Optical emission study of plasma vortex rings at atmospheric pressure air

L Y Volodin and A S Kamrukov
Bauman Moscow State Technical University, 5 2nd Bauman Str., Moscow, 105005, Russia
E-mail: volodinlu@yandex.ru

Abstract. The article presents the results of high-speed spectral measurements of the emission spectrum of plasma-vortex formations formed by an atmospheric pulsed plasma torch based on an electrical explosion of a conductor. Spectrum registration is carried out in the stage of autonomous existence of vortex formations. It is shown that the emission spectrum contains the Planck continuum, due to the presence of condensed oxides, and the molecular bands of AlO. Based on the obtained data, the dependence of the temperature dynamics over time was obtained by the method of spectral pyrometry.

1. Introduction
Pulsed injection of supersonic plasma jets in atmospheric pressure air leads to the formation of various hydrodynamic structures [1–7]. In studies [3–7], the plasma jet was transformed into long-lived plasma-vortex formations. The radiation time of such structures significantly exceeds the energy deposition time. A hypothetical formation mechanism of these rings is considered in the paper [3]. The formation process of vortex rings consists of shock-wave braking, the formation of a rarefaction zone, reverse flow and circulation. An autonomous plasma vortex is formed at the end of the plasma jet outflow.

Most studies are aimed at investigation of the dynamics of vortex structures for various parameters of the plasma jet. It is obvious that the characteristics of such vortex formations depend on the initial characteristics and the material of the plasma jet. The vortex structures formed during the injection of electrothermal plasma of metals are of particular interest to solve practical problems. In particular, plasma vortex formations are considered in [3, 4] as highly efficient sources of optical radiation. Relaxing plasma jet in this case is a highly active environment in which there is an active involvement of atmospheric air and initiated chemical reactions [8]. Experimental study of such reactive vortex flows is difficult in view of their spatial and temporal nonstationary and the multifactor nature of the processes occurring in them.

This work is devoted to high-speed optical spectroscopy of plasma vortex formations at the stage of their autonomous afterglow, in order to study the processes occurring in them and determine their temperature characteristics.

2. Experimental
For injection of a plasma jet into the air, a pulsed plasma torch based on a localized electrical explosion of the conductor was used. The plasma generator (figure 1a) consists of a polyvinyl chloride
(PVC) channel (diameter 10 mm, length 35 mm) and two electrodes, one of which is made in the form of a nozzle through which a plasma jet flows. The dielectric channel on the outside is reinforced with a metal shell. Before each experiment, a metal cylindrical foil is installed in the channel for connecting the electrodes. In this series of experiments, aluminum was used as a plasma-forming metal.

The plasma torch is powered by a pulse capacitive storage $C_0 = 330 \ \mu F$ (figure 1b). The operating voltage of the battery is 2.5–4.5 kV. The initiation of the discharge occurs when a high-voltage pulse is fed into the electrode gap of the trigatron.

A pulsed jet is formed when the foil installed in the channel is the electric exploded. The discharge current is a damped sinusoid consisting of two half-waves (damping ratio 0.37, oscillation period 110 $\mu$s). The mass of the foil and the charging voltage are chosen so that the electric explosion occurs at the maximum of the first half-wave of the current [9]. The characteristic value of the peak electrical power at the time of the electric explosion, with a foil mass of 120 mg and the charging voltage of 4.0 kV, is 75 MW. The dynamics of the flow and formed toroidal vortex structures were recorded using a high-speed digital video camera Videosprint. Solar S100 spectrometer (spectral range 200–1000 nm, spectral resolution 1.0 nm) was used to study the spectral characteristics. The optical fiber of the spectrometer was located perpendicular to the axis of the outflow at a distance of 350 cm from the cutoff plane of the generator nozzle. The registration of the spectra was performed frame by frame with a frequency of 1400 fps, the exposure times of each frame were 18–40 $\mu$s. The recording equipment was launched at the moment of discharge initiation, using the synchronization system.

![Figure 1. Experimental setup. a – pulse generator; b – scheme of the experimental stand.](image)

3. Results

To ensure a strong contrast of the image was used a mode in which the overexposed pixels of the camera matrix begins to reset the excess charge. In this case, the brightness inversion occurs on the frame. This feature of the camera allows to visualize the vortex structure. Figure 2 shows frames of the process of outflow and the formation of vortex plasma.

![Figure 2. Frames of the process of plasma vortex formation (frame width – 300 mm).](image)
The first frame shows an extended plasma jet. With further movement there is an increase in the radial size, the expansion of the plasma jet. On the frame corresponding to 4 ms, the structure of a stream consisting of a vortex core and its surrounding atmosphere is clearly manifested. The form of formation is close to spherical. In the process of further movement, the vortex formation begins to acquire the shape of an ellipsoid that is flattened in the direction of move. When moving to the vortex core, atmospheric air is actively involved in the vortex sheet, and by 8 ms the brightness of the vortex sheet drops significantly and most of the substance in it and its displacement downstream.

The recorded spatial-integrated spectra of an autonomous toroidal plasma-vortex formation are shown in figure 3.

![Figure 3. The emission spectrum of plasma vortex ring.](image)

The spectrum of the plasma vortex ring is represented mainly by the Planck continuum, due to the condensed particles, produced by electrical explosion [10, 11]. The spectrum contains the line of the aluminum atom (394.4 nm and 396.2 nm), and the molecular bands of AlO (transition B^2Σ⁺ → X^2Σ⁺) located in the region 450–550 nm. The character of the spectrum is maintained in time until the end of registration.

The presence of condensed particles in the spectrum of the thermal continuum makes it possible to determine the temperature using the spectral pyrometry method. The essence of the method consists in rebuilding the recorded spectrum in Wien coordinates (temperature coordinates), in which the black body spectrum has the form of a straight line [12]. The radiation of plasma formation is,

\[ B_\lambda (\lambda, T) = \frac{\varepsilon(\lambda, T) \cdot C_1}{\pi \cdot \lambda^2} \cdot \left[ \exp \left( \frac{C_2}{\lambda \cdot T} \right) - 1 \right]^{-1}, \]

where \( \varepsilon(\lambda, T) \) is the spectral emissivity; \( C_1 \) and \( C_2 \) are the first and second radiation constants; \( \lambda \) is the wavelength; \( T \) is the real temperature.
For the case of \( \exp(C_2/\lambda T) >> 1 \) (Wine region), with both parts logarithmized and transformed, the expression takes the form

\[
\ln \left( \frac{B_2(\lambda, T) \cdot \lambda^2}{\varepsilon(\lambda, T)} \right) = \text{const} - \frac{1}{T} \cdot \frac{C_2}{\lambda}.
\]

If the emissivity \( \varepsilon(\lambda, T) \) in a certain region of the spectrum is constantly or weakly depends on the wavelength, which is typical for most metals and their oxides, then the spectrum takes the form of a straight line. The temperature is determined by the cotangent of the tilt angle of the linear sections.

Determination of temperatures for which the black body profiles are plotted in the figure was carried out on the spectral range of 555–1000 nm, in which there were no molecular bands. Note that the spectral profiles of the black body also fit the shortwave region of the spectrum (300–400 nm). Figure 4 shows the temperature dependence of the plasma-vortex formation on time.

![Figure 4. The dependence of the temperature of the plasma-vortex formation on time.](image)

As can be seen from the presented dependence, the temperature of the plasma-vortex formations lies in the range from 3200–3520 K and changes little in time. According to the data [13], the boiling point of aluminum and its oxide (Al\(_2\)O\(_3\)) is 2790 and 4000 K. That is, aluminum is in a gaseous state, as evidenced by the presence of a weak line in the recorded spectrum. The boiling point of the oxide is 4000 K, which is higher than the recorded temperature level.

4. Conclusions
In this work, an optical study of plasma vortex rings in atmospheric air was carried out. For this, high-speed spectral recording was used. The emission spectrum of the vortex formation is represented by the Planck continuum, against which there are atomic aluminum lines and AlO molecular bands. The continuum is due to the presence of condensed oxides in the vortex flow. A good coincidence of the spectrum with the black body curve in the wavelength range of 555–1000 nm indicates that the vortex formation is a gray body. The temperature of the plasma vortex formation varies slightly in time from 3520 to 3200 K.

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