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Distribution of brightness, temperature and radiation force in multizone pyrotechnical flare

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Processing of pyrotechnic composition flare image by developed software allows you to select the shape and dimensions of the shining body of the flare, divide it into zones according to the brightness level, determine the temperature and radiation force of each isolated zone. The temperature of the flare zone was determined by comparing the brightness of the flare zones with the brightness of a known object. In the work shown, the maximum of the temperature in the flare reaches 2523 K, and the radiation force in the visible spectrum is 442 W/sr.

Keywords: pyrotechnic composition, flare, zone, brightness, temperature, radiation force, luminous body.

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Introduction

The flare of the pyrotechnic composition is a high-temperature two-phase reacting stream. Starting from the reaction surface of the condensed phase, the parameters of the two-phase flow change. Dispersed particles, whose concentration in the flare is high, react both with the gas component of the flow and with components containing fuel and oxidizer. Combustion in a flare is accompanied by radiation in different spectral ranges. Registering instruments record the radiation energy in a narrow spectral range. The radiation of the dispersed phase obeys the laws of thermal radiation with emissivity close to unity [1].

The flare radiation has a pronounced brightness inhomogeneity. Radiation intensity dI_i of the flare region depends on its brightness L and the area of region dS:

$$dI_i = \int_S L_i dS.$$

Brightness L, in turn, depends on temperature T, emissivity factor ε and obeys the Stefan–Boltzmann law for gray bodies. To determine the radiation strength of the flare, it is necessary to carry out integration over all flare regions. However, there is still no information in the literature about the temperature of a pyrotechnic flare, and the experimental method is practically the only solution to the problem of the power of studying such objects.

There are different points of view on the issue of the structure of the flare of the pyrotechnic composition. Zaripov [2] based on the analysis of the interference patterns of combustion comes to the conclusion that there is a combustion region in the pyrotechnic flare due to the oxygen of the environment. According to Zaripov, air diffuses into the flare along its entire length. It begins at the cut end surface of the burning sample, and at some distance from the cut, the surrounding air already reaches the center of the flare. The section from the reaction layer of the condensed phase near the surface to the point at which the surrounding air reaches the center of the flare, Zaripov proposed to call as the core. Then it turns out that the core, which makes the greatest contribution to the radiation of the flare, is formed only due to the initial components of the combustible mixture, and air does not take part in this process. With this approach, it is difficult to explain that heterogeneous systems with fuel overload in the original system have the highest brightness and radiation intensity. Usmanov [2] considers a flare as a certain volume of aerosol, where heterogeneous combustion processes take place. He pays special attention to the modes of the outflow of combustion products and believes that there must be a turbulent section in the flare. According to Usmanov, the presence of laminar jets at the base of the flare indicates that the dispersion of the condensed phase substance is not carried out immediately from the entire surface. The contact of the jets with subsequent merging during their expansion at a certain height from the surface leads to turbulization of the flow. Usmanov did not consider the issue of air penetration into the flare, but emphasized that a special combustion mechanism is possible in the torch, which consists in the independent combustion of individual elementary volumes of the combustible mixture. He believes that the combustion of metal particles proceeds throughout the entire volume of the flare, but then it is difficult to explain the fact that in most compositions the brightness of the flare has a maximum at the combustion surface and rapidly decreases along the height of the flare. He also believes that since there is no unambiguous definition of the flare structure today, it is important to consider the role of each region in the combustion and radiation processes.

When determining the temperature of a two-phase system in which intense chemical reactions take place, two fundamentally different methods are used: the probe method and the photopyrometry method. Under conditions of two-phase flows, thermocouple sounding has a number of disadvantages [3]. First of all, being a contact method for determining temperature, probe thermometry introduces an undesirable effect on the system under study. Typically, a thermocouple introduces aerodynamic, thermal, and chemical perturbations. The influence of the thermocouple can be reduced by reducing the junction size. But at the same time, the temperature resistance of the probe in high-temperature flows decreases and the area probed by the thermocouple decreases. Note that this method is used to record the local temperature and to obtain the temperature field of the object under study, it is necessary to use a survey rake, and this leads to a complication of the measurement system and an increase in the error of the method.

These considerations predetermined the intensive development of photopyrometry methods, which consist in recording the electromagnetic radiation of combustion products in the visible, ultraviolet, and infrared parts of the spectrum. Back in the 60s of the last century, various methods of photo-pyrometry were proposed, which are successfully used to study various phenomena in a gas flare and in plasma [4,5]. An analysis of these methods shows that they are of little utility for studying the processes occurring in modern pyrotechnic compositions. In the flare of such subjects there are a large number of metal particles in the solid and liquid phases, introduced to increase the brightness of the radiation of the flare, there are intermediate products of their combustion. However, many phenomena occurring in the flare, as mentioned above, have been little studied. To create physical models of the processes occurring in the flare of pyrotechnic compositions and to create samples with optimal properties, for example, having the maximum brightness of the flare, it is important to develop new pyrometry techniques based, in particular, on the capabilities of modern television and computer technology.

In present publication, the first step has been taken towards the development of a technique that allows one to determine the flare parameters necessary to create a physical model of a pyrotechnic flare. In the work, an optical-television device was used, specially designed to study the parameters of a structurally inhomogeneous flare of new pyrotechnic compositions. The purpose of the work was to debug the technique and software for finding the exact boundary of the flare, taking into account the inhomogeneity in the distribution of the brightness of its glow, determining the temperature field, the region of maximum glow and the total strength of the flare radiation.

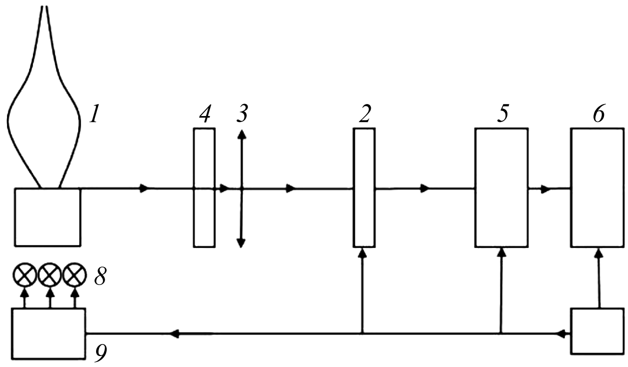

Figure 1. Experimental unit block diagram.

Study subject, experimental technique and methodology

The study subject was a pyrotechnic composition based on Magnesium powder, an inorganic oxidizer and an aromatic Hydrocarbon fuel. The mixed mixture of powders of the composition was pressed into a cardboard shell with an inner diameter of 20 mm at a specific pressure of 1500 kgf/cm^2. The samples were burned under room conditions.

The block diagram of the experimental unit is presented in Fig. 1. The image of the flare (*1*) was formed using the „Industar-50"̃(*3*) lens on the CCD matrix of a PIC-741 (*2* video camera). The image obtained with the help of peripheral devices (*5*) was entered into the computer (*6*) and stored in memory as a separate file in bmp format. The frame also contained images of spirals of several halogen lamps (*8*) of the KGM-150 type. The lamps were powered by a stabilized power supply (*9*). A certain voltage was applied to each lamp, as a result of which the spirals of the lamps had different brightness and temperature. The unit was powered from a common power supply (*7*). Placement of various light filters (*4*) in front of the camera lens made it possible to study objects in different spectral ranges, ranging from ultraviolet (300 nm) to near infrared (1100 nm) spectral range. The shooting speed of the video camera was 25 fps. The duration of registration was limited by the amount of hard disk memory.

Using the original software, the image was divided into separate lines and elements in lines i.e. pixels. Each pixel in a black & white image had 256 brightness levels. To use a digital image as a means of determining the photometric characteristics of an optical image, it is necessary to establish a correspondence between the illumination in the optical image and the digital values of the signals in the electronic image. This dependence is expressed by a linear section of the characteristic curve [6]. The use of light filters

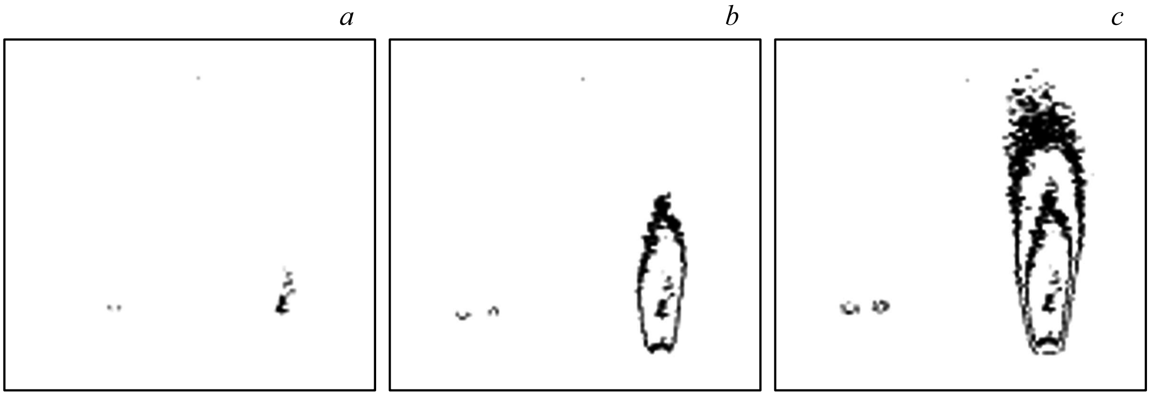

Figure 2. Isophote family. Brightness levels (in arb. units): (*a*) 128, (*b*) 102, (*c*) 76. The image of the comparison object is to the left of the flare.

for different optical density and aperture of the lens allows one to fit into the linear section of this characteristic curve.

The software used electronic filters, which, running through the lines of the image, digitized the image in a new way, increasing its contrast [7]. The boundaries of the flare are determined by the same electronic filter. If in successive five pixels the brightness gradient turned out to be positive $(dL/dx > 0)$, then the first pixel was the boundary of the flare. Borders were defined on the left and right sides of the image. Resulting array of flare boundaries makes it the possible to calculate its visible area:

$$S = \int_0^{h_{\max}} D dh,$$

where $D = x_2 - x_1$ is diameter of the flame in the selected line, x_1 and x_2 are coordinates flare boundaries. The height integration boundaries were set in the program from the flare base, and the value of $h_{\max}$ was chosen from the condition $L = \overline{L}_f$ at the maximum height, where $\overline{L}_f$ is brightness of the image background.

Assuming that the flare is an axisymmetric object, one can calculate its volume:

$$V = \frac{\pi}{4} \int_0^{max} D^2 dh.$$

In this case, the volume of the flare is the sum of the volumes of disks with a height of one pixel and a diameter equal to the diameter of the flare.

Next, the flare image brightness distribution array is processed in the Maple mathematical environment. The software allows one to extract 2D from the 3D brightness distribution, which represent the dependencies $L(x)_y$ or $L(y)_x$ along the *ox* or *oy* axes, respectively, for given values coordinates y or x. In addition, it is possible to select pixels with the same brightness value, the sequence of which is a line i.e. isophote. The operator can select lines with a certain brightness value L_i. The family of isophotes divides the flare into regions according to the level of brightness.

It was believed that if a pyrotechnic flare has sharp optical inhomogeneities, then the region bounded by isophotes with brightnesses L_i and L_{i+1} has certain optical properties. The selected zone was assigned an average brightness:

$$\overline{L} = \frac{L_i + L_{i+1}}{2}.$$

Certain difficulties arise in determining the absolute brightness of a region in the course of measurements and processing the results. For this reason, calibration in the measurements was carried out by comparing the brightness of the flare region with the brightness of a known object, the temperature of which was determined in advance. When photographing a flare, an object with known emissivity and temperature was placed in the frame. The coil of a KGM-150 halogen lamp served as such an object. The temperature of the coil at a fixed filament current was measured with a brightness pyrometer „Promin?". Having several lamps with different filament currents, it is possible to obtain several objects of comparison with a different set of temperatures in one frame.

By setting the brightness value of the image, you can find the maximum brightness of the object of comparison and at the same time select the isophote in the flare of the same brightness. Then this isophote can be assigned the maximum temperature of the comparison object. The procedure for comparing the brightness of the comparison object and the flare in arbitrary units (arb. units) is shown in Fig. 2.

The temperature of the ith isophote, taking into account the Stefan–Boltzmann law for the given spectral range, was determined as follows [8]:

$$T_i = T_0 \sqrt[4]{\frac{L_i}{L_0}},$$

where T_0, L_0 are maximum temperature and brightness of the lamp filament. Our analysis showed that, in practice, a family of isophotes is a family of isotherms.

The brightness of the flare region determined in the selected spectral range according to the Stefan–Boltzmann

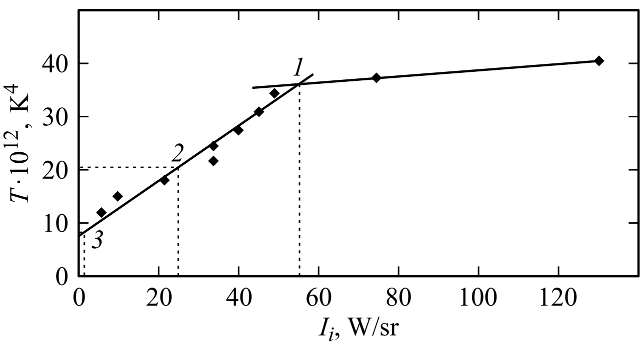

Figure 4. Dependence diagram $T^4(I)$.

law makes it possible to determine the radiation strength of a separate flare region [9,10]:

$$I_i = \int_{S_i}^{S_{i+1}} L_i dS,$$

where S_i and S_{i+1} —are the areas of the selected regions.

The radiation force of the entire flare I is equal to the sum of the radiation forces of all its regions:

$$I = \sum_{i=1}^{n} I_i.$$

Results and discussion

The image of the flare, obtained through a dense neutral filter HC−12, is shown in Fig. 3, *a*, isophotes differing from each other by a certain pitch in brightness — in Fig. 3, *b*. As can be seen from the figure, the flare has a brightness inhomogeneity (Fig. 3, *c*). The brightest region of the flare extends in height from 60 to 120 mm from its base (Fig. 3, *b*), with increasing height, the brightness of the flare monotonically decreases (Fig. 3, *d*).

The table shows the main photometric characteristics of the flare in the visible range of the spectrum. The brightness of the flare diapasons are given in arbitrary units. The brightness of the image background level is equal to $L_F = 64$ arb. units, and the conditional background temperature is 1660 K. The total radiation intensity in the visible range of the spectrum is $I_0 = 442.5$ W/sr. As can be seen from the table, the main radiation comes from the high-temperature regions of the flare. The radiation intensities of the first and second regions with respect to the radiation intensity of the entire flare are 29.3% at $T_1 = 2523$ K and 16.8% at $T_2 = 2471$ K, respectively .

The regional structure of a pyrotechnic flare makes it possible to determine the shape and dimensions of the main luminous body. To determine these parameters, one should present a graph of the dependence of the fourth power of its temperature on the radiation intensity (Fig. 4).

The curve has a slope break (point 1) corresponding to a region with brightness $L_1 = 223$ arb. units and radiation intensity $I_1 = 54$ W/sr. The temperature of this region is 2471 K. This isotherm divides the flare into central and peripheral regions according to the radiation intensity. The area of the central region is equal to $S = 27.35\,\text{cm}^2$, the intensity of its radiation is $I = 204.2$ W/sr, which is 46% of the radiation of the entire flare. The central region is the main luminous body of the flare in the visible range of the spectrum, limited by the isotherm $T_1 = 2471$ K.

Optical sensors register radiation at the level of half maximum brightness (point 2) and it is equal to $L_2 = 127.5$ arb. units. The radiation intensity at this point of the flare is $I_2 = 26$ W/sr, the temperature is $T_2 = 2121$ K, and the area of the luminous body is $S_2 = 107\,\text{cm}^2$ with a total radiation intensity of 400 W/sr. The most sensitive optical sensors can detect radiation at a level of $0.2L_{max}$ (point 3). In this case, the brightness is $L_3 = 60$ arb. units, the radiation intensity is $I_3 = 4.5$ W/sr, the temperature is $T_3 = 1660$ K. The area of the luminous body of the flare is $S_3 = 179\,\text{cm}^2$. The limiting conditions for detecting radiation at point 3 describe the parameters of the selected video camera.

In the present work, the calculations of the radiation intensity were carried out under the assumption that the main contribution to the radiation is made by particles of metal and other solid components of the flare, the radiation of which obeys the laws of thermal radiation with a emissivity factor close to unity. In addition, it was assumed that the absorption, reflection, and scattering of radiation by these particles can be neglected. Therefore, the results obtained should be considered as the first step towards determining the parameters necessary to create physical models of the flare of such pyrotechnic devices. To determine the physical properties of the flare, taking into account the real coefficients of emissivity, coefficients of reflection, absorption and scattering of particles presented in the flare, additional studies are needed. These studies are the subject of further work by the authors.

Conclusion

To date, there is no physical model of modern pyrotechnic devices and, accordingly, a unified methodology that allows one by flame radiation to determine the brightness field in different spectral ranges, the temperature field, the flare radiation intensity and the contribution of separate flare regions to it, In the present work, steps are taken to solve this problem in the visible range of the spectrum. Based on the study of the properties of the flame plume of a sample consisting of Magnesium powder, an inorganic oxidizer and an aromatic Hydrocarbon fuel, the following conclusions can be drawn.

1. A device has been created, consisting of a set of light bulbs of different brightness, a television camera, a computer and original software, which allows, taking into account the

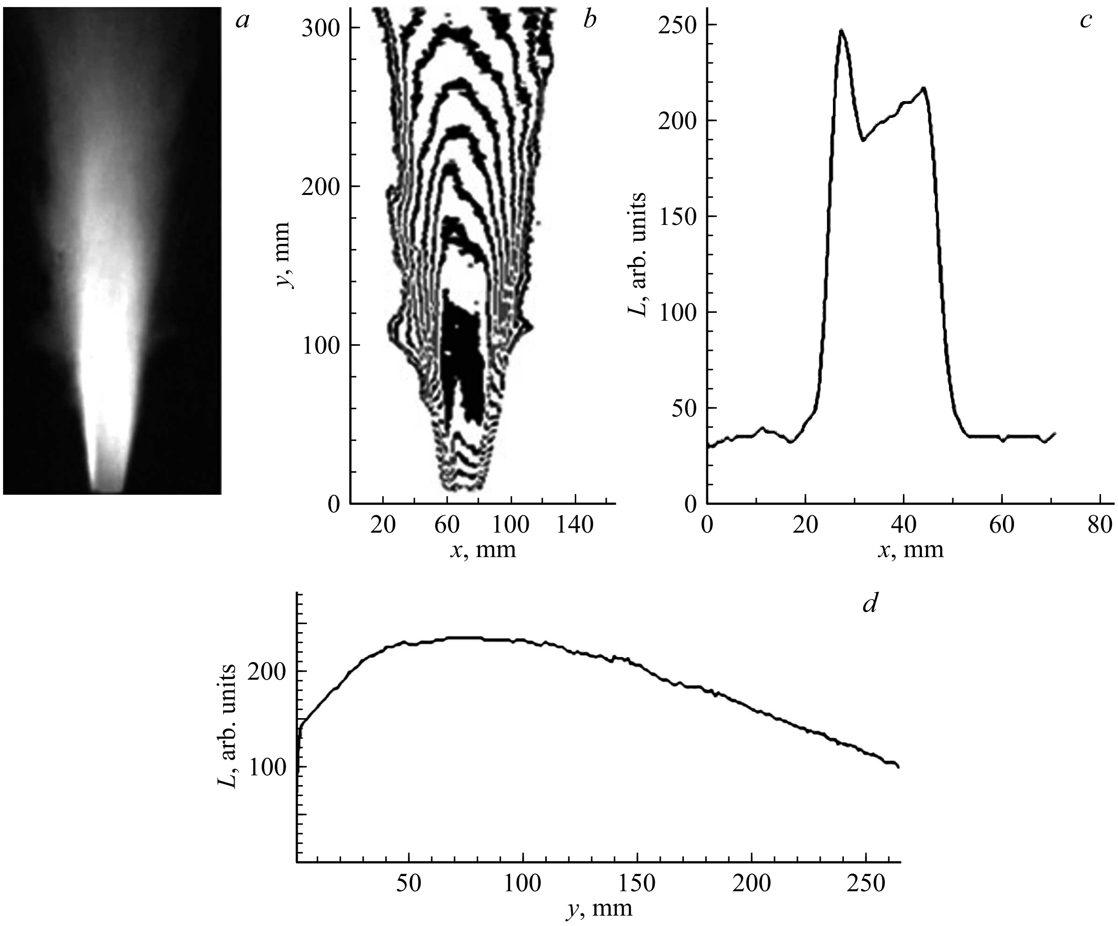

Figure 3. Flare of pyrotechnic composition: *a*) photo of a flare through a dense light filter, (*b*) isophotes, (*c*) distribution of brightness along the *ox* axis ($y = 6$ mm), (*d*) brightness distribution along axis *oy* ($x = 70$ mm).

Main photometric characteristics of flame regions

Li, arb. units	255	235	215	194	174	153	135	115	94	74
S_i, cm^2	9.10	18.75	11.76	11.90	13.75	16.80	19.73	29.99	19.94	16.41
T_i, K	2523	2471	2415	2356	2291	2221	2153	2066	1968	1851
I_i, W/sr	129.9	74.3	49.0	45.0	39.9	33.4	33.8	21.4	9.8	6.0
I_i/I_0,%	29.3	16.8	11.0	10.1	9.0	7.55	7.63	4.83	2.21	1.35
$T^4 \cdot 10^{12}$, K^4	40.5	37.3	34.0	30.8	27.5	24.4	21.5	18.2	15.0	11.7

inhomogeneous structure of the object image, to construct lines (regions) of the same radiation brightness for different wavelengths in the range from 400 to 760 nm , as well as determine the boundaries of the torch.

2. Based on the data obtained, taking into account the macroscopic axisymmetry of the flame and a number of hypothesis and assumptions, the temperature fields and the radiation intensity of the flare are found.

3. It is shown that the main luminous body of the flare is limited by the isotherm $T_1 = 2471$ K, in the visible range of the spectrum has an area $S = 27.35\,\text{cm}^2$, the intensity its radiation is $I = 204.2$ W/sr. The total intensity of radiation of the flare in the visible range of the spectrum is 442.5 W/sr, the maximum temperature in the flame is 2523 K.

4. The developed photometric method can be recommended for diagnosing the radiation of optically dense flares of pyrotechnic compositions. This method is less time-consuming and does not require large time expenditures and expensive equipment.

5. The disadvantage of this study is the assumption that the main contribution to the radiation is made by particles of metal and other solid components of the flare thermal

radiation with radiation obeys the laws of thermal radiation with emissivity factor close to unity. In addition, it was assumed that the absorption, reflection, and scattering of radiation by these particles can be neglected.

To eliminate these shortcomings, further research is needed.

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Conflict of interest

The authors declare that they have no conflict of interest.

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