Gas-dynamic structure of a plasma jet in He and Ar, striking the surface of a liquid and a plane dielectric

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Abstract. The results of experiments on the interaction of an argon plasma jet with a liquid are presented. The effect of a coaxial barrier discharge on the gas-dynamic regime of a plasma jet of helium, freely blown into ambient air, and also colliding with a solid surface, is studied. Three orientation helium jets were studied - the jet is directed up, down and horizontally. Schlieren images of a jet were compared with visible images of a plasma jet. It is concluded that the main effect of the discharge on the gasdynamic regime of the jet is associated with gas heating in the discharge zone.

1. Introduction
Axisymmetric jets of nonequilibrium non-thermal plasma at atmospheric pressure are successfully used to process liquids and modify the surfaces of thermally unstable materials, inactivate microorganisms, sterilize medical equipment, etc. [1-3]. The widespread use of plasma jets (PJ) was made possible thanks to the successes achieved in studying the physical mechanisms of formation of plasma jets [4-6] and establishing optimal conditions for their generation. The bulk of the currently obtained experimental and theoretical results relates to studies of PJs that freely flow from a gas-discharge system into open space. However, of practical and scientific interest are studies of PJ striking the surface to be treated, liquid or solid. In this paper, the results of experiments on the effect of a barrier discharge (BD) on the gasdynamic regime of a PJ blown into ambient air, as well as on the interaction of an argon and helium PJ with a liquid and solid surface oriented perpendicular to the incident jet are presented. PJ of three directions were studied - up, down and horizontally. Schlieren images of the jet were compared with its visible images.

2. Experiment and results
The experiments were carried out with PJ in a stream of argon or helium, blown into ambient air. The PJ was formed by a coaxial BD, which was ignited in a 60 mm long quartz tube with an internal diameter of 2.5 mm and an external diameter of 4.1 mm. A high-voltage electrode made of molybdenum wire with a diameter of 0.3 mm was placed on the axis of the tube. The distance from the tip of the wire to the tube exit is 30 mm. The low-voltage electrode was a strip of copper foil 20 mm wide wrapped around the outer surface of the tube. The frequency of the sine wave voltage exciting...
the BD was 85 kHz. The PJ orientation, its velocity, and the voltage amplitude were varied in the experiment. Oscillograms of the BD current and voltage were recorded, according to which the electric power of the BD was calculated. Oscillograms were recorded with a Tektronix DPO-2012B oscilloscope (100 MHz, 1GS / s). The flow rate was measured by a Pitot tube. The gasdynamic structure of the PJ was studied by an IT-228 side-shift mirror interferometer [7]. The PJ image was shot with a Canon EOS 550 camera.

2.1. Interaction of argon gas and plasma jets with a liquid

The experiment has been conducted with PJ in laminar mode. The output nozzle of the BD was at a distance of 22 mm from the surface of the liquid poured into a glass vessel with a diameter of 36 mm and a height of 60 mm. The liquid depth was 15 mm. The velocity of the jet above the liquid surface was 25 m/s. The power of the BD was 5 W. Typical images of PJ interacting with a liquid are presented in Figure 1. As can be seen, gas and plasma jets create several effects when interacting with a liquid.

![Figure 1](image1.png)

Figure 1. Photo of the liquid irradiated with: (a) an Ar gas jet without discharge; (b) an Ar plasma jet.

1) The jets push the liquid and produce a strong deepening in it right down to the bottom of the vessel upon impact. 2) The jets spray liquid settling in large drops on the vessel walls and the BD outlet nozzle. 3) The jets produce foam on the liquid surface moreover the jet with the plasma produces smaller foam bubbles. 4) In addition, a lot of thin streamers appear from the surface of a conductive foam that close on the PJ, when a PJ impacts on a liquid. Streamers arise randomly in the space around the PJ, and their presence negatively affects the stability of the BD current regime. Interestingly, the PJ does not hit along the gas stream axis, but deviates to the side wall of the crater produced in the liquid. Perhaps this effect and the streamers appearance are due to the electric charge accumulation in the liquid introduced into it by the plasma jet.

2.2. The effect of BD, the velocity and orientation of the helium PJ on the length of the laminar region

Data on the heating of a helium jet in a BD: $\Delta T \equiv P/pVSC_p$ (P is the BD power, $\rho$ is the specific density of He, V is the flow velocity in the tube, $S$ is the tube cross section, $C_p$ is the specific heat of He at constant pressure ($\rho = 0.178$ kg / m$^3$, $C_p = 5.19$ kJ / kg deg) and Reynolds numbers in the tube $Re = Vd/\nu$ ($\nu$ is the kinematic viscosity, d is the inner diameter of the tube) are given in Table 1.

| $V_0$, m/s | $V_0d$, cm$^3$/c | P=8 W (U=2.9kV) | $\Delta T$, K | v, cm$^3$/c | Re | P=11 W (U=3.9kV) | $\Delta T$, K | v, cm$^3$/c | Re | P=15 W (U=5.1kV) | $\Delta T$, K | v, cm$^3$/c | Re |
|-----------|----------------|----------------|-------------|-------|---|----------------|-------------|-------|---|----------------|-------------|-------|---|
| 15        | 375            | 120            | 276         | 165   | 2.6 | 260           | 225         | 3.2   | 236          | 36          | 900   | 62.5 | 1.8 | 747 | 86 | 1.9 | 714 | 117 | 2.2 | 623 |
| 36        | 1250           | 43.5           | 1038        | 60    | 1.8 | 991           | 81.5        | 1.9 | 969          | 50          | 2125  | 29  | 1.6 | 1764 | 40 | 1.7 | 1722 | 54  | 1.8 | 1682 |


The maximum Reynolds number was without a discharge at \( V = 85 \text{ m/s} \) and is equal to \( \text{Re} = 1700 \). Thus, in all regimes, both with discharge and without it, the Reynolds number in the tube was less than the critical value \( \text{Re} \approx 2300 \), and therefore the gas flow inside the tube corresponded to the laminar regime. Schlieren photos of helium PJ at different orientations are shown in Figure 2. All photos were taken with the same exposure of 8 ms. It can be seen that the BD strongly influences the length of the transition of the laminar jet to the turbulent PJ regime at PJ speeds up to 35 m/s. In this range, the greater the BD power, the shorter the length of the laminar region. However, this effect weakens with increasing PJ velocity and at \( V > 35 \text{ m/s} \), the transition length is practically independent of the BD power and becomes close to the length characteristic of a jet without a discharge. A possible reason is that at high flow rates, the gas heating in the jet by the discharge becomes very small, and therefore the role of gas heating in the turbulence of the jet is significantly reduced.

| V=15 m/s | V=85 m/s | V=15 m/s | V=85 m/s |
|----------|----------|----------|----------|
| U=0 kV   | U=5.1 kV | U=0 kV   | U=5.1 kV |

| V=15 m/s | V=85 m/s | V=15 m/s | V=85 m/s |
|----------|----------|----------|----------|
| U=0 kV   | U=5.1 kV | U=0 kV   | U=5.1 kV |

| U, kV    | V=15 m/s | V=85 m/s |
|----------|----------|----------|
| 0        |          |          |
| 5.1      |          |          |

**Figure 2.** Schlieren photos of a free He gas and He plasma jet at different jet orientations: a) from top to bottom; b) from bottom to top; c) horizontally. The discharge parameters and flow velocities are indicated above each photo. The jet is blown into the surrounding room air. In the photo (c) at \( V = 15 \text{ m/s} \), the buoyancy of a light helium jet in air is visible.
Data on the length of the laminar region of the helium jet under different experimental conditions, obtained from processing a large set of schlieren photos, are presented graphically in Figure 3. This figure clearly shows that at high jet velocities ($V > 35 \text{ m/s}$) the influence of BD on the length of the PJ laminar region becomes insignificant for any jet orientation. At high speeds, the top-down jet orientation has the strongest effect on the length of the laminar region of the helium stream. A possible reason is related to the influence of convective effects, i.e. with the buoyancy of light helium in the air.

![Figure 3](image)

**Figure 3.** The length $l^*$ of the laminar region of the helium jet at various jet velocities, voltage amplitudes, and three jet orientations: a) horizontally, b) from top to bottom; c) from bottom to top.

It is interesting to compare the dimensions of a gas and plasma jet at different jet velocities and orientations. Such information is shown in Figure 4, which shows schlieren photos of a gas jet and visible images of a plasma jet with a top-down flow orientation as an example. Two different gasdynamic regimes were chosen, in one of which the PJ is completely in the laminar region of the gas jet, in the other PJ is completely in the turbulent gas jet.

![Figure 4](image)

**Figure 4.** The dimensions of gas and plasma jets at different jet velocities and top-down flow orientations. The spatial scale in the schlieren photos of the gas stream and photos of the visible luminescence of the PJ is the same. The PJ photos exposure time is 40 ms ($V = 15 \text{ m/s}$) and 25 ms ($V = 85 \text{ m/s}$), $U = 5.1 \text{ kV}$.

As can be seen in Figure 4, the helium jet occupies a much larger longitudinal and transverse dimension in space than the thin PJ located inside it. The shape of the tail of the PJ depends on the gas jet regime. If the PJ is completely inside the laminar gas jet, then the transverse size of its tail monotonously decreases down to zero. In the case of a turbulent jet, pulsations of the gas flow randomly and quickly sweep the “tail” of the PJ, therefore, the photo shows an averaged image of the “tail” in the form of a diffuse brush. With the same voltage amplitude, the turbulence of the gas jet even increases the length of the PJ. Apparently, this is due to the fact that the strong expansion of the turbulent helium jet shields the thin PJ from the surrounding air and prevents the penetration of oxygen into it.
2.3. The influence of the BR, the velocity and orientation of the PJ on its spreading over a flat surface.

A set of schlieren photos of a gas jet and a PJ impinging on a flat dielectric surface located 35 mm from the tube exit is shown in Figure 5. Note that a faint PJ luminescence in schlieren photos is not visible. As can be seen in Figure 5, the most intense turbulence of the gas jet at / near the target is observed when the helium jet is oriented “top-down” at all its speeds, and the ignition of the BD even more intensifies the turbulence process.

![Schlieren photographs of a gas and PJ in the presence of a target at a distance of 35 mm from the edge of the discharge tube. The orientation of the jets: a) horizontally; b) from top to bottom; c) from bottom to top.](image)

Figure 5. Schlieren photographs of a gas and PJ in the presence of a target at a distance of 35 mm from the edge of the discharge tube. The orientation of the jets: a) horizontally; b) from top to bottom; c) from bottom to top.

The smallest level of turbulence is observed when the helium jet is oriented backward from the bottom up. The size difference between the turbulent eddies adjacent to the target (eddies are small) and those that arise at a certain distance from the target (eddies are large) is clearly visible at high jet velocities. In the case of horizontal orientation, the gas jet spreading over the target is asymmetric due to the buoyancy of helium in the air. The displacement of air with a helium flow from a large region
around the interaction zone of the PJ with the target observed by the top-down orientation suggests a small effect of ambient air on the plasma chemistry of the plasma-surface process at high PJ speeds and a small distance between the target and the discharge zone.

3. Conclusion
a) The main effect in the interaction of argon PJ with a liquid, is associated with the deformation of the liquid surface, the magnitude of which depends on the kinetic energy of the jet. The jet pushes a strong deepening in the liquid at high speed. Since the PJ leaves the cavity along its walls, the presence of the cavity substantially increases the contact area between the active plasma particles and the liquid, which is a useful effect. However, spraying a liquid with a jet negatively affects the stability of the current regime of the barrier discharge.

b) It was found that at low speeds of the helium jet (V <35 m/s), the barrier discharge reduces significantly the length of the laminar region of the jet flowing freely into the surrounding air. This effect is associated with gas heating in the discharge zone. Gas heating decreases and the BD influence on the length of the laminar region is greatly weakened at high flow velocities. The presence of a solid barrier (target) in the PJ path affects significantly the gasdynamic regime of the jet. Intense displacement of the surrounding air by a helium flow from a large region around the interaction zone between the PJ and the target is observed when the high-speed jet is oriented “top-down” and a small distance between the target and the discharge zone. This suggests a small effect of air on the plasma chemistry of the helium plasma-surface process.

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