Thermal imaging complex with tracking function for joint research of microheterogeneous processes and macrokinetics of SHS phenomenon

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Abstract. The paper presents the features of the method of chrono-topographical analysis of high-resolution thermal imaging data. Robotic foundations of the organization of a thermal imaging complex with a tracking function and the formation of a single chronographic map of the SHS phenomenon based on the results of temperature observations in several areas are described. It is shown that with the same measurement error of the propagation velocity of a SHS wave, a complex with a tracking function has a greater information power than a thermal imaging system with a single observation area. The approbation of the measuring complex during the investigation of SHS in the model Ni-Al system was performed. A joint analysis of heterogeneous processes revealed a similarity in the character of the propagation of combustion centers along the SHS wave front and the motion of the front itself. Based on the chronographic maps of the SHS process, it was found that there were two types of foci in the reaction wave, which differed in the dynamics of the boundary propagation along the front.

1. Introduction
The phenomenon of self-propagating high-temperature synthesis (SHS) is a combination of processes occurring on different spatial and temporal scales [1-4]. The specificity of the research methods and the dynamic range of measuring instruments limit the area of joint observation of heterogeneous processes. Therefore, on the basis of experimental data it is difficult or impossible to establish a causal relationship between relatively slow processes occurring at the macro level and superfast processes that develop in microregions. Analysis of the truncated data generates the SHS model, which only partially generalizes knowledge about the object of study.

In the experiment, the signal from the observed phenomenon and the dynamic range of the measuring device can be coordinated in two ways. First, to use a priori properties of the observed phenomenon to select methods for recording and processing data in order to expand the dynamic range of the measuring instrument. Secondly, to plan such an experiment that will reduce the entropic power of the signal from the object of study. For example, the lack of heat in a discrete medium leads to a slowdown in the microheterogeneous processes involved in the formation of an SHS wave. In this case, the time resolution of the thermal imaging system of the optical range becomes sufficient for the simultaneous study of the dynamics of microheterogeneous processes and movement of the combustion wave front [5].

The purpose of this work is to show that on the basis of a thermal imaging complex with a tracking function, it is possible to conduct a joint analysis of the heterogeneous processes of the SHS phenomenon and establish the relationship between them.
2. Study of the macrokinetics of the SHS by a series of high-resolution thermal imaging

The discreteness of the propagation of a SHS thermal wave in time, and the spatial inhomogeneity of its structure, limit the measurement accuracy of the macrokinetic parameters of the phenomenon. To suppress this effect in the experiment, data are recorded by optical devices with low spatial and temporal resolution. In the known methods of measuring the velocity of propagation of a SHS wave, such an approach makes it possible to achieve an error of 1–6% [6–8]. However, the spatio-temporal averaging of data in low-resolution thermal imaging systems blocks the simultaneous study of microheterogeneous processes and the macrokinetics of SHS. High-resolution thermal imaging allows you to explore the dynamics of individual foci in the combustion wave, but to determine the macrokinetics of the observed phenomenon requires special data processing methods.

The method of chrono-topographic analysis (CTA) processes high-resolution thermal imaging information in four-dimensional space (two coordinates of the object projection, time, temperature). It is able to determine the elements of the combustion wave front with a given depth of chemical transformation and emphasize the systemic properties of an ensemble of such elements on space-time maps. So, the integral chronographic map of the SHS in the wave mode of combustion reveals the property ergodicity of the front propagation process (figure 1). As a criterion for the ergodicity of this process, there is the similarity of a chronographic map and a flat model, for which the estimates of the expectation of the front speed are equal both at different points in time and at different points in space.

![Figure 1](image1.png)  ![Figure 2](image2.png)

*Figure 1. Integral chronographic map of the SHS phenomenon.*

*Figure 2. The dependence of the logarithm of the relative error of measuring the velocity of propagation of a SHS wave by the CTA method on the values of m and k.*

When measuring by the XTA method, the propagation velocity of a SHS ($V_n$) wave, the error depends on two parameters: $m$ is the number of measuring cross-sections of the observation region (the number of marks on the X axis); $k$ is the average number of foci of combustion in the cross-section. The results of the study of the error of measuring $V_n$ by the CTA method are shown in figure 2.

The differential form of the chronographic map makes it possible to identify individual foci in the reaction wave, to study their thermodynamics and interaction (figure 3). Joint analysis of thermal images and differential chronographic map allows you to build a topographic map of the phenomenon of SHS. It shows areas where the development of individual foci combustion during the entire observation period (figure 4). The topographic map allows us to estimate how the combustion depression in SHS contributes to the structurization of the final product, and to determine the characteristic dimensions of the sample areas with a high depth of chemical transformation of the initial components.

Based on the ergodicity of the SHS phenomenon in wave-burning mode, the results of thermal measurements from several observation areas can be combined on a chronographic map. If measurements in all observation areas are tied to one space-time coordinate system, then drawing up a chronographic map that is uniform for them allows increasing the values of $m$ and $k$. Such an approach makes it possible to control the accuracy of the measurement of parameters of macrokinetics the SHS phenomenon by high-resolution thermal imaging data.
3. The implementation of the tracking function in the thermal imaging complex

Thermal imaging of high-resolution SHS shows that there is a portion of the boundary of the foci of combustion that moves along the front. Depending on the thermal effect, the rate of propagation of combustion along the front can be 1-3 orders of magnitude higher than the speed of the wave in the normal direction. Therefore, in order to detect the interrelation of these movements, it is necessary to increase the frame rate of thermal imaging by 1-3 orders of magnitude compared to the minimum required for controlling the macrokinetics of SHS.

For most streaming cameras with solid-state photo detectors, the frame rate depends on the number of elements polled. The reduction in the number of lines of recorded images in the direction normal to the front of the SHS wave makes it possible to increase the shooting speed proportionally. Consequently, by changing the aperture of the area being sighted one can achieve acceptable characteristics of measuring instruments.

However, the size of the field of observation in the direction normal to the front affects the accuracy of the determination of SHS macrokinetics indicators. The reduction of the sighted area in the normal direction reduces the value of \( k \) and increases the error in measuring the propagation velocity of the CBC wave and other macrokinetic parameters (figure 2). This limitation can be overcome by adding a tracking function to the complex of thermal imaging measuresments.

In [11], a tracking thermal imaging complex with the following principle of operation is described in detail. High-speed shooting of the SHS phenomenon is performed in a certain area of the sample with a fixed camera. Moreover, in real time, the following is performed: the transfer of thermal images to a computer, their processing, determining the number of frames that can be taken before the process leaves the observation area, and predicting the coordinates of the new observation area. As the forecast data is updated, it is transmitted to the controller of the measuring complex, which controls the shooting
process. As soon as the number of frames that need to be registered becomes zero, the controller moves the measuring module to a predetermined position. Prediction of the position is carried out taking into account the measurement of the reaction front velocity in real time so that when moving the measuring module could outrun the combustion front and start shooting the SHS phenomenon in the new observation zone after relaxation of natural oscillations (figure 5).

**Figure 5.** Block diagram of a thermal imaging complex with tracking function.

For example, a VideoSprint (Russian) camera with a photo matrix dimension of 1280×1024 has a maximum shooting speed of 488 frames per second (fps). Let the spatial resolution of a thermal imaging system based on it is 5 microns. If the average size of the combustion foci in the measuring section is $L_n = 173 \, \mu m$, then in the process of recording thermal imaging data, $m=1280$, $k=29.6$, and the error in measuring the velocity of propagation of a SHS wave by the CTA method is 0.22% ($\ln(\delta V) = -1.5$) (see figure 2). Suppose to study the laws of thermodynamics of individual foci of combustion in a SHS wave, a response speed of 8 times higher is required. In this camera, this can be achieved by reducing the aperture of the interviewed photocells in the direction of propagation of the combustion wave - 1280×128 elements. Then the frequency of shooting can be increased to 3904 fps. Reducing the aperture of the sighted area will cause a reduction $k$ to the value of 3.7 ($m=1280$), and the speed error will increase to the level of 5.5% ($\ln(\delta V) = 1.7$). If the observation of SHS is performed in 8 zones using the tracking function, then the size of the synthesized aperture will be exactly the same as in the case of shooting in a single zone with a sensor dimension of 1280×1024. Each area of observation in the process of shooting with tracking will correspond to its video segment and chronographic map. The CTA method allows to combine several chronographic maps based on the data on the position of each observation area and the time of thermal measurements. In this case, $k$ will return to level 29.6, and the error in measuring the front velocity will be less than 0.22%. However, the information power of a thermal imaging system with a tracking function will be 8 times higher. This will allow using high resolution thermal imaging data to simultaneously measure the parameters of microheterogeneous processes and macrokinetics of the SHS phenomenon.

4. Approbation and discussion of the results
Approbation of a thermal imaging complex with a tracking function was performed during an experimental study of the SHS phenomenon in the 3Ni+Al system. The observation of high-temperature synthesis was carried out with a spatial and temporal resolution of 5.8 μm and 1 ms, respectively. The size of thermal images - 1260x512. The magnitude of the acceleration at the beginning and end of the motion of the measuring module was 1.5 m/s². The average distance between the sighted areas (the size of the blind zone) was 120-180 microns. Registration of SHS for each sample was carried out in 6-9 zones. On average, a synthesis of 3-4 product layers was recorded in each observation area. The velocity of propagation of the reaction front was determined from the general integrated chronographic map of the SHS phenomenon, which was 2.63 mm s⁻¹. The coefficient of velocity variation at a significance level of 0.05 was 0.15%.

In the temperature images of figure 6, the development of the combustion foci along the SHS wave front — along the X axis — is presented, while the front of the Ni₃Al synthesis reaction moved in the direction of the Y axis. The experiment showed that the speed of propagation of the boundary of the foci along the wave front of the SHS is finite and can be measured by high-resolution thermal imaging. To determine the magnitude of the propagation velocity of the foci of combustion along the front, a differential chronographic map was used. A fragment of such a card is shown in figure 6-c.

Figure 6. Dynamics of combustion foci along the Ni₃Al SHS wave front: a - temperature images of one cycle of development of the foci (main) along the front, showing the stages of flash and cooling (size of the visible area - 7.31x2.16 mm); b - temperature images showing the stages of development of the secondary focus; c - differential chronographic map of high-temperature synthesis of a single product layer in the area of interest, including the foci dynamics at a) and b).

It shows that the spread of the foci along the front is discrete. There is a stage at which the velocity of the boundary of the foci is 0.25-0.4 m/s. At the same time, the temperature in the border (adding) area of the focus increases sharply to the level of 1910-1937 K. Let's designate it as a flash stage. The outbreak is followed by a stage when the rate of development of the focus decreases to almost zero, and the temperature at the head of the focus decreases to the average level characteristic of its large area.
This stage can be designated as a stage of depression reaction. The chronographic map (figure 6-c) and the thermal imaging of high-resolution SHS (figure 6-a) show that the outbreak and depression stages of the reaction follow each other cyclically and relate to the evolution of the same focy. The differential chronographic map demonstrates that speed fluctuations occur around a certain average, which in Figure 6-c can be defined as the slope of the regression line. The average rate of propagation of focy forming the different layers of the product in the sample is approximately the same. In experiments on the synthesis of Ni₃Al, its value was 68.5 mm/s. Thus, the nature of the development of the focy in the X direction has all the signs of the propagation of the front of the SHS wave in the Y direction, which were described by the pioneers of this phenomenon [12].

The chronographic map of the SHS phenomenon (figure 6-c) shows that at the flash stage a secondary focus forms, which propagates along the SHS wave front, but in the opposite direction relative to the primary focus. Figure 6-b shows a series of temperature images of the evolution of the secondary focy. Secondary focy differ from primary focy by the dynamics of propagation. According to the chronographic map, the velocity of propagation of secondary focy remains almost constant over the entire time of their existence. Mean value in the experiment, measured over a variety of secondary focy, was 156 mm/s. The sizes of the primary and secondary focy in the direction normal to the front of the SHS wave are also different. For primary focy, the size is in the range of 580–800 microns, and for secondary ones, 250–400 microns.

5. Conclusions

Representation of thermal imaging data in the form of an integral chronographic map provides a criterion for identifying the ergodicity of SHS in the mode of wave combustion. Based on it, the CTA method allows one to control the measurement error of the macrokinetics parameters of the SHS phenomenon by expanding the amount of high-resolution thermal imaging information obtained from several areas of observation. According to the results of testing the thermal imaging complex with the tracking function, it was concluded that the discrete nature of the propagation of the reaction front is inherited from the combustion focy, since they form the wave of high-temperature synthesis. High-resolution thermal imaging data show that two types of focy with different dynamics are formed in the SHS wave. Thus, the developed thermal imaging complex is capable of observing and measuring the parameters of heterogeneous processes in the SHS phenomenon.

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