Three-color pyrometry study of radiation and gas dynamic processes in a heterogeneous plasma-vortex ring

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Abstract. The paper presents the results of a study of a heterogeneous plasma vortex ring using the three-color image pyrometry technique. The vortex ring is formed during deceleration of a supersonic pulsed aluminum plasma jet in atmospheric air. A technique for calibrating a digital camera and a post-processing process for images are proposed that makes it possible to visualize the internal structure of the vortex. As a result of the study, the effect of vortex separation of condensed and gas flow components was experimentally demonstrated.

1. Introduction

It was reported on the design of a new type of pulsed sources of high-power broadband radiation with a high efficiency of converting stored energy into radiation [1-3]. The sources are based on the pulsed supersonic plasma jet generation and its transformation into a large-scale plasma-vortex formation with an afterglow time that is orders of magnitude greater than the energy deposition time. The use of active metals as plasma-forming material leads to combustion reactions intensification in the vortex volume with atmospheric air [1]. Despite a number of studies, the plasma vortex formation is a relatively poorly understood form of a highly turbulent vortex flow [4-6]. To optimize the characteristics of the radiation sources, it is necessary to conduct a number of fundamental research aimed at studying the physical processes occurring in the plasma formations.

In previous studies [7, 8], the radiation spectrum of a plasma vortex was recorded and the effect of partial optical transparency of the radiation emerging from its volume was discovered. This work is a continuation of research and is aimed at studying the radiation-gas dynamic processes occurring in a plasma-vortex formation in various spectral ranges using the three-color image pyrometry method.

Three-color pyrometry is widely used to study the temperature fields of various heated objects, including high-speed radiating flows [9-12]. The traditional technique makes it possible to determine the color temperature using various spectral channels. As a rule, closely spaced and free from the molecular bands and atomic lines spectral ranges are used. In this study we deliberately register both molecular and gray condensed phase radiation emitted from the optically transparent volume to visualize transport processes in a plasma vortex ring.

2. Experimental

2.1. Digital camera calibration

The image pyrometry system was build using Canon 550D digital camera with CMOS sensor. The main camera features that make it possible to use it for scientific research are 14-bit ADC and possibility to...
recording RAW image [12]. Additionally, the camera could be launched from an external triggering device. It is extremely important to have the accurate camera channel’s spectral sensitivity for pyrometric measurements, so an experimental set-up for its measurement was assembled (figure 1).

**Figure 1.** Experimental set-up for measurement spectral sensitivity of digital camera: (a) apparatus; (b) images of the exit window at various positions of the diffraction grating.

Set-up included DSF-452 spectrograph, Solar S100 spectrometers, and SI 10-300 tungsten ribbon filament lamp as a broadband radiation source. The lamp (1) was located in front of the entrance slit of the DFS-452 spectrograph (2), and an emission spectrum (4) was observed in the output window of the spectrograph (3). A camera (5) was installed in front of the output of the spectrograph and shoot the spectrum (figure 1b) through a narrow split (6) in a Plexiglas plate installed on the DFS-452 output unit. Images were saved in the RAW format. Optical fiber (7) of the Solar S100 spectrometer (8) with flat-field correction was fixed under the split (9), and made it possible to control the current relative intensity and wavelength.

The emission spectrum in split (6) was changed by rotating the diffraction grating in the DFS-452 and was performed in 5 nm step by rotating the grating. A series of recorded images was decoded using the Dcraw [13], resulting in the formation of spatial arrays of 14-bit frame brightness values. Spectral frames for different camera channels (R, G, B) were analyzed in the Matlab R2020b. The resulting spectral sensitivity of the Canon 550D RGB-channels are shown in figure 2a. Additionally, it was found that the output signal from the pixels depends linearly on the exposure value (figure 2b).

**Figure 2.** Characteristics of a digital camera Canon 550D:
(a) spectral sensitivity of RGB channels; (b) digital output vs. exposition time
An Ocean Optics DH-3 CAL calibration source with known spectral and energy characteristics was used as a spectral brightness standard. As a result, the calibration coefficients of the camera RGB channels were found, which make it possible to convert a digital signal from pixels into absolute values of the spectral brightness.

2.2. Image post-processing

Recent high-speed optical emission study of plasma vortex rings has shown that the emission spectrum of the vortex ring is maintained in time, and condensed Al₂O₃ particles are a gray body emitter [7]. Figure 3 shows the characteristic emission spectrum of a vortex ring and the channels spectral sensitivities of Canon 550D digital camera.

Figure 3. Typical emission spectrum of plasma vortex ring and RGB spectral sensitivity of Canon 550D.

The figure shows the spectral brightness corresponding to the various flow components such as Al₂O₃ and gas phase monoxide AlO. The total brightness recorded by the B-channel corresponds to the radiation of the condensed and gaseous phases:

\[ B_B = B_{\text{Al}_2\text{O}_3} + B_{\text{AlO}}, \]

where \( B_{\text{Al}_2\text{O}_3} \) and \( B_{\text{AlO}} \) are average spectral brightness of Al₂O₃ and AlO in the channel B band (\( \lambda_B = 450 \text{ nm, } \Delta \lambda_{0.5} = 85 \text{ nm} \)).

The brightness of the long-wavelength R-channel (\( \lambda_R = 600 \text{ nm, } \Delta \lambda_{0.5} = 75 \text{ nm} \)) is due to the emission of only condensed gray body Al₂O₃:

\[ B_R = B_{\text{Al}_2\text{O}_3}. \]

In study it was shown that the molecular bands emission has a high optical density [8]. In this regard, the total spectral brightness of channel B is close to the brightness of the blackbody. This allows us to estimate the thermodynamic temperature by

\[ T \approx \frac{C_2}{\lambda_B} \left( \ln \left( \frac{C_1}{\lambda_B^3 \cdot B_B} + 1 \right) \right)^{-1}, \]

where \( C_1 \) and \( C_2 \) are the first and second radiation constants.

Note that the brightness in different spectral ranges and temperature are functions of the coordinates \((r, z)\) in the frame plane. The spectral brightness of Al₂O₃ and AlO can be determined from measurements of the long-wavelength channel R using the ratio for gray body:

\[ B_R(\text{Al}_2\text{O}_3) = B_B(\text{Al}_2\text{O}_3) \left( \frac{\lambda_B}{\lambda_R} \right)^3 \frac{\exp\left[ C_2 / (\lambda_B T) \right] - 1}{\exp\left[ C_2 / (\lambda_R T) \right] - 1}, \]

\[ B_R(\text{AlO}) = B_R - B_R(\text{Al}_2\text{O}_3). \]
2.3. Experimental details – vortex ring imaging

The experimental setup for producing plasma vortex rings and visualization its structures is shown in figure 4. A pulsed electrical explosion plasma generator was used to inject a plasma jet in atmospheric air. The design of the generator is described in detail in [14]. We used aluminum foil as plasma forming material. The generator was powered by a capacitor bank \( (U_0 = 3.9 \text{ kV}, W_0 = 2.5 \text{ kJ}) \).

![Scheme of the experimental stand.](image)

The discharge was switched by a trigatron by applying a high-voltage pulse from the initiation unit. The delay time between the start signal and the initiation was no more than 1 \( \mu \text{s} \). The discharge current is a damped sinusoid consisting of two half-waves (the quasi-half-period is \(~ 50 \mu \text{s}\)). The maximum current is reached by \(~ 28 \mu \text{s} \) and is equal to 60 kA.

Canon 550D has a trig delay \( \tau_{\text{del}} \) (jitter), that varies from 70 to 200 ms. The lifetime of the vortex ring is several ms, so a synchronization system was used. Synchronization of processes was carried out using a pulse generator assembled on the basis of Arduino Uno.

Arduino generated a trigger signal on the Canon 550D, and after a jitter time \( \tau_{\text{del}} \), a frame exposure started \( (t_{\text{exp}} = 250 \mu \text{s}) \). Programming the delay between camera launches and generator initiation made it possible to register various stages of the evolution of the plasma formation.

3. Results and discussion

Figure 5 shows the brightness temperature fields of the vortex formation in different spectral ranges for the moment of time corresponding to the maximum radiation power \( (~1.3 \text{ ms}) \).

![Distributions of plasma-vortex structure brightness temperatures in different spectral regions.](image)

Figure 5. Distributions of plasma-vortex structure brightness temperatures in different spectral regions: (a) \( \lambda_B = 450 \text{ nm}, \Delta \lambda_{0.5} = 85 \text{ nm} \); (b) \( \lambda_G = 530 \text{ nm}; \Delta \lambda_{0.5} = 95 \text{ nm} \); (c) \( \lambda_R = 600 \text{ nm}; \Delta \lambda_{0.5} = 75 \text{ nm} \).
The profiles of the brightness fields in different spectral ranges are significantly different, structurally inhomogeneous, with several brightness extrema, which is due to the complex gas-dynamic structure of the flow.

The maximum brightness temperatures are reached in the vortex tail and, depending on the spectral range, are 2700-3250 K with maximum values in the blue region of the spectrum. The brightness temperatures maps recorded by the spectral channels B and R, a vortex structure with maximum temperatures of ~3100–3250 K is clearly visualized. According to estimates made using the B channel image, vortex core occupies ~1/3 of the volume of the surrounding vortex atmosphere. It should be noted that in some measurements we have observed temperatures in the vortex core reaching values close to the temperatures of stoichiometric aluminum combustion ~ 3350–3400 K.

Figure 6 shows the brightness distributions of AlO and Al$_2$O$_3$ condensed phase for spectral channels B ($\lambda_B$=450 nm) and R ($\lambda_R$=600 nm). The non-linear dependence of the brightness on temperature and optical density does not allow one to directly correlate it with the concentrations of emitting particles. However, as analysis of the brightness distribution of various flow components shows, a significant part of AlO gas-phase monoxides is localized in the vortex core. The radial brightness distribution of AlO is similar to previously demonstrated in [8] and corresponds to the emission of a partially transparent vortex ring. The brightness distribution of Al$_2$O$_3$ is close to hyperbolic and is due to the radiative transfer of radiation in the spherical volume of the vortex atmosphere. Relatively weak brightness extrema observed against the background of a quasi-hyperbolic distribution (figures 6b) indicates the presence of a small amount of condensed phase in the vortex core.

![Figure 6. Spectral brightness distributions for $\lambda_B$=450 nm (top) and $\lambda_R$=600 nm (bottom): (a) two-dimensional field; (b) radial - along cross-section I; (c) axial - along cross-section II.](image-url)
The reason for the structural inhomogeneities of radiation is probably the feature of turbulent vortex rings to hold the initial material of the plasma jet in vortex core. The observed effect was demonstrated for vortices in a chemically active environment [15-17].

The aluminum is held in the vortex core and reacts with atmospheric air, so high-temperature products of various phase compositions are produced. Emission AlO oxides, due to the anisotropy of diffusion across the vortex line (the effect described in [18]), are localized in the core. Condensed Al$_2$O$_3$ macroparticles leave the core under conditions of vortex motion, fill the vortex atmosphere, and subsequently being forced out into the vortex wake.

4. Conclusions

A digital camera and a three-color pyrometry technique have been applied to investigate the heterogeneous plasma vortex ring. Image post-processing algorithm has successfully been applied to visualize internal vortex structures. It has been established that the vortex core is characterized by a high concentration of optically dense gas-phase AlO oxides. The temperature level reached in the vortex core is 2700-3250 K. The vortex atmosphere consists of a low-temperature condensed Al$_2$O$_3$ phase, which leaves the vortex core due to vortex motion.

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