Anomalous high-velocity outbursts ejected from the surface of tungsten microdroplets in a flow of argon-air plasma

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Abstract. For the first time, a phenomenon of high-velocity outbursts ejected from the surface of liquid tungsten microparticles in a flow of argon-air plasma under atmospheric pressure was observed. As tungsten particles sized 50 to 200 µm moved in a plasma flow, stratified radiating spheres up to 9 mm in diameter formed around such particles. The spheres were sources of high-velocity outbursts whose ejection direction coincided with the direction of the plasma flow. The velocity of the anomalous outbursts amounted to 3-20 km/s. In the outburst images, the distribution of glow intensity along outburst tracks exhibited a wavy decaying behavior with a wavelength of 5-15 mm. Possible physical factors that could be the cause of the phenomenon are discussed.

1. Introduction
The phenomenon of high-velocity discharges was first observed in our experiments aimed at the study of the formation and fractionation process of melt droplets, and at the measurement of the velocity and temperature of such droplets during a plasma-arc wire spraying process implemented for depositing coatings on a Plazer 30-PL-W spraying facility [1-3]. A specific feature of the method was using, as the spray material, a conducting wire fed into the plasma flow behind the exit plane of the plasma-gun double nozzle; this wire simultaneously served the function of the electric-arc anode. Thus, in the experiments, completely melted spray particles came off from the wire end into the plasma flow. The optical study was performed using an original spectral-brightness pyrometry diagnostics facility developed by researchers from Ugra State University (Khanty-Mansiysk) and Institute of Theoretical and Applied Mechanics SB RAS (Novosibirsk) [3-5]. The latter system comprised a digital video camera, which registered images of individual spray particles in the form of particle tracks, and a visible range spectrometer, which registered the integral optical emission spectrum of the two-phase jet.

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2. Experimental

In our experiments, spraying of steel and tungsten wires 1.6 to 2 mm in diameter was performed. A detailed description of the operating conditions of the spray facility was given elsewhere [2, 3]. According to our estimates, the mass-mean temperature of the argon plasma was about 13 thousand degrees, and the velocity of the plasma-torch flow was greater than 2.5 km/s. The diagnostic system included an HD1-1312 (Photon Focus AG) video camera, which was equipped with a 1312x1082 CMOS photosensor, and an LR-T1 (Aseq Instruments) photospectrometer, with spectral range 300-1000 nm. The optical path of the video camera contained a bandpass optical filter with central wavelength 575 nm (FWHM 40 nm). The frames were registered at a rate of 55 fps. The objective lens of the video camera provided for a filming spatial scale of 51.9 µm/pixel. The focal plane of the video-camera optical system was coincident with that of the photospectrometer optical system. The region in which the measurements on the spectrophotometer were conducted was a 10-mm diameter circle located at the center of the camera frame.

A typical frame taken from the two-phase flow during the spraying of steel wire is shown in Fig. 1a. In the right-hand side of the frame, a bright optical emission due to the electric arc and due to the most heated region of the plasma is observed. Individual spray droplets had sizes ranging from 50 to 200 µm, and they formed tracks several millimeters long. Typical velocities of such droplets were 40-80 m/s. A similar pattern of a two-phase jet was also observed during the plasma spraying of other materials (alloys of the NiAl, NiCrBSi and NiCoCrAlY systems, ZrO$_2$ and Al$_2$O$_3$ oxides, and others) [3-6].

![Fig. 1. Images of a two-phase plasma jet seeded with melted spray droplets: a – steel, b – tungsten. The exposure time of the frames is 30 µs (left frame) and 10 µs (right frame).](image)

In the registered images of the two-phase plasma jet with moving tungsten droplets (see Fig. 1, b), two new phenomena were observed: (i) appearance of bright tracks crossing the entire frame in the direction of the plasma jet; 2) formation of bright luminous regions, shaped as spheres, around some of the tungsten droplets. In the registration of the jet with tungsten droplets the frame format was 800x800 pixel (the physical size of the observation region was 42x42 mm), and the exposure time was 10 µs. Thus, the velocity of an object that traversed the observation region in the exposure time exceeded 4.2 km/s (42 mm / 10 µs). Below, we give a description of observed phenomena and an analysis of their assumed nature.

3. Results

Numerous registered frames provide confirmation to the fact that the sources of the high-velocity outbursts were melted spray particles that moved in the plasma jet. For instance, a bright luminous region 1-2 mm in size is observed around such particles in Fig. 2. Simultaneously, the frame involves ordinary particle tracks about 100 µm wide and 0.5-1 mm long. Interestingly, all the high-velocity outbursts are directed along the direction of the local motion of plasma in the two-phase jet. A study of the integral emission spectrum of the jets revealed no additional bands or lines in experiments with tungsten in the working spectral region of the video system, 555 to 595 nm. Besides, from the continuous portion of the emission spectrum, 520 to 650 nm, dispersed-phase temperatures in the jet section located 9 cm downstream from the nozzle exit were determined by the spectral pyrometry method [7, 8]; for the flows with steel and tungsten droplets, those temperatures proved to be
respectively 2730-3090 K and 3650-3890 K. The recorded frames show that, in this spectral region, the optical emission due to plasma is insignificant, and the measured temperatures can therefore be assumed to refer to the hottest dispersed-phase particles.

Consider in more detail an individual particle with a high-velocity outburst (Fig. 3). A region sized approximately 1.5 mm in immediate vicinity of the particle is occupied by the radiation which was most likely emitted by the brightest part of the gas discharge. Around the particle, a series of nearly spherical luminous contours about 2 mm, 4 mm, 6 mm, and 9 mm in diameter is observed; with increasing contour diameter, the contour brightness decreases in value while the contour center gets displaced toward the external region of the plasma flow (in Fig. 3, in upward direction).

As it is seen in all the images of the completely registered high-velocity outbursts, the track ends of these outbursts are all linearly skewed (see Fig. 3, a). The latter regularity can be explained by the operating algorithm of the CMOS photosensor, which accumulates photosignal even during period when a charge is being stored in the FD (floating-diffusion) zone waiting for read out [9]. In fact, the charge accumulation times in neighbor rows were different, and this circumstance enables the determination of the velocity of the moving objects in the frames from the inclination of their cross-sections. The clock frequency of the A1312 photodetector (Photon Focus AG) was 40 MHz; hence, the readout times for the signals in neighbor rows differed by \( \tau = 25 \text{ ns} \). A schematic representation of a raster image of the track end of an outburst is shown in Fig. 3, b with the aim of introducing designations for the track tip length, \( N_x \), and for the track tip width, \( N_y \) (both quantities are measured in pixels). The velocity of an outburst can be calculated by the formula \( V = (s \cdot N_x) / (\tau \cdot N_y) \), where \( s \) is the image spatial scale. For the track in Fig. 3a, the calculation performed using values \( N_x = 52 \), \( s = 51.9 \mu m \), \( \tau = 25 \text{ ns} \) yields for the outburst velocity a value of \( V = 6350 \text{ m/s} \). Taking into account the fact that the length of the entire track is 22 mm, it can be argued that the frame in Fig. 3a was registered 3.5 \( \mu s \) after the outburst was formed. The calculated velocities of all other measured tracks predominantly fall into the range from 3 to 10 km/s, the maximum values reaching 20 km/s. It is worth noting that the obtained values well agree with the lower estimate for velocity 4.2 km/s.

Figure 4 (left) shows images of a several tracks of high-velocity outbursts; in particular, the upper track is the track shown in Fig. 3a. Evidently, the track widths of the various high-velocity outbursts range from 0.2 to 1 mm. Also, Fig. 7 (right) shows the distribution of brightness along the tracks. It is significant that the track brightness varies along the track length, and it exhibits a wave pattern. The wavelength of the waves varies from one track to another, and it falls into the range from 5 to 15 mm, the wavelength of the individual tracks increasing in magnitude with distance from the parent particle. In the upper graph of Fig. 4, a sawtooth structure with a period of 1-1.2 mm is seen. On close inspection, such a structure with a characteristic size of 4-5 mm can also be seen on the middle graph.
Consider spherical discharges around tungsten particles which present sources of the high-velocity outbursts. Figure 5 shows, to identical scale, images of 17 different independent discharges. We assume that the various sizes (ranging from 1 to 10 mm) of the luminous regions in those images refer to various stages of their expansion process. It is seen that, irrespective of its size, a luminous region has a stratified structure that involves a series of bright rings. A high-velocity outburst arises after, in the expansion process, the spherical region reaches a size of 8-10 mm, the outburst always being ejected in the plasma flow direction (in the frames, from right to left).

Fig. 4. Images of individual tracks of high-velocity outbursts (left) and the distribution of luminosity along the tracks (right).

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Fig. 5. Images of electric discharges in the plasma jet. The individual images are independent fragments taken from different frames; these images therefore bear no relation to each other.
4. Discussion
As it was noted above, the mechanism underlying the observed phenomenon still remains unclear. However, the obtained experimental data suggest that, in our experiments, we observed electric gas discharges followed by directed ejection of charged particles (electrons). Apparently, for realization of gas discharges, the formation of regions with strong electric fields is necessary. Under conditions of a dispersed plasma flow, such regions may arise due to the thermoionic emission of electrons from the surface of metal particles. As a result, a spray particle acquires a positive charge while the electron cloud around the particle turns out to be charged negatively. The occurrence of the observed phenomenon in the experiments with tungsten droplets can be explained by the high melting temperature of tungsten. Indeed, according to the Richardson-Dushman law, the thermoionic emission of electrons from the surface of melted W, Ta and Mo heated to a high temperature is 2-4 orders of magnitude more intense in comparison with the group of Cr, Fe, Co and Ni metals [10].

The nature of the stratified structure of the luminous spheres is probably similar to the nature of the alternating bright and dark regions in the near-cathode zones of glow discharges [11]. For instance, O.A. Nerushhev et al. [12] examined, under laboratory conditions, a steady stratified spherical glow discharge 5-10 cm in diameter that burned in rarefied atmosphere of molecular gases with an admixture of high-molecular substances. The factors that cause the occurrence of directed high-velocity outbursts still remain unclear; however, it can be hypothesized that those factors are most probably related with the electron motion.

5. Conclusions
A new phenomenon was observed while studying the interaction of melted tungsten droplets with low-temperature argon-air plasma using an optical system based on a digital video camera. Around each of the metal particles, whose sizes ranged from 50 to 200 µm, there formed a spherical luminous region sized up to a few millimeters; this region exhibited a stratified structure. After the expansion of such a sphere to a size of 8-10 mm, there occurred an outburst of spray material from the surface of the metal particle in the direction of the plasma flow. The velocity of the outbursts amounted to 3-20 km/s, and the radiation intensity in the outburst wakes exhibited a wavy behavior.

We relate the observed phenomenon to the high rate of the thermoionic emission of electrons from the surface of liquid tungsten particles and to the formation of a space-charge region around such particles. The discovered phenomenon calls for further study; we believe that, as a result of such a study, the exact nature of the phenomenon will be established.

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