal substrate leads to change of the shape of plasma jet at the point of its striking. This phenomenon is attributed to gas-dynamic effect – to the dragging of air by the fast moving surface. It was revealed that the wind induced by fast moving substrate can lead to the separation of jet from the surface and lowering the efficiency of plasma treatment. It was found out that Ar plasma can form thin current filaments twisted by a spiral.

References
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