Effect of the speed of the flat substrate movement on the air plasma jet transversal spreading at its impinging the surface

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Abstract. Low-temperature plasma jets are used to treat both the motionless and moving objects (targets or substrates). The gas-dynamic aspects of the plasma jet's interaction with the target are important and have to be taken into account in selecting the most efficient plasma processing parameters. Clearly, the spreading of plasma jet over a fast-moving surface is significantly different from its spreading over a fixed target. This question is investigated by the example of the interaction of an air plasma jet with a surface of fast-rotating dielectric disk. It is shown the change in the shape of the jet striking perpendicularly the moving substrate happens due to the movement of a thin layer of the ambient air adjacent to the fast-moving surface. This effect can have a noticeable influence on the reactive particles transfer from the plasma jet onto the surface to be treated.

1. Introduction
Round jets of non-equilibrium low-temperature plasma generated by flow discharges of different types are used for the treatment of both the motionless and moving objects (targets or substrates) [1-5]. To date, plasma systems based on the use of inert electro-positive gases (He, Ar, N2) or mixtures thereof with small additives of electro-negative gases have been the most developed on the technical and scientific sides [6-10]. The main reason is that the electric discharge at atmospheric pressure is most easily excited in electro-positive gases. In addition, the lifetime of reactive plasma particles created by discharge is greatest in these gases compared to that in the air at atmospheric pressure. At the same time, plasma jets generated in atmospheric airflow are highly sought after in both practical applications and scientific research.

Experiments were carried out with a circular plasma jet created by the coaxial barrier discharge in an atmospheric airflow. The experiments explored in detail the gas-dynamic features of the plasma jet's interaction with the flat surface of a fast-moving target. The fact is the surface moving rapidly in the surrounding stationary ambient air involves in the motion a boundary layer of the air. In its turn, the involved airflow can have a significant influence on the shape of the plasma jet adjoining the surface of the moving target being treated. Besides, the spatial structure of the jet near the moving surface can have a noticeable effect on the processes of the reactive particles transferring from the plasma jet onto the surface to be treated. This question is investigated by the example of the interaction of an air plasma jet with a rapidly rotating dielectric disk made of organic glass.
2. Experiment and the obtained results

The scheme of the experiment is shown in Figure 1a. The plasma jet was formed by the coaxial dielectric barrier discharge (CDBD) in airflow at atmospheric pressure. The CDBD was excited by the electric sinusoidal voltage with a frequency of 85 kHz in a ceramic tube (Al2O3, dielectric permittivity $\varepsilon \approx 8.5$) having an internal diameter of 2.2 mm, an external diameter of 5.3 mm and a total length of 50 mm. The low voltage (the grounded) electrode was a strip of the copper foil of 50 $\mu$m in thick and 20 mm in length wrapped around the ceramic tube on its outside. The downstream end of the copper foil was 10 mm away from the tube outlet. Molybdenum wire of 0.3 mm in diameter was used as a high voltage electrode (HVE) located on the tube axis. The downstream end of the HVE is offset 1 mm upstream from the upstream edge of the copper foil. The airflow velocity $V_g$ through the discharge tube was varied from 38 to 75 m/s. At these velocities, the Reynolds number is lower than the critical value ($Re^* \approx 2300$), therefore the airflow in the tube was in the laminar regime. However, when leaving the tube, the jet quickly went into the turbulent mode, since the critical Reynolds numbers for causing turbulence in the flooded jets are at least an order of magnitude less than $Re^*$ for the laminar flows in round tubes.

The plasma jet was directed to a 180 mm diameter rotating disc made of organic glass. The linear speed of the disc $V_d$ at the plasma jet impact point was varied up to 85 m/s due to the change in its rotational speed. Experiments were carried out at two distances $d$ of the dielectric target from the gas discharge tube output: $d = 3\text{mm}$ and $d = 6\text{mm}$. The choosing of such close distances of the target from the tube outlet is due to the small length of the active part of the air plasma jet caused by the fast quenching of the active plasma particles by air molecules at atmospheric pressure. At the same time, the jet velocity at such distances practically remained the same as that at the leaving the tube.

In the experiment, the discharge current and voltage were recorded by the Tektronix DPO-2012B digital oscilloscope (100 MHz, 1GS/s). The characteristic current and voltage oscillograms of the CDBD are shown in Figure 1b. The current and voltage oscillograms were used to calculate the CDBD electric power, on the basis of which the air heating at the discharge zone outlet was estimated. The jet velocity at the tube exit and the air velocity near the rotating disc were measured by a Pitot tube with an inner diameter of 1 mm. The rotation speed of the disc was determined on the base of the measured interruption frequency of the laser beam passing through the small hole in the disc. The periodic signal of the transmitted beam was directed to the PMT and recorded by the oscilloscope. Knowing the measured rotation speed of the disc and the radius of the point where the plasma jet impinges the disc, the linear velocity of the disc $V_d$ at this location was determined. A visible image of a free plasma jet and the jet striking a moving target were recorded by the Canon EOS 550 D camera. Figure 2a shows a plasma jet inflowing freely into ambient air when there is no target in its path.

![Figure 1](image-url)  
**Figure 1.** a) Scheme of the experimental setup. b) The current and voltage characteristic oscillograms of the CDBD in atmospheric airflow, discharge power $W = 85$ W, jet velocity $V_g = 75$ m/s, linear disc velocity $V_d = 85$ m/s.
A set of images of a jet perpendicularly falling on a motionless flat target (dielectric disk) is shown in figure 2. The photographs clearly show the change in jet configuration near the target surface at different jet velocities and the target distances from the jet exit from the discharge tube. The parameters of the experiment are specified at the bottom in the caption of the figure. Photographs 2b-2d are the reference ones because they give an image of a plasma jet falling on a fixed disk. It can be seen in this case, the jet spreads symmetrically over the disc in the radial direction. One may see also, the falling jet separates from the disc surface more and more with the increase in the radial distance from the impinging point. This effect is associated with an increase in the thickness of the boundary layer of the adjoining jet with the distance from the jet impinging point. The higher the velocity of the impinging jet, the stronger this effect is expressed.

![Figure 2](image1.png)

**Figure 2.** a) Image of the air plasma jet generated by the CDBD, freely inflowing into the ambient air, jet velocity $V_g = 75$ m/s, discharge power $W = 85$ W. b) - d) A set of images of an air plasma jet perpendicularly falling on a motionless flat target (dielectric disk). Jet velocity $V_g$: b) 75 m/s; c), d) - 38 m/s. Linear disk speed $V_d$ at the jet striking point: b), c), d) - 0 m/s. Distance $d$ from the discharge tube output to the disk: b), c) - 6 mm; d) - 3 mm. The voltage amplitude $U$ driving the CDBD: $U = 7.2$ kV. The exposure time of all pictures is the same: 2 s.

Photos in figure 3 show an image of a plasma jet falling on a rotating disc. There is clearly a significant asymmetry in the impinging jet pattern caused by the near wall airflow involved in the movement by the rotating disc. On the windward side, the impinging jet is shortened in the length and is visibly taken off the surface, swirling at high rotation speeds of the disc into a vortex-like structure. On the upwind side, the impinging jet is pulled out and pressed tightly against the disc surface. The vicinity of the plasma jet to the moving surface is expressed the stronger, the closer (or greater) the linear disc velocity to the velocity of the incident jet.

![Figure 3](image2.png)

**Figure 3.** A set of images of an air plasma jet perpendicularly falling on a flat rotating target (dielectric disk). Vertical arrows show the movement direction of the rotating disc. Jet velocity $V_g$: a),
b), c) – 75 m/s. Linear disk speed $V_d$ at the jet striking point: a), b), e) – 85 m/s; c), d) – 29 m/s. Distance $d$ from the discharge tube output to the disk: a), b), c) – 6 mm; d), e) – 3 mm. The voltage amplitude $U$ driving the CDBD: a) – 6.4 kV; b), c), d), e) – 7.2 kV. The exposure time of all pictures is the same: 2 s.

It is interesting to compare the noted above effect of disk rotation on the impinging air plasma jet with a similar effect on the light gas - helium jet falling on the rotating disc (see [6]). This comparison is shown in the images shown in figure 4.

![Figure 4](image-url)

**Figure 4.** Comparison of the shapes of air (left) and helium plasma jets falling on a rotating disc. 6 images are given for the helium jet. Linear speed of the disc at the point of the air jet impact $V_d = 85$ m/s; for helium jet $V_d$ (m/s): 1 – 85; 2 – 70; 3 – 51; 4 – 29; 5 – 4.5; 6 – 0.

On the left in Figure 4, an image of an air plasma jet is shown. On the right in Figure 4, a set of helium jet images at different disk speeds is presented. The linear disk speed at the place of jet fall was being changed from 85 m/s to zero. Figure 4 shows the shape of the helium plasma jet is also asymmetric with respect to the incident direction, as it is observed for the air impinging jet. Note here the asymmetry of helium jet increases with the linear velocity of the moving target. However, there is a very significant difference in the behavior of helium and air plasma jets. The air jet on the downwind side fits tightly against the moving surface, while the light helium jet is separated completely (on the downwind and windward sides) from the disc surface by the airflow created by the rotating disc. In such a case, the transfer of the reactive particles from the helium plasma jet onto the moving surface is greatly reduced. This fact indicates the inefficiency of using helium plasma jets to treat fast-moving surfaces.

3. Discussion

In order to explain the results presented in Figure 3, we give a schematic structure of a near-wall jet of air spreading over a fixed and moving surface (Figure 5). In the case of a fixed target (Figure 5a), the jet spreading over a surface is axially symmetrical. Note here the jet current lines gradually left from the surface due to the thickening of the boundary layer with increasing radius. The difference in the jet spreading over the moving surface is that in this case, there is at the surface a thin layer of the air involved in the movement by the moving surface due to its viscous adhesion to the surrounding air. The airflow engaged with moving surface interacts with the boundary layer of the jet and changes its characteristics. The picture of this interaction is qualitatively shown in Figure 5b for the case when the surface moves from left to right.

When oriented "from left to right," the conjugated with the surface airflow on the left side moves against the near-wall jet, and on the right side coincides with the direction of the near-wall jet. In the case of the high speed of surface movement, on the left side in the total boundary layer of the jet, there is a return flow, so the velocity distribution in this area will be non-monotonic (Figure 5b). Such a velocity distribution is typical for the boundary layer after its separation from the surface when the gas
flows around the convex surface. In other words, on the left side, the airflow engaged with the surface plays the role of return flow - it separates the near-wall jet from the surface and twists it into a vortex-like structure. On the right side, the coupled flow changes the jet velocity distribution in such a way as to eliminate its inner boundary layer and thereby reduce the thickness of the outer boundary layer of the impinging jet. In other words, on the right side, the coupled airflow strongly presses the impinging jet against the moving surface.

Figure 5. Schematic structure of the impinging jet spreading over the motionless substrate (a) and over the surface moving from left to right (b). In the case of (b), there is at the surface a thin layer of the airflow that is created by the moving surface. The velocity distribution in the boundary layer in the left part of the near-wall jet is non-monotonic. Such a velocity distribution is typical for the boundary layer after its separation from the surface when the gas flows around the convex surface.

4. Conclusion
Movement of the flat surface in the course of its plasma treatment is accompanied by involving in the movement of a thin layer of ambient air adjacent to the surface. The thin layer of airflow engaged with surface leads to the asymmetry of plasma jet spreading over the moving surface. On the windward side, the near-wall jet is shortening and separating from the surface, swirling at high velocities of the coupled airflow into the vortex-like structure. On the downwind side, the near-wall jet is lengthening and pressing against the moving surface. Pressing the plasma jet to the surface is expressed the more strongly the closer the velocity of the surface movement to the velocity of the incident jet. This effect promotes the faster transfer of reactive particles from the plasma jet onto the surface to be treated and thereby increases the efficiency of the plasma treatment.

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