Trace-analysis of a combustion wave thermal instability using high-speed video images: experiment and simulation modeling

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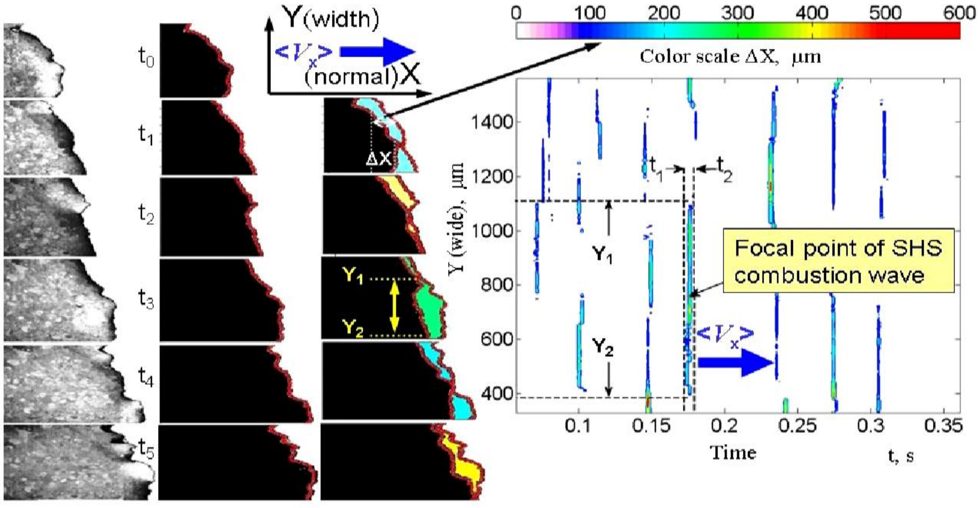
Abstract. The paper presents a method for identifying the thermal instability mode of a combustion wave during self-propagating high-temperature synthesis (SHS) of materials during high-speed television recording. Compressing video data using the differential chronoscopy method (DCS) reduces the data size by more than 1000 times without losing information about the motion of the combustion wave of the SHS, and the result is obtained as a two-dimensional chronogram, the mathematical model of which is presented for the Ni-Al system with an admixture of inert powder impurities from 1 to 15 % Statistical characteristics based on the analysis of traced images of DCS maps are suggested for recognizing the critical mode of the SHS combustion. The sensitivity of recognition of changes in the discrete thermal structure of SHS wave is estimated using the proposed statistical characteristics of the trace transformation images of the DCS maps. In addition, using the various functional "cores" of the Trace transformation, the highest value of this sensitivity was determined. As a result of this comparison, the most effective of the considered functional “cores” of the Trace transformation was determined, which allows defining unstable combustion modes in SHS technology. Comparison of the histograms of the distribution of Trace-matrices for the experiment and simulation showed good agreement.

1. Introduction

For study of the combustion kinetics of dispersion-phase systems and the evolution of the discrete decay of the thermal structure of the wave of self-propagating high-temperature synthesis (SHS) in locally unstable regimes of microheterogeneous combustion, the micro video filming with a high spatial and temporal resolution is widely used [1-3], as a result of which it is necessary to execute the processing of large-scale data sets [4, 5]. Spatial differential chronoscopy (DCS) is a method of two-dimensional visualization of the stream motion of a video data that come out of a binarization procedure according 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 luminance of the video data stream [6, 7]. Depending on the analysis task, the binarization threshold is chosen according to the characteristic ignition or phase transitions temperatures, which is important for the study of the kinetics of SHS [8, 9]. The aim of the paper is to describe the data compression algorithm by computing a differential chronogram of the SHS process based on the results of high-speed video recording of the combustion wave propagation, and also demonstrating the possibility of Trace analysis to determine the stability criterion of the chemical reaction of SHS.

2. Experimental procedure

For automation of the study of the SHS combustion wave propagation processes an optoelectronic micro pyrometric complex [10] based on the nanosecond resolution system "Video-Sprint NanoGate" (NPK Videoscan, Russia) with the image analysis and image processing program "Fiji-ImageJ" (NIH, USA) [11] was used. The initial data format is the avi-file of video recording, from which the sequence of static frames is cut out in the interval of the investigated time interval (as shown in)). Figure 1a).



(a) (b) (c) (d)

Figure 1. Stages of the computing of a differential chronoscopy (DCS) map of the SHS process: (a) sequence of static frames; (b) the sequence of frames with the selected wave fronts; (c) the interframe difference ΔX (t, y); (d) DCS map of the SHS combustion wave in a mixture of Ni-Al powders.

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

The methodology (algorithm) for computing the DCS map includes three consecutive stages.

1. *Threshold binarization of the 2-dimensional image* $R_t(x,y)$ for isolating of one-dimensional curve of the combustion front (Fig. 1(b)). In practice, the threshold is chosen from the brightness value ($0.7R_{max}$) of the characteristic ignition temperature, 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 gradient $T_t(x,y)$ in each row y. This is easily done in the ImageJ program using contour selection procedure by the Laplace gradient mask.

2. *The interframe difference of the coordinates* $\Delta X_t(y)=X_t(y)-X_{t-\Delta t}(y)$ of the combustion front for each row y of the image (Fig. 1(c)). It is obvious that this value characterizes the instantaneous normal component of the propagation velocity of the SHS wave along the sample, and also the size of the local source of microheterogeneous combustion. For example, as seen in Figure 1(c), in the rows with coordinates $Y1$ and $Y2$, the interframe motion of the combustion front ($\Delta X_t(y)=0$) is not observed, but in all intermediate rows the front advanced on an average by the same distance ΔX, i.e. the characteristic size of the combustion local source can be estimated by the value $S=\Delta X(Y_1-Y_2)$.

The replacement of the coordinates of the normal component x (the number of the pixel in the row) of the combustion front velocity by the time coordinate t (frame number in the series). The graphical display of "coherent" (simultaneously coordinated) processes at this replacement ordered in the form as a DCS map. As shown in Figure 1(d), local sources of microheterogeneous combustion acquire an ordered form of a quasiperiodic wave structure, the temporal coherence of which is determined by the constant period of thermochemical induction between the layers, and spatial coherence is determined by a competition between the thermal conductivity and diffusion when the composition of adjacent layers and their density are destroyed. When the variables x = <Vx>t by the time coordinate t are replaced, the chronogram becomes the instantaneous velocity field V(x,y) of heat transfer.

3. Method of Computer Simulation

The statement of the computer simulation problem for idealized SHS regimes was based on the space-time structure of the experimental DCS maps and the additional conditions of combustion chemical physics, according to which the trajectory of the chemical reaction becomes unstable when stoichiometric ratio is more than 15%. In our case, this is confirmed experimentally by introducing impurities in the form of inert or alloying additives [4], as can be seen from Figure 2.

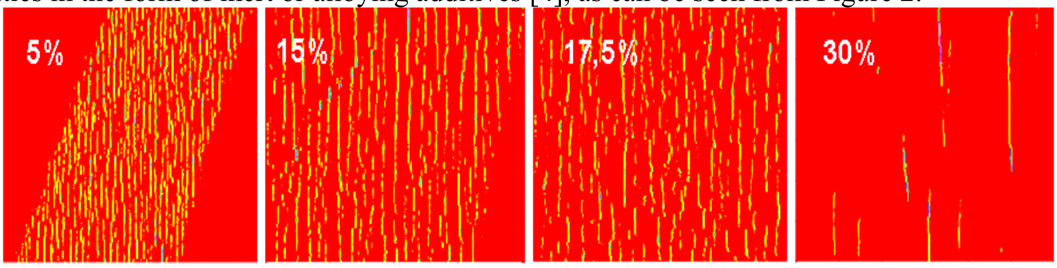


Figure 2. Experimental DCS-maps of the combustion wave in the Ni-Al system with a change in the proportion of the inert additive.

As it was established earlier [3], the discreteness of the SHS thermal structure in this case is directly proportional to the mass fraction of additives in the range up to 12-15%, and above - the wave breaks up, the combustion becomes locally unstable and passes into a damped or pulsating relay-race regime. The method of pattern recognition based on the Trace transform for identifying of the transient modes of SHS was chosen [10], because this method was well recommended in solving similar problems of determining the invariants of high-velocity emissions in plasma-arc spraying technologies [11, 12]. The simulation model of the DCS map of the SHS combustion wave under conditions of dilution of the initial mixture with an inert additive was calibrated according to the experimental data given above. This model is shown in Figure 3(a) together with examples of their matrix Trace images for the "typical" functionals T3, T4 and T5 corresponding to different harmonics of the Radon-Nicodim transformation [10]:

$$T_3: \quad T(f(t)) = \left| \int_{c^*}^{\infty} e^{i5\log(r)} r f(t)\,dt \right|,$$

$$T_4: \quad T(f(t)) = \left| \int_{c^*}^{\infty} e^{i3\log(r)} f(t)\,dt \right|,$$

$$T_5: \quad T(f(t)) = \left| \int_{c^*}^{\infty} e^{i4\log(r)} \sqrt{r}\, f(t)\,dt \right|.$$

The Trace transform functional (for example, T3, T4 or T5) integrates the brightness values f(t) of the DCS map points along the projection direction t, rotated by a positive angle φ relative to the vertical axis of the DCS map and spaced a distance r from the center of the DCS map (of matrix image). That is, in Figures 3(b) and 3(c) (and also in Fig. 4), the vertical coordinate (the row number of the Trace image matrix) corresponds to r, and the horizontal coordinate (column number of the Trace image matrix) is the rotation angle φ, varying from 0 to 360 degrees (the possible smallest step is 1 degree).

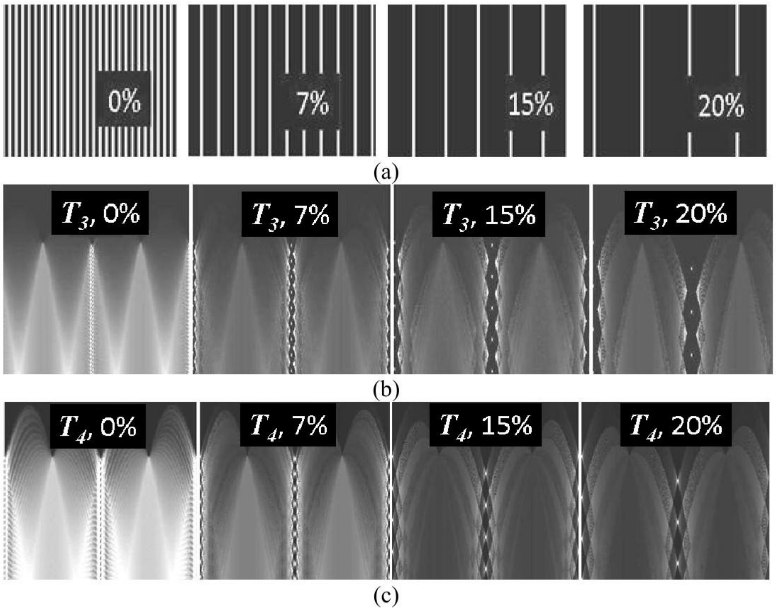


Figure 3. Model interpretation of the combustion wave: (a) DCS map with an inert additive of 0%, 7%, 15%, 20%; (b) Trace images of the functional T_3; (c) Trace images of the functional T_4.

4. Methods of Chronogram Analysis

As can be seen from the formulas for T_3, T_4 and T_5, the sensitivity of the recognition depends on the choice of the Trace-functional when changing the discreteness of the SHS wave: fan structures are characteristic for T_3; T_4 recognizes the slope of the wave; T_5 monitors the parabolic heat transfer profile. In order to determine the best sensitivity of recognition of the critical combustion regime, when the 15% dilution of mixture is achieved, the differences of Trace images for DCS maps of nonzero percentage of dilution relative to the "base" Trace image were analyzed (see Figure 4(a)), i.e. the analysis of the sequence of differences between the matrix of the "base" Trace image (0% inert impurity) and the matrix of the next current Trace image (corresponding to the following current percentages of dilution by inert: 1%, 7%, 15%, 20%). Also, the analysis of the differences of the "adjacent" Trace-images was carried out (dilution step in 1%, Fig. 4(b)), i.e. analysis of the sequence of differences between the matrices of adjacent (neighboring) Trace images (corresponding to pairs of percentages of dilution by inert: 0% and 1%, 6% and 7%, 14% and 15%, 19% and 20%).

The results of the two analysis options (Figure 4(a), 4(b)) make it possible to conduct a statistical analysis of the behavior of their brightness histograms as the inert additive increases from 0 to 20% (Fig. 5).

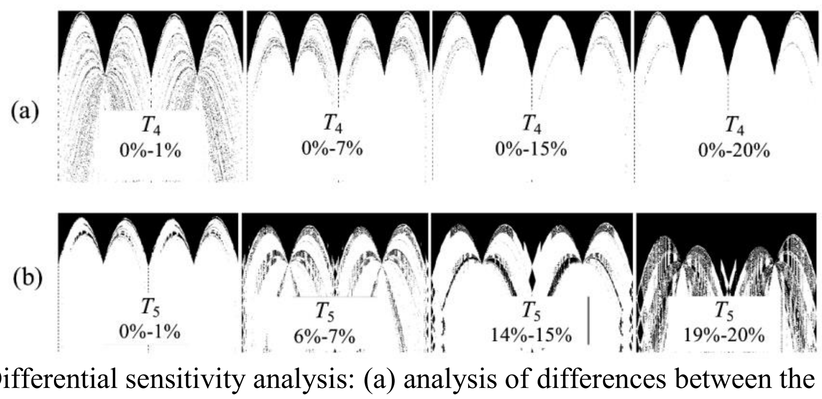


Figure 4. Differential sensitivity analysis: (a) analysis of differences between the matrix of the "base" Trace image (0% inert impurity) and the matrix of the next current Trace image (corresponding to the following current percentages of dilution by inert: 1%, 7%, 15%, 20%) on the basis of the functional T_4; (b) analysis of the differences of "adjacent" Trace-images on the basis of the functional T_5.

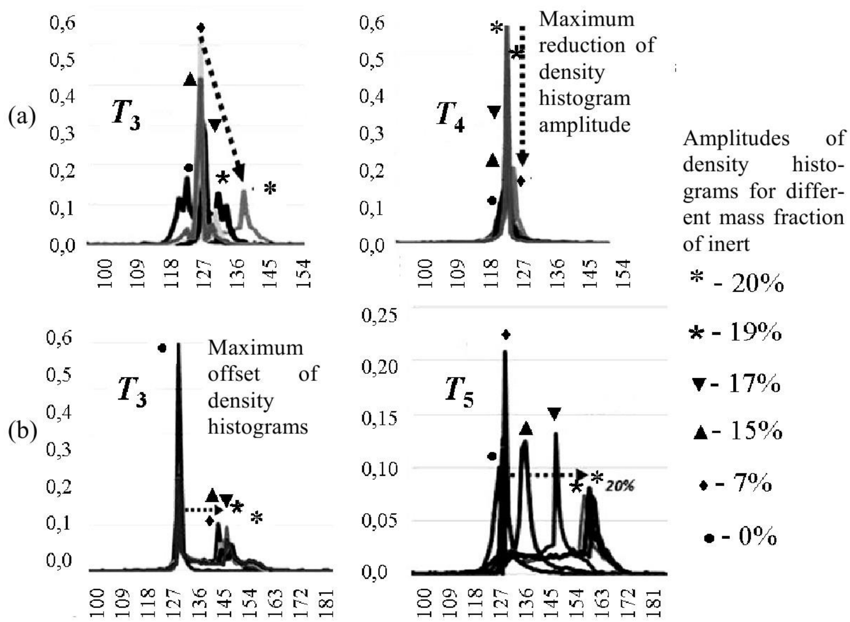


Figure 5. Statistical parameters of density histograms for recognition of critical combustion conditions of SHS: (a) reduction of amplitude of density histograms of values in the differences between the matrix of the "base" Trace image (0% inert impurity) and the matrix of the next current Trace image (corresponding to the following current percentages of dilution by inert: 7%, 15%, 17%, 19%, 20%) on the basis of functionals T_3 and T_4; (b) "offset" of density histograms of values in the differences between the matrices of adjacent (neighboring) Trace images (corresponding to pairs of percentages of dilution by inert: 0% and 1%, 6% and 7%, 14% and 15%, 16% and 17%, 18% and 19%, 19% and 20%) on the basis of functionals T_3 and T_5.

5. Results and discussion

Obvious signs (parameters) of the behavior of the distribution density histograms (Figure 5), obtained during the analysis of the sequence of differences between the matrix of the "base" Trace image (0% inert impurity) and the matrix of the next current Trace image (corresponding to the following current percentages of dilution by inert: 0 , 7, 15, 17, 19, 20%), are a 3-fold decrease in the distribution amplitude for the functional T4 and the maximum offset of the distribution density histograms for the functional T5 when analyzing the differences of the "adjacent" Trace images corresponding to pairs of percentages of dilution by inert: 0% and 1%, 6% and 7%, 14% and 15%, 16% and 17%, 18% and 19%, 19% and 20%. The functional T3 should be recognized as the least effective for solving problems of recognition of critical SHS regimes.

6. Conclusions

1. The proposed chronographic approach allows us to compactly visualize the propagation of SHS in the wave combustion mode and to execute the ergodic analysis by methods of Fourier and Trace transforms.
2. The use of data compression by the method of differential spatial chronoscopy (DCS), taking into account the one-dimensionality of the combustion front lines and the boundaries of isothermal zones, allows not only to get rid of the masking influence of the random structure of powder mixture on the geometry of the combustion front. In addition, DCS method also allows to estimate the stability of the SHS wave and the heat transfer regime in classical terms of the spatial and temporal coherence of the wave process.
3. 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

unstable combustion regimes at the introduction of inert additives that change the Arrhenius pre-exponential factor and the kinetics of the reaction.

7. References

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