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High-speed visualization of combustion synthesis discrete reaction waves: coherent heat microstructures

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Abstract. The paper shows new possibilities for studying the effects of microheterogeneous combustion by the method of high-speed micro-thermal imaging. On each video frame, the area of the microfocal reaction, where local superadiabatic heating occurs has been identified,. All the discrete regions of heat generation were combined on a common image of the thermal microstructure of the combustion reaction wave. The characteristic size of the foci of combustion in the Ni-Al system was from 150 to 300 μm, which is 5 times larger than the size of the largest powder particles. It was found experimentally that the combustion front propagates only in the local regions of superadiabatic heating and the motion has a discrete step. The thermal microstructure has the form of a quasiperiodic sequence of layers, the spatial direction of which weakly depends on the position of the combustion front with respect to the horizontal. To verify this fact, which contradicts the classical theory of wave stability in the spin combustion mode, the differential chronoscopic analysis of the interframe difference in the motion of the combustion front line was selected. As a result, it was shown that, independently of the geometry of the combustion front, a synchronous and quasi-periodic occurrence of new local combustion sites is observed. The period of thermochemical induction between each discrete step of motion was from 0.1 to 0.2 ms. Thus, the data of the 2D thermal map of differential chronoscopy (DCS) allow visualization of the SHS combustion wave in the form of coherent thermal structures with quasiperiodic parameters.

1. Introduction

To study *in situ* the combustion kinetics of disperse systems and the evolution of the thermal decomposition of a wave of self-propagating high-temperature synthesis (SHS) in locally unstable modes of microheterogeneous combustion [1-3], it is possible to use only micro-video registration with high spatial and temporal resolution [4], which leads to processing of large data sets [5]. Spatial differential chronoscopy (SDC) is a method of two-dimensional visualization of the flow of binary video data relative to a given brightness threshold, in which one of the spatial coordinates is replaced by a time coordinate, and the time derivative of this coordinate plays the role of the brightness of the video data stream [6, 7]. Depending on the analysis task, the binarization threshold is selected in accordance with the characteristic temperatures of ignition or structure formation, which is important for studying the kinetics of SHS [8, 9]. The aim of the work is to describe the algorithm for obtaining the differential chronogram of the SHS process based on the results of high-speed video recording of the propagation of the combustion wave.

2. Experimental technique

To record the high-speed propagation of the SHS combustion wave, an optoelectronic micro-pyrometric complex was used [10]. It is based on the nanosecond video resolution system "Video Sprint NanoGate" (Videoscan, Russia) with the image analysis and image processing program Fiji-ImageJ (NIH, USA) [11]. An experimental test bench for studying the thermal microstructure of the combustion front is shown in figure 1.

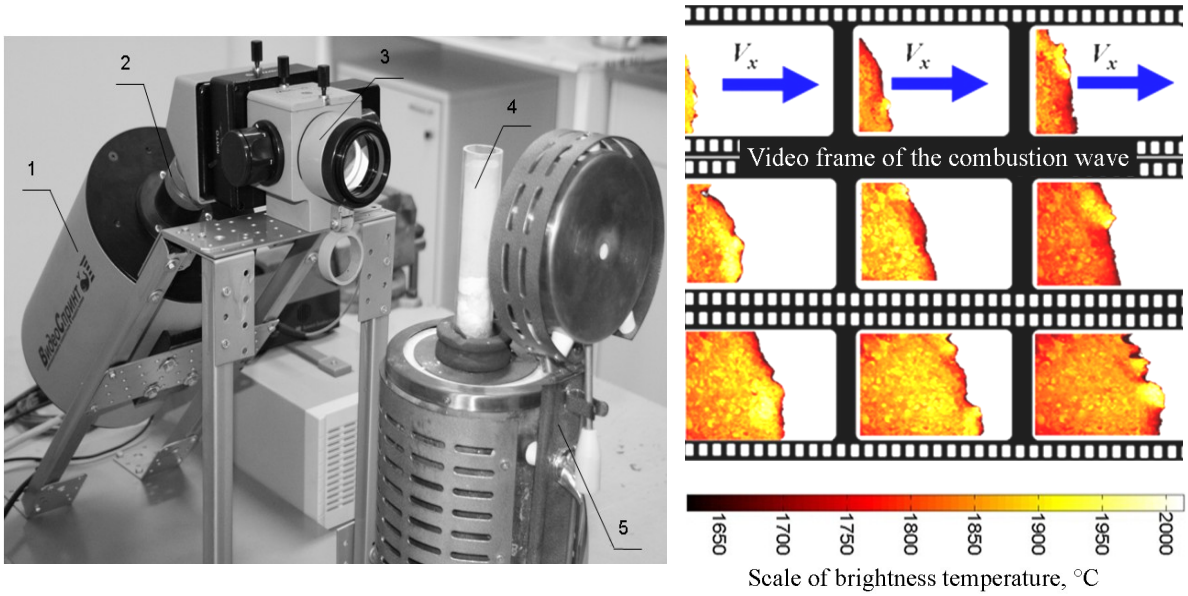

Figure 1. Experimental setup for studying the thermal microstructure of the combustion front: 1 – high-speed streak camera "Video Sprint NanoGate"; 2 – block of optical filters for brightness pyrometry; 3 – microscope objective; 4 – quartz reactor for observing the combustion wave in a powder mixture; 5 – tubular furnace for initial heating.

Spatial resolution of 5.85 μm/pixel provides magnification in the optical system of the MBS-10 microscope, and the time resolution Δt from 20 μs to 2 ms per frame provides the scanning frequency of the photomatrix in the frame format (1200×800 pxl). In our example, the frame rate was 500 Hz. When calibrating the camera using a temperature reference lamp (TRU 1100-2350), the brightness values of the frame $R_t\ (x,\ y)$ can be replaced by the field of "brightness" temperatures $T_t\ (x,\ y)$, where x – the pixel's horizontal coordinate ($1 < x < 1200$), y – coordinate in the column ($1<y< 800$), $t=t_0+N$, Δt – time count of the current frame in the selected series, if t_0 is the start time of the video recording, N – the frame number in the series.

3. Methods of data processing

The initial data format of video recording is the avi-file, from which the sequence of static frames is cut out in the interval of the investigated time interval, as shown in figure 1a. The method of visualization and construction of SDC includes three consecutive stages.

3.1. Threshold binarization

Threshold binarization of the 2-dimensional image $R_t\ (x,\ y)$, to isolate the 1-dimensional curve of the combustion front (figure 1b). In practice, the threshold is chosen from the brightness value of the characteristic ignition temperature ($0.7R_{max}$), but in theory the $X_t\ (y)$ coordinate of the combustion front corresponds to the inflection of the temperature profile and must be determined from the x coordinate

of the maximum of the gradient $T_t(x,y)$ in each line y. Using the ImageJ software, this is easily done using the Laplace gradient mask selection procedure.

3.2. The inter-frame difference

The inter-frame difference of the coordinates $\Delta X_t(y)=X_t(y)-X_{t-\Delta t}(y)$ of the combustion front for each line y of the image (figure 1c). It is obvious that this value characterizes the instantaneous normal component of the propagation velocity of the SHS wave along the sample, as well as the size of the local source of microheterogeneous combustion. For example, as seen in figure 1c, there is no interframe motion of the combustion front ($\Delta X_t(y)=0$) in the Y_1 and Y_2 coordinates, but in all intermediate rows the front has progressed on average by the same distance ΔX, then the characteristic size of the local focus can be estimated by the value $S=\Delta X(Y_1-Y_2)$.

3.3. The replacement of the coordinates

The replacement of the coordinates of the normal component x (the number of the pixel in the line) of the combustion front speed by the time coordinate t (frame number in the series), allows the graphical display of "coherent" (simultaneously coordinated) processes in the form of a SDC map.

4. Results and Discussions

As shown in figure 2d, individual foci of microheterogeneous combustion acquire an ordered form of a quasiperiodic wave structure, the temporal coherence of which is determined by the same period of thermochemical induction between layers, and spatial coherence reflects competition between the mechanisms of thermal conductivity and diffusion if the composition of adjacent layers and their density are not homogeneous. A simple change of variable in the form: $x = \langle V_x \rangle t$, can easily convert the chronogram to the instantaneous velocity field map $V(x,y)$ of heat transfer.

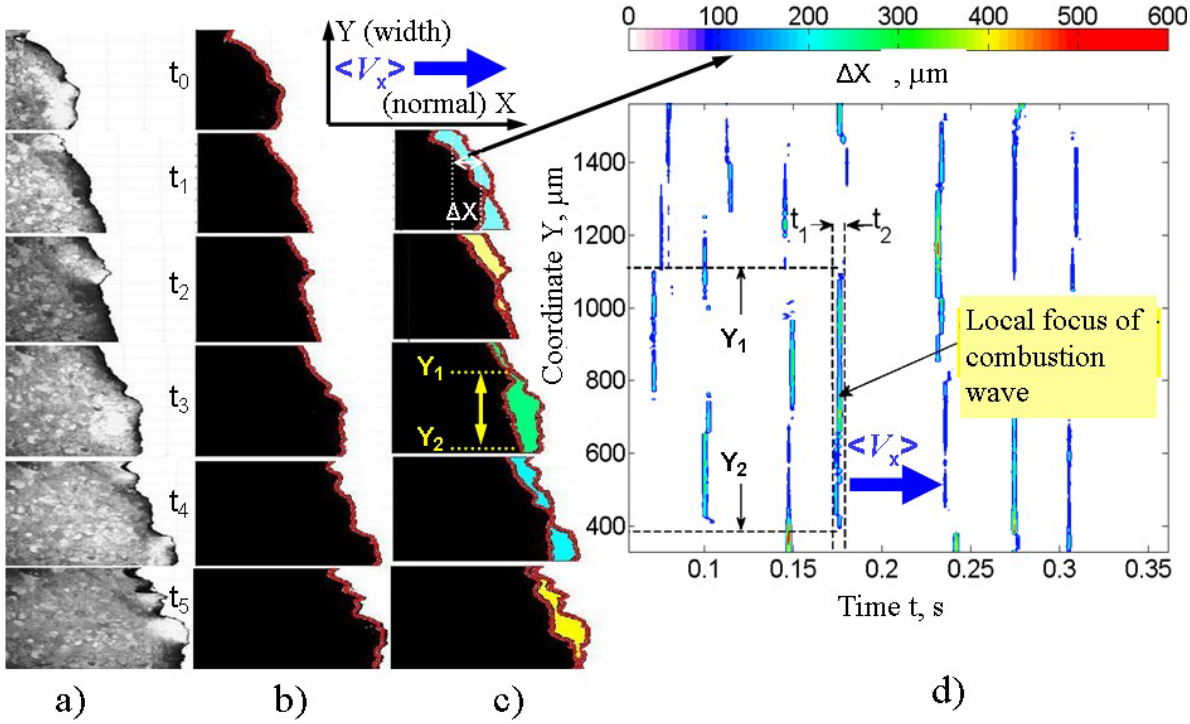

Figure 2. The technique of visualizing the combustion wave in the form of a differential process chronogram: a) sequence of frames of a high-speed video camera; b) binarization and separation of the combustion wave front; c) the interframe difference in motion of the combustion front; d) map of local foci of the combustion wave on the differential chronogram of the SHS process.

The influence of the random structure of the powder mixture of the initial products on the motion of the front of the combustion wave quasiperiodically changes the temperature, velocity, and direction of propagation of the combustion wave in the process of self-propagating high-temperarure synthesis. The task of analyzing the microheterogeneous combustion structure, which is a «discreteness problem» for SHS [1], calls for the development of means for analyzing the local instability of the motion of the SHS combustion wave [12]. The solution to this problem is seen in the application of mathematical methods for compressing video data by introducing the interframe difference into the signal processing path and parametrizing the results of differential chronoscopy (DCS) using Fast Fourier transform (FFT), Trace transform (TT) or Hough algorithms [13-15].

5. Conclusion

- Using the method of differential spatial chronoscopy, taking into account the one-dimensionality of the front of the combustion front and the boundary of the isothermal zones, we can not only get rid of the masking effect of the random structure of the powder mixture of the initial products from the geometry of the combustion front, but also determine the quantitative evaluation of the stability of SHS waves and heat exchange regimes in classical terms of the spatial and temporal coherence of the wave process.
- The degree of compression of the information on the motion of the combustion wave reaches a value of 1:5000, which makes it possible to effectively accumulate an experimental database on the diffusion-thermal instability of the combustion regime while maintaining inert additives that can change the Arrhenius number and reaction kinetics.

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