

# Propagation of atmospheric pressure helium plasma jet into ambient air at laminar gas flow

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**Abstract.** The formation of an atmospheric pressure plasma jet (APPJ) in a gas flow passing through the discharge gap depends on both gas-dynamic properties and electrophysical parameters of the plasma jet generator. The paper presents the results of experimental and numerical study of the propagation of the APPJ in a laminar flow of helium. A dielectric-barrier discharge (DBD) generated inside a quartz tube equipped with a coaxial electrode system, which provided gas passing through it, served as a plasma source. The transition of the laminar regime of gas flow into turbulent one was controlled by the photography of a formed plasma jet. The corresponding gas outlet velocity and Reynolds numbers were revealed experimentally and were used to simulate gas dynamics with OpenFOAM software. The data of the numerical simulation suggest that the length of plasma jet at the unvarying electrophysical parameters of DBD strongly depends on the mole fraction of ambient air in a helium flow, which is established along the direction of gas flow.

## 1. Introduction

Study of the “plasma – biological objects” interactions has become one of the main current trends of research on gas discharge plasma technologies [1-5]. There are many important reasons for considering low-temperature plasma as a new breakthrough instrument in biology [1], medicine [1-5], food [6] and agriculture [7] industries. The most rapidly spreading tools for producing low-temperature plasma at atmospheric pressure are plasma jet sources based on a dielectric-barrier discharge, in particular, generators of helium or argon jets propagating in ambient air.

To introduce such plasma sources into existing technological procedures and to create new technologies based on atmospheric pressure plasma jets (APPJ), a number of optimization problems should be solved. At first, we should be able to predict the distance of the propagation of a plasma jet into the surrounding air.

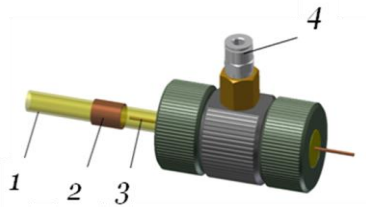
Some authors point out that a limited distance of plasma jet propagation (ionization wave propagation) in the ambient air is determined with the concentration of plasma supporting gas [8, 9], but they do not mention the influence of applied voltage. When the plasma supporting gas is injected from the generator into air, its mixing with the air occurs, and its concentration along the length of plasma jet decreases. The propagation of ionization waves is limited by the certain value of air admixture. The data suggesting this have been obtained for plasma jets generated in inert gases flows directed along the upward vertical at the applying of rectangular unipolar high-voltage pulses [8] and sinusoidal high voltage [9].



The given paper presents the first results of checking conclusions of [8, 9] for a helium plasma jet generated by sinusoidal voltage in a gas flow directed along upward and downward verticals.

## 2. Experimental set-up

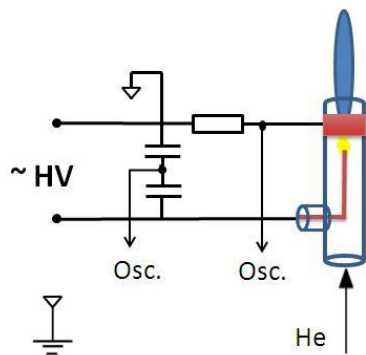
To generate a plasma jet, we used a discharge cell with axisymmetric electrode system “inner wire – outer ring” which is presented in Figure 1.



**Figure 1.** The sketch of the discharge cell. 1) quartz tube; 2) grounded electrode; 3) high-voltage electrode; 4) gas flow pipe fitting).

As a dielectric barrier, quartz tubes with the inner diameters of 5.58 and 7.49 mm and the thickness of walls of 1 mm were used. The inner electrode of copper wire 1.5 mm in diameter was placed inside the tube along its center line at the distance of 7.5 mm from the edge of the tube. The outer electrode was a 5-mm-wide copper-foil strip wrapped around the tube at the distance of 5 mm from its edge.

Sinusoidal high voltage pulses with the peak-to-peak magnitude of 4 kV and frequency of 21 kHz was applied to the inner electrode. A schematic diagram of the experimental set-up with the system of electrical measurements is shown in Figure 2. The voltage signals from the electrodes were recorded with a capacitor voltage divider with a division ratio of 1:1350, while current signals were recorded with a non-inductive resistive shunt of 89  $\Omega$ . The signals were recorded by Agilent DSO-X 2014A oscilloscope (Agilent Technologies, USA).



**Figure 2.** A schematic diagram of the experimental set-up with the system of electrical measurements.

As a plasma-supporting gas, high-purity helium was used. Gas flow rate was controlled by a Bronkhorst EL-Flow F-201AC flowmeter in a range of 0-45 l/min. Some additional details of the gas flow system can be found in [10].

To estimate the experimental length of a generated plasma jet, it was photographed using Nikon D80 DSLR equipped with Sigma 28-200 Macro lens.

## 3. Brief description of computational model

A helium laminar jet submerged into air was simulated using OpenFoam 2.1.1 program package. To optimize the calculations and take into account an axial symmetry of the problem, a segment of  $50 \times 300 \text{ mm}^2$  with the angle of 4 degrees was considered with different density of computational mesh  $(0.3-1) \times 0.5 \text{ mm}^2$ . Physical parameters of a helium flow (fraction of air, density, heat conductivity, viscosity) were given according to the industrial certificate of gas production.

The solver *twoLiquidMixingFoam* of OpenFOAM was modified in accordance with the problem. Unsteady-state equations of gas dynamics for an axially-symmetric helium jet submerged into air are as follow:

- 1) the mass conservation law (continuity equation):

$$\frac{\partial \rho \alpha_i}{\partial t} + \nabla \cdot (\rho \vec{g} \alpha_i) = -\nabla \cdot (-\rho D \nabla \alpha_i), \quad (1)$$

where  $\alpha_i$  is the mass fraction of each species ( $i = 1$  is for helium species;  $i = 0$  is for air species);  $\rho$  is the density of the gas mixture;  $\vec{g}$  is the gas mixture velocity;  $D$  is the diffusion coefficient for species in the gas mixture (for the laminar regime of the gas flow it depends on the gradient of component concentration);

- 2) motion equation:

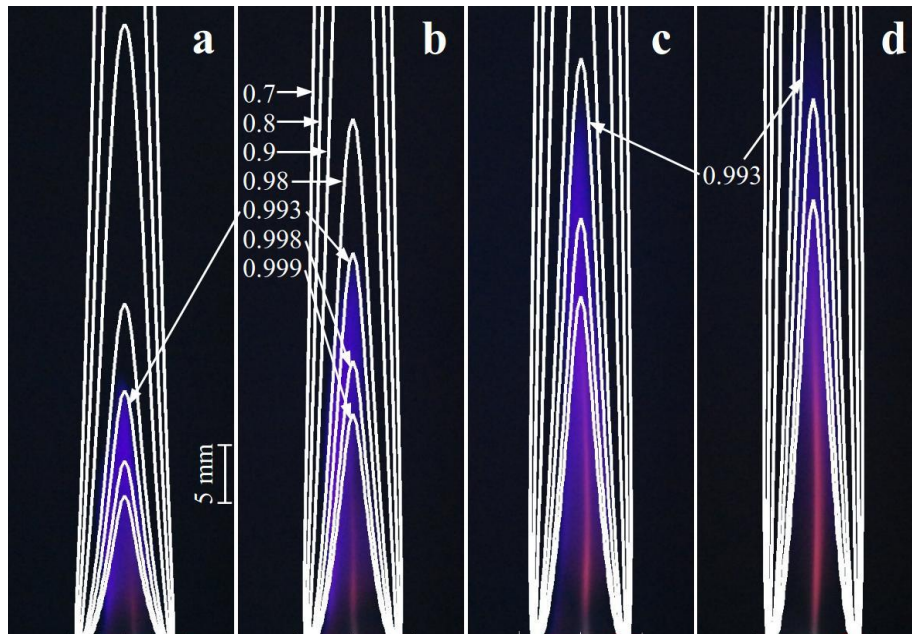
$$\frac{\partial \rho \vec{g}}{\partial t} + \nabla \cdot (\rho \vec{g} \vec{g}) = -\nabla p + \nabla \cdot (\tilde{\tau}) + \rho \vec{g}, \quad (2)$$

where  $p$  is pressure;  $\tilde{\tau}$  is the stress-tensor with due consideration of the force of viscous tangent friction;  $\rho \vec{g}$  is gravitational force.

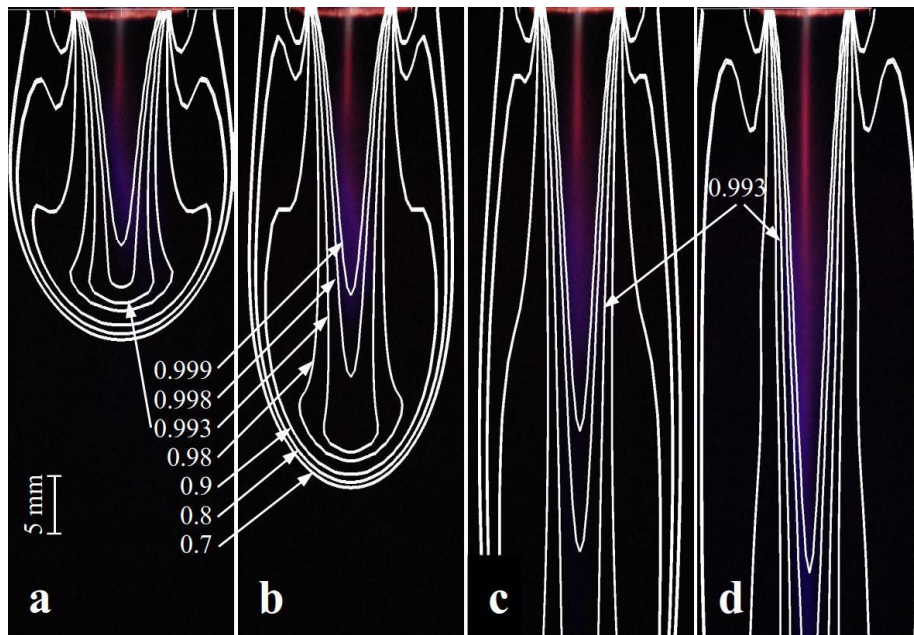
The calculation was carried out for the laminar regime of a helium flow in air at different helium flow rate.

#### 4. Preliminary experimental results and discussion

The calculation results of helium concentration profiles were compared with the photos of generated APPJ. The matching of simulation results with the experimental findings are depicted in Figures 3 and 4 for the gas flow direction along upward and downward verticals, correspondingly. The parameters of voltage supply were set as follows: peak-to-peak voltage was 4 kV, pulse frequency was 21 kHz. The discharge current was up to 15 mA.



**Figure 3.** Photos of the plasma jet generated in a laminar helium flow directed along upward verticals through the tube of 7.49 mm in a diameter at the gas flow rates of a) 1.36, b) 2.09, c) 3.03, and c) 4.08 m/s. White lines are helium concentration profiles obtained by computational simulation.



**Figure 4.** Photos of the plasma jet generated in a laminar helium flow directed along downward vertical through the tube of 7.49 mm in a diameter at the gas flow rates of a) 1.31, b) 1.73, c) 2.5, d) and 3.34 m/s. White lines are helium concentration profiles obtained by computational simulation.

Dependences of the dimensionless length of APPJ for the gas flow directed upward and downward through the tubes of different diameters versus Reynolds number are shown in Figures 5 and 6.

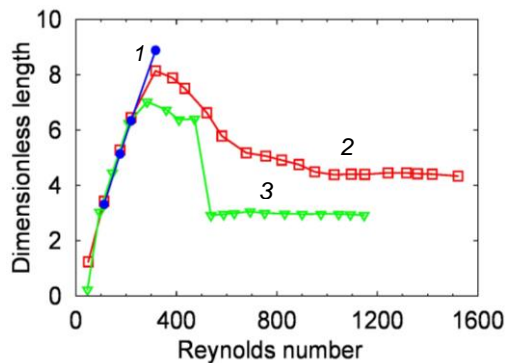
Reynolds number is  $Re = \frac{\rho_{He} \cdot \mathcal{G} \cdot d}{\mu_{He}}$ , where  $\rho_{He}$  and  $\mu_{He}$  are the density ( $\frac{kg}{m^3}$ ) and dynamic

viscosity ( $\frac{\mu N \cdot s}{m^2}$ ) of helium at atmospheric pressure and temperature of 20 °C, respectively;  $\mathcal{G}$  is gas

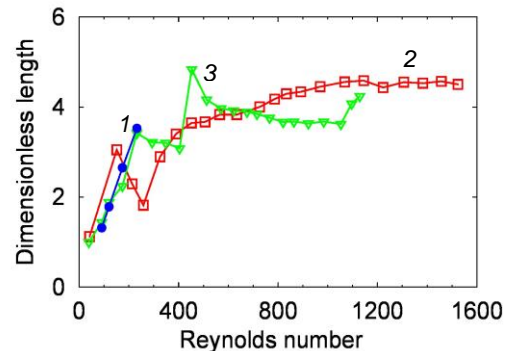
outlet velocity ( $\frac{m}{s}$ );  $d$  is the inner diameter of the discharge tube (m).

The APPJ length increases as a linear function of a gas flow rate under laminar regime. For Reynolds number exceeding 200-300, a laminar gas flow begins to transfer into a turbulent one, and the deviation of dependence of APPJ length from the linear function appears. Under the developed turbulent regime (Reynolds numbers is more than 500) for both directions of gas flow and both diameters of the tubes, the dimensionless APPJ lengths were approximately of 4. Under this regime, air effectively mixes with helium, and the length of mixture plasma jet does not depend on the gas flow orientation in space.

Comparison of the experimental and calculated data showed that for the laminar regime the expansion boundary of APPJ is limited by the helium concentration of 0.987-0.996 at the discharge generation by a peak-to-peak voltage of 4 kV with frequency of 21 kHz (Figures 5 and 6).



**Figure 5.** Dimensionless plasma jet length ( $L_{jet}/d$ ) versus Reynolds number ( $Re$ ) for helium flow along upward vertical through the tube of 5.58 (curve 2) and 7.49 (curve 3) mm in a diameter in comparison with the simulation results (curve 1).



**Figure 6.** Dimensionless plasma jet length ( $L_{jet}/d$ ) versus Reynolds number ( $Re$ ) for helium flow directed along downward vertical through the tube of 5.58 (curve 2) and 7.49 (curve 3) mm in a diameter in comparison with the simulation results (curve 1).

We should note that the plasma jet propagation is connected with the propagation of ionization waves (guided streamers). Thus, the air impurity influences APPJ length, since ballast air interrupts the resonant transmission of radiation by the ionization wave.

For the other modes of the applied voltage, APPJ length versus gas flow rate is slightly different, but the general trend corresponds to the data given above.

## 5. Conclusion

According to the series of presented data, the limit boundary of APPJ expansion in helium at laminar regime is determined by the achievement of the certain volume concentration of air impurity, which gradually increases with the distance from the tube outlet.

For the laminar regime, the propagation area of guided streamers corresponds to the boundary of the relative helium volume concentration of 0.987-0.996 for discharge at peak-to-peak voltage of 4 kV and frequency of 21 kHz. At the same time, the length of APPJ linearly increases with the rising of gas flow rate.

Some calculations in comparison to more extensive experimental data are planned to be carried out.

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### **Acknowledgments**

This work was partially supported by Saint Petersburg State University (grant no. 0.37.218.2016) and the Russian Foundation for Basic Research (grant no. 16-08-00870).