УДК 53.82.63
DOI: 10.18822/byusu20220109-20

SPIN INSTABILITY OF TECHNOLOGICAL COMBUSTION MODE IN A WAVE OF SELF-PROPAGATING HIGH-TEMPERATURE SYNTHESIS

Angelica A. Grigoryevskaya
Bachelor, Trainee Researcher of Mechanics and Mathematics Faculty,
Novosibirsk National Research University.
Novosibirsk, Russia
ORCID: 0000-0002-9909-7337
E-mail: a.a.grig@bk.ru

Pavel Yu. Gulyaev
Doctor of Technical Sciences,
Professor of the Institute of Oil and Gas,
Yugra State University.
Khanty-Mansiysk, Russia
ORCID: 0000-0002-4337-1253
E-mail: p_gulyaev@ugrasu.ru

This study was partially funded by a scholarship from the Novosibirsk City Hall
(by the City Hall resolution of August 24, 2020 N 2587).

The results of a computer experiment to determine the invariant properties of the Trace transform of a two-dimensional chronogram of wave propagation in the spin combustion mode of the Ni-Al system are presented. The chronogram model was chosen in the form of four sets of isocline lines, the angle of inclination of which corresponded to the value of the tangential velocity from 16.5 to 41.8 m/s. A high degree of shift invariance of the Trace-transformation nodes was found, the error in determining the coordinates of which is limited only by the presence of the initial additive geometric noise in the image of the differential chronogram of the combustion wave. Scale invariance properties in practice provide a dynamic magnification range of 40 dB.

Keywords: SHS combustion wave, instability, spin combustion, chronoscopy, Trace transformation, scale invariance, criterion.

СПИНОВАЯ НЕУСТОЙЧИВОСТЬ ТЕХНОЛОГИЧЕСКОГО РЕЖИМА ГОРЕНИЯ В ВОЛНЕ САМОРАСПРОСТРАНЯЮЩЕГОСЯ ВЫСОКОТЕМПЕРАТУРНОГО СИНТЕЗА

Григорьевская Анжелика Анатольевна
бакалавр, стажер-исследователь
механико-математического факультета
ФГАОУ ВО «Новосибирский национальный
исследовательский университет»,
Новосибирск, Россия
ORCID: 0000-0002-9909-7337
E-mail: a.a.grig@bk.ru

Гуляев Павел Юрьевич
доктор технических наук,
профессор Института нефти и газа,
ФГБОУ ВО «Югорский государственный университет»
Ханты-Мансийск, Россия
ORCID: 0000-0002-4337-1253
E-mail: p_gulyaev@ugrasu.ru

Представлены результаты компьютерного эксперимента по определению инвариантных свойств Trace-преобразования двумерной хронограммы распространения волн в режиме спинового горения системы Ni-Al. Модель хронограммы была выбрана в виде четырех наборов изоклинных линий, угол наклона которых соответствовал значению тангенциальной скорости от 16,5 до 41,8 м/с. Обнаружена высокая степень инвариантности к сдвигу узлов Trace-трансформации, погрешность определения координат которых ограничивается только наличием исходного аддитивного геометрического шума на изображении дифференциальной хронограммы волны горения. Свойства масштабной инвариантности на практике обеспечивают динамический диапазон увеличения 40 дБ.

Ключевые слова: волна горения СВС, неустойчивость, спиновое горение, хроноскопия, Trace-преобразование, масштабная инвариантность, критерий.

Introduction

Currently, technologies for finishing 3D-printing of metal-ceramic products, such as laser cladding of powders and plasma spraying on the surface of machine parts, have become widespread, but high-temperature synthesis (SHS) technology has the highest productivity [1-3]. The high productivity of technologies for producing nanostructured composites by the SHS method is limited only by the rate and stability of technological combustion [4]. As noted in [5], when using strengthening additives based on amorphous boron, the combustion wave propagates in a mode close to a thermal explosion. On the scale of microheterogeneity of the initial powder mixture, the characteristic time of synthesis and structure formation in the SHS front does not exceed 1 ms [6]. A short time of physical processes requires the use of optoelectronic measuring complexes of nanosecond resolution [7, 8], which make it possible to control not only the temperature and velocity in the combustion wave [9, 10], but also the diffusion-thermal stability of the SHS wave [11], especially in the case of low-exothermic synthesis of materials [12-14] or in the case of introducing a large mass fraction of inert functional additives [15, 16]. Thus, an urgent task is the development of a high-performance computational technology for processing large volumes of video data coming from recording the propagation of the SHS combustion wave [17], which can be solved by compressing information using the differential chronoscopy (DCS) method based on image binarization and calculating the interframe difference [18], and the subsequent application of the Trace-transformation [19, 20] for recognizing the causes of local instability of the microheterogeneous front combustion [21, 22]. The physical basis that ensures the feasibility and high efficiency of the application of these computational algorithms in practice are such features of solid-flame combustion as the competition between the processes of oxidant diffusion and heat removal from the reaction zone [23], which are manifested in the phenomenon of temperature hysteresis of the velocity of the combustion front movement [24] and the prolonged stage depression of the combustion wave for the time of thermo-chemical induction required for ignition of the next layer of exothermic mixture of products [25]. The calculation of the interframe increment of the combustion front coordinate used in the DCS method, due to the constancy of the thermal diffusivity and heat capacity of powder particles from one material, introduces the invariance of the DCS map, which displays the motion of the combustion front isotherm lines, regardless of the particle size [26]. In this case, although the initial spatial shape and structure of the SHS front is largely determined by the random structure of the powder mixture and the diffusion-thermal instability of the combustion process [27], the spatial structure of the differential 2D-map of the DCS has a strictly ordered form of periodic isoclines of the trajectories of the combustion front, separated by equal intervals heating time and thermochemical induction [28]. Violation of this ordering makes it possible to quickly identify unstable combustion modes using formal features used in Trace analysis [29].

The aim of this work is to study the invariant properties that formal features of instability of spin combustion should have when changing the scale of the image and a shift of front in space during the motion of the SHS wave

Description of the problem

The theoretical foundations of mathematical modeling of combustion modes were laid in [18, 28], where the model consists of the heat conduction equation and the kinetic equation:

$$c\rho_0 \frac{\partial T}{\partial t} = \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi^2} + \frac{\partial^2 T}{\partial h^2} \right) + \rho_0 Q \frac{\partial \eta}{\partial t}, \tag{1}$$

$$\frac{\partial \eta}{\partial t} = \begin{cases} k_0 (1-\eta)\exp(-\dfrac{E}{RT}) & \eta < 1, \\ 0 & \eta \geq 1 \end{cases},$$

with the generally accepted designation of physical quantities, except for cylindrical coordinates: r is the radius, φ is the polar angle, h is the layer height.

The 2-dimensional model described here uses temperature for several layers of porous powder packaging:

$$\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + f;$$

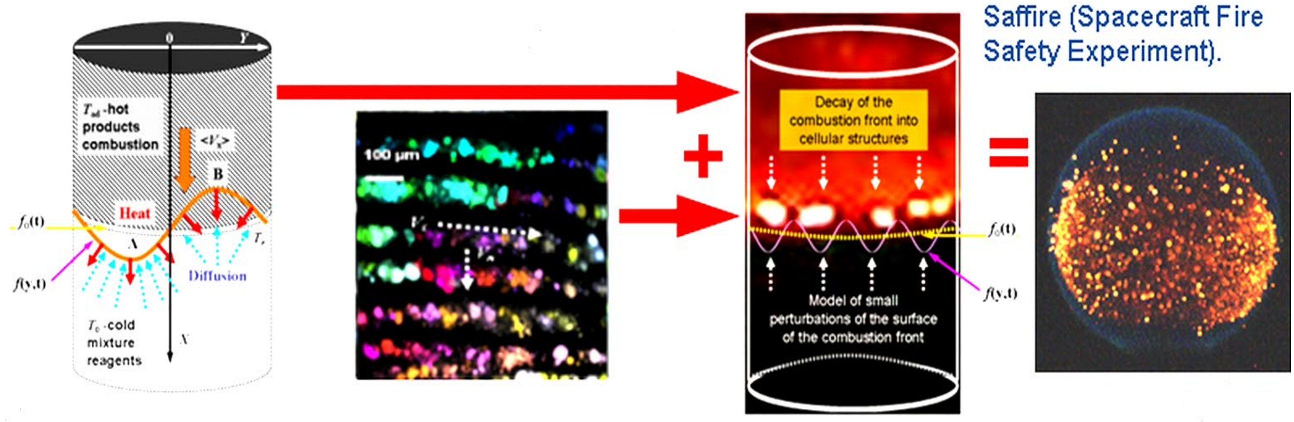
$$\frac{\partial A}{\partial t} = L\left(\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} \right); \tag{2}$$

Here are indicated: T- layer temperature; A_{Ni}, B_{Al} – the corresponding concentration of the components of the mixture in the layer; the coefficients *k, L*, and *M* can be set in the whole table space from the generated initial mixture structure file [18].

When analyzing the stability of the combustion front for equations (1) and (2) in the works of Zeldovich and Barenblatt [27, 30], as a visual feature of the decay of the thermal diffusion flame front into small thermal structures, characteristic scales were introduced into consideration in the form of a model of small perturbations:

$$x=f(y, t)=\varepsilon \exp(iky + i\omega t + \varphi t) \sim \varepsilon \exp(\varphi t) \sin(ky), \tag{3}$$

where: $f(y, t)$ – combustion front surface; ε is a small value; k is the wave number of the transverse disturbance; ω is the circular frequency for the time of thermochemical induction; φ is the temperature decay decrement of the Michelson heating zone (see Figure 1a, 1c).



a. b. c. d.

Figure 1. Visualization of the combustion wave front instability: a – laminar mode [27, 30], b – spin mode [18, 34], c – discrete mode [31, 32], d – combustion mode by "hot spots" in space [33]

The instability of the visually observed sample combustion rate V^* along the OX axis is related to the local curvature of the combustion front by the following relationship:

$$V^* = < V_x > + \frac{E(D-\alpha)}{2RT_{ad}} \times \frac{\partial^2 f(y,t)}{\partial y^2}. \tag{4}$$

Here are denoted: $<V_x>$ – unperturbed velocity of propagation of a flat front; E is the activation energy; T_{ad} is the combustion temperature; D is the diffusion coefficient of the fuel mixture component; α is the coefficient of thermal diffusivity of the mixture of powders; h is the dimensionless heat transfer efficiency coefficient from the reaction zone. In this case, the reaction temperature of technological combustion in a disturbed wave front must satisfy the following conditions:

$$T_r = T_{ad} + (T_{ad} - T_0) h \times e^{iky + i\omega t + \varphi t}. \tag{5}$$

The next significant result in the study of the thermal instability of the SHS combustion wave was the work [34], in which it was shown that under certain conditions (4) and (5) the combustion front breaks, and after that one or several "hot spots" begin to move along the surface of the sample as shown in Figure 1b and 1c. This type of combustion was called "spin mode". Analyzing the results of numerical experiments [18], the authors determined the range of values of the parameter α, when a flat front that satisfies the above conditions (2) – (5) will be unstable:

$$\alpha_{unst} = 9{,}1 \frac{cRT_{ad}^2}{EQ} - 2{,}5 \frac{RT_{ad}}{E} \leq 1. \tag{6}$$

Here c is the specific heat capacity; R is the universal gas constant; Q is the thermal effect of the reaction. Figure 2 shows the results of a computer model of the SHS spin mode [18] and a physical experiment [12].

From equation (5), the instability of the combustion wave can occur at the critical value of the parameter h, which decreases in the absence of convective heat transfer, which is a feature of combustion in weightlessness. In 2020, the NASA experiment (Saffire) was completed, which showed [33] that under microgravity conditions, combustion has two phases: a long depressive phase, the so-called "cold combustion", and rapid combustion in chaotically located "hot spots" (see Figure 1d).

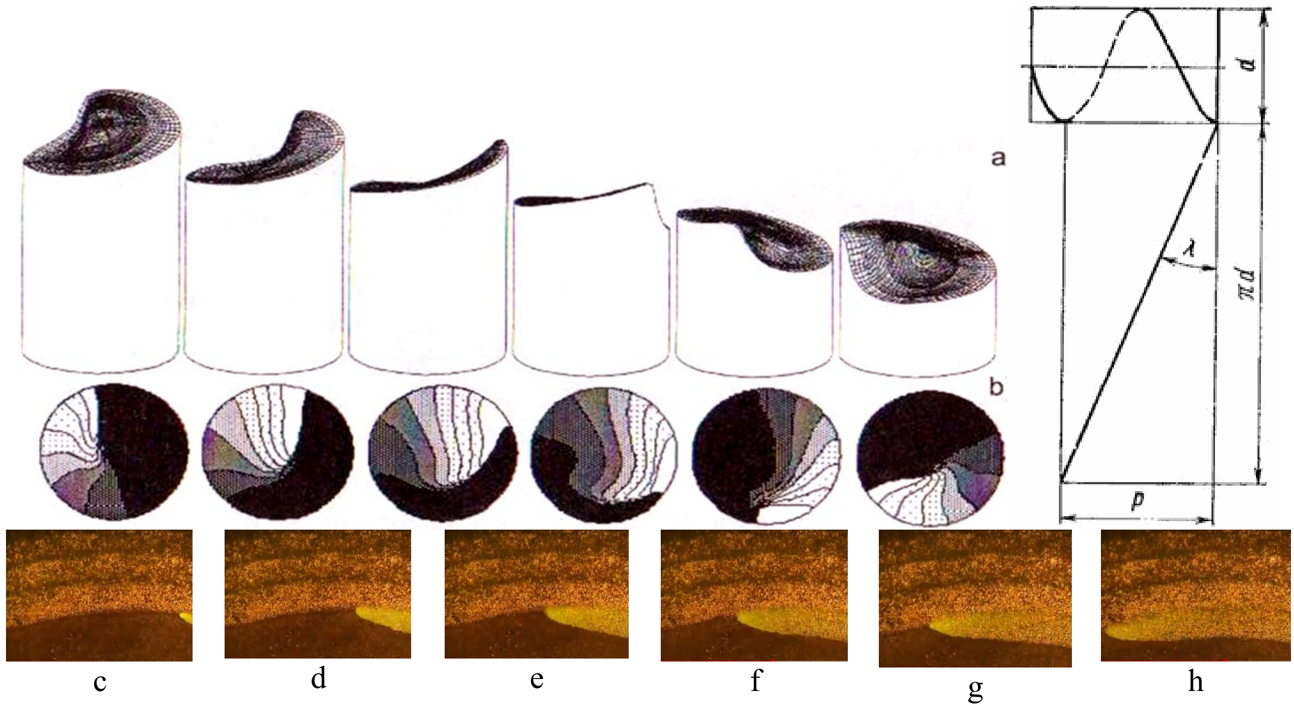


Figure 2. Visualization of SHS combustion front propagation in the spin mode: a and b – computer model [18]; c, d, e, f, g, h – an experiment of recording a combustion wave using high-speed brightness micropyrometry (the higher temperature, the brighter corresponding area) [12]

With uniform rotational and translational motion of the combustion wave along the vertical axis, the angle of elevation of the helix λ is determined from the relationship:

$$tg\lambda = \frac{P}{2\pi r} = \frac{P}{\pi d}, \tag{7}$$

where P is helix pitch, r is the shortest distance of a point from the axis of rotation; d is the diameter of the cylindrical sample on which the combustion wave propagates in the spin mode (see Figure 2). The authors of work [18] showed the correspondence of condition (6), for small values of λ and tg(λ), to formula (7). Thus, the angle of inclination of the helical surface (7) can be considered as a simple visually observable criterion for the stability of a combustion wave in the spin mode.

Considering the above, in Figure 3 one can see the following signs of an unstable spin combustion regime: : a – disintegration of the front into "hot spots"; b – - two stages of combustion "fast" and "depressive" determining the time of thermochemical induction and the thermal thickness of the SHS wave ; c – isoclines on the DCS map when burning in stable mode.

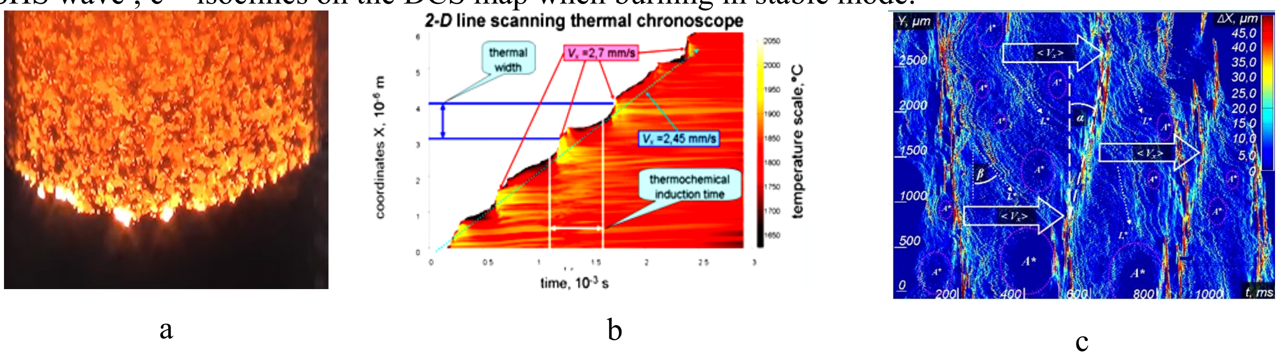


Figure 3. Visual signs of spin instability of the SHS combustion wave in the Ni-Al system

Computer experiment technique

Previously [23, 24, 28], in all experimentally obtained two-dimensional combustion wave chronograms (2D CCS map), three combustion zones can be conventionally distinguished: 1 – unstable ignition; 2- stationary; 3 – change in the direction of spin combustion when the wave is extinguished, as shown in Figure 4.

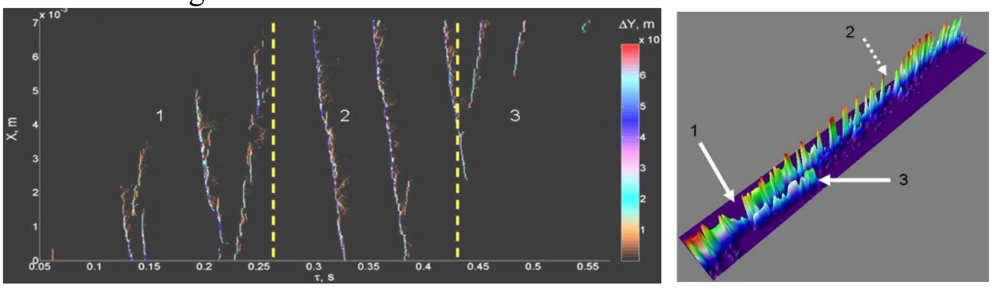


Figure 4. DCS-map of spin instability: 1- node of “strong” instability; 2 – node "weak" instability; 3 – a branch of a part of the combustion front in the direction of the opposite spin.

Figure 5a shows how the Trace transform computes the functional T with respect to the parameter t along the trace line, which is not necessarily integrable in the usual sense. In the stable spin combustion mode, the DCS map is a set of periodic isoclines, and this results in point nodes in the 2D image of the Trace transform, as shown in Figure 5b.

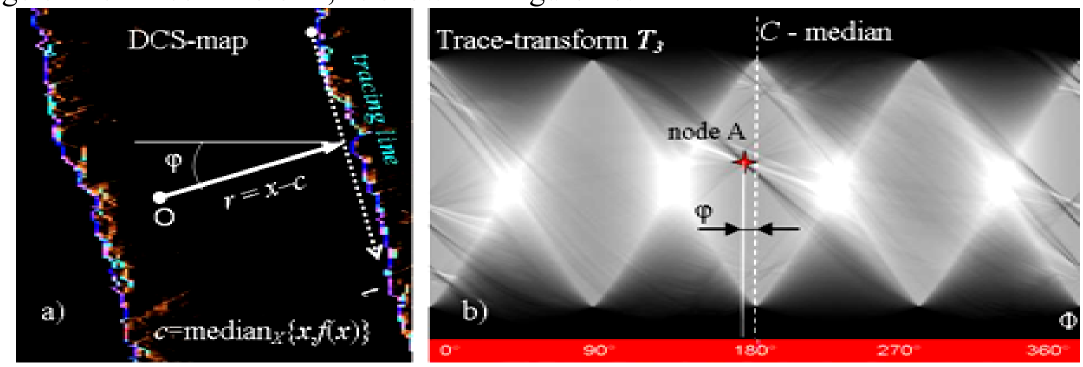


Figure 5. DCS-map (left) and emergence of nodes in the Trace-transform sinogram (right)

Of all the currently known types of functionals (see Table 1) used in standard Trace-transformations for solving pattern recognition problems in artificial intelligence systems [29], we chose Radon Transform, in the form:

$$R(\rho,\varphi) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta(\rho - x\cdot\cos\varphi - y\cdot\sin\varphi)dx\cdot dy, \tag{8}$$

where $f(x,t)$ is a two-dimensional differential chronogram DCS-map of the SHS combustion wave, and all the remaining variables correspond to the designations in Figure 5 and Table 1.

Table 1 – A set of standard Trace transforms T(f(t)) [29]

Equation	Note	Equation	Note
$T_1=\int_0^{\infty} f(t)dt$	Radon transform	$T_{12}=\int_{c^*}^{\infty}\sqrt{r}\,f(t)dt$	c^* signifies the nearst integer to $\boldsymbol{c}$
$T_2=[\int_0^{\infty}\lvert f(t)\rvert^2 dt]^{\frac{1}{2}}$	Diffusion law	$T_{13}=\int_{c^*}^{\infty} rf(t)dt$	$\boldsymbol{t}=(x,y)$
$T_3=[\int_0^{\infty}\lvert f(t)\rvert^4 dt]^{1/4}$	Rayleigh's law	$T_{14}=\int_{c^*}^{\infty} r^2 f(t)dt$	$f(\boldsymbol{t})=f(x,y)$

$T_4=\int_0^\infty \lvert f(t)'\rvert dt$	$f(t)'=(t_2-t_1),(t_3-t_2),\dots(t_n-t_{n-1})$	$T_{15}=$ median$_{t^*}\{f(t^*),\lvert f(t^*)'\rvert^{1/2}\}$	$f(t^*)=\{f(t_{c^*}),f(t_{c^*+1}),\dots,f(t_n)\}$
$T_5=$ median$_t\{f(t),\lvert f(t)\rvert\}$	Weighted median	$T_{16}=$ median$_{t^*}\{f(t^*),\lvert f(t^*)'\rvert^{1/2}\}$	l=c*,c*+1,…,n;
$T_6=$ median$_t\{f(t),\lvert f(t)'\rvert\}$	Median	$T_{17}=\lvert\int_{c^*}^\infty e^{i4\log(r)}\sqrt{r}\,f(t)dt\rvert$	$c=$median$_{t^*}\{l,\lvert f(t)\rvert^{1/2}\}$
$T_7=[\int_0^{\frac{n}{2}}\lvert F\{f(t)\}(t)\rvert^4\, dt]^{1/4}$	F – discrete Fourier Transform	$T_{18}=\lvert\int_{c^*}^\infty e^{i3\log(r)}f(t)dt\rvert$	
$T_8=\int_0^{\frac{n}{2}}\left\lvert\frac{d}{dt}M\{f(t)\}\right\rvert dt$	M –median over a length 3 window	$T_{19}=\lvert\int_{c^*}^\infty e^{i5\log(r)}rf(t)dt\rvert$	
$T_9=\int_0^\infty rf(t)dt$	$(\frac{d}{dt})$ difference	$T_{20}=\int_c^\infty \sqrt{r}\,f(t)dt$	$r=\lvert l-c\rvert;l=1,2,\dots,n;$
$T_{10}=$median$_t\{l,\lvert f(t)'\rvert^{1/2}\}$	of successive samples	$T_{21}=\int_c^\infty rf(t)dt$	$c=\frac{1}{S}\int_0^\infty l\lvert f(t)\rvert dr$;
$T_{11}=\int_0^\infty r^2f(t)dt$	$r=\lvert l-c\rvert;l=1,2,\dots,n;$ $c=$median$_t\{l,f(t)\}$	$T_{22}=\int_c^\infty r^2f(t)dt$	$S=\int_0^\infty\lvert f(t)\rvert dr$

The results of a computer experiment for determining the scale and shear invariance of the Trace transform of a two-dimensional chronogram of the propagation of a wave of self-propagating high-temperature fusion (SHS) in an unstable spin combustion mode are presented [7, 8]. Model chronograms were taken in the form of four sets of isocline lines, the slope of which corresponded to the value of the tangential velocity from 16.5 to 41.8 m/s, selected based on the analysis of high-speed video recording of the combustion wave in the Ni-Al system [12].

The range of isocline slopes (4, 6, 8 and 10 degrees), in which stable spin combustion in the Ni-Al system was modeled, corresponds to the theoretical values of the tangential spin combustion velocity component in the range from 16.5 to 41.8 m/s, registration which are not yet available for experimental observation, as shown in Figure 6.

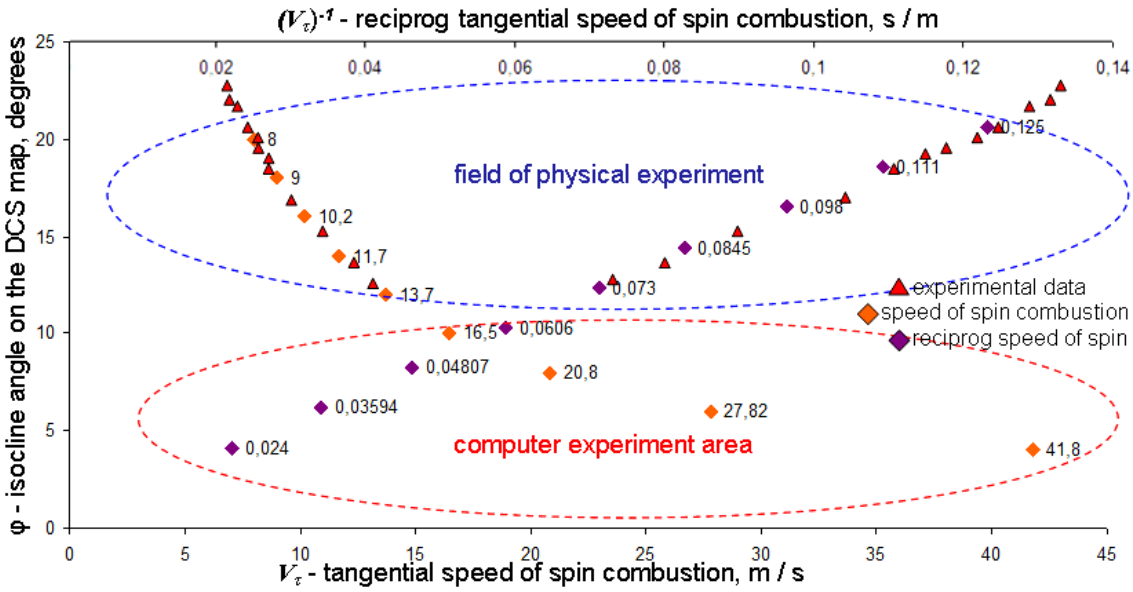


Figure 6. Choice of the domain for determining the parameters of the DSC model of spin combustion

The planning of the experiment is shown in Figure 7a, which shows examples of partitioning into analysis windows W1, W2, W3, W4 of "reference" phantoms from (ideal) DCS chronograms – differential chronoscopy maps [24, 26, 28].

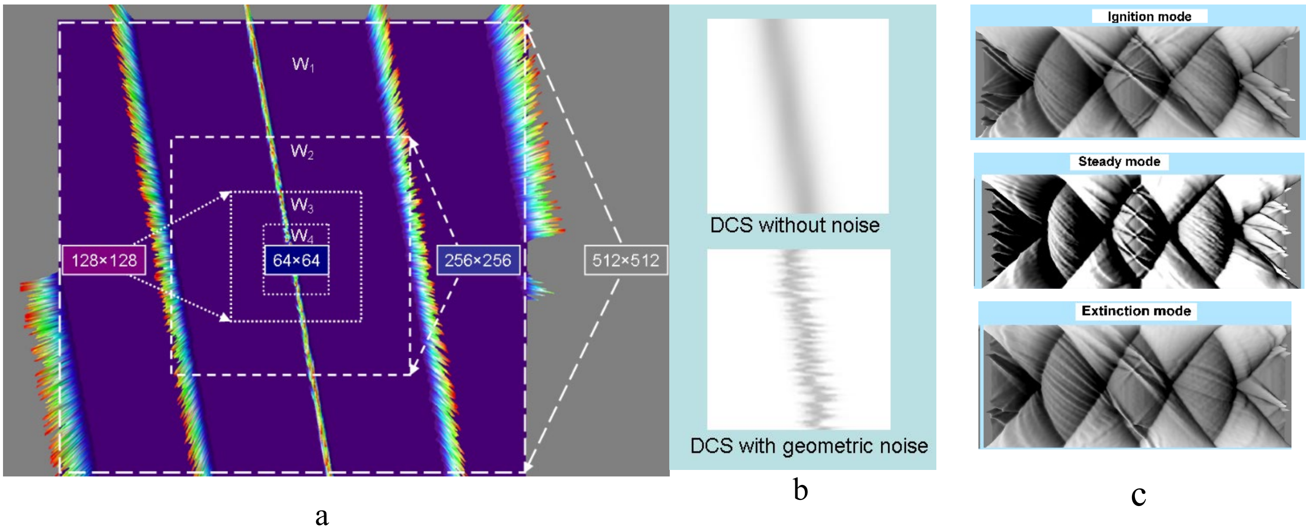


Figure 7. Stages of planning a computer experiment and the model of the DCS-map of spin combustion: a – analysis windows with a change in scale; b – DCS isoclines with and without noise; Trace-sinograms for identifying signs of instability of spin combustion

We have used the property of "ideal" spin combustion (7), for which the DCS chronogram is a family of isoclines. The angle of inclination of the isocline corresponds to the speed and direction of spin combustion: counterclockwise or clockwise "right" or "left" screw sign is determined by the "gimlet" rule. Figure 7b shows an example of an ideal DCS phantom isocline, and below with geometric noise. In the experiment, the noise/signal ratio was taken equal to 1:1 (i.e., the thickness of the "isoclinic" line is equal to the value of the dispersion of the random deviation).

Results and discussion

An indicator of spin instability can be the deviation of the i-th node of the sinogram from the median symmetry axis C by the angular value φ_i (see Fig.5b). The Triple trace-feature can be given in the form $\Pi=\Sigma(\varphi_i\times\rho_j)$, where ρ_j is the statistical weight of the local maximum A_i or B_i in the histogram of the corresponding diametral functional P (Fig.5c).

The scale invariance was checked using a test set of chronograms corresponding to four values of the optical magnification factor when recording a combustion wave: ×1, ×2, ×4, ×8.

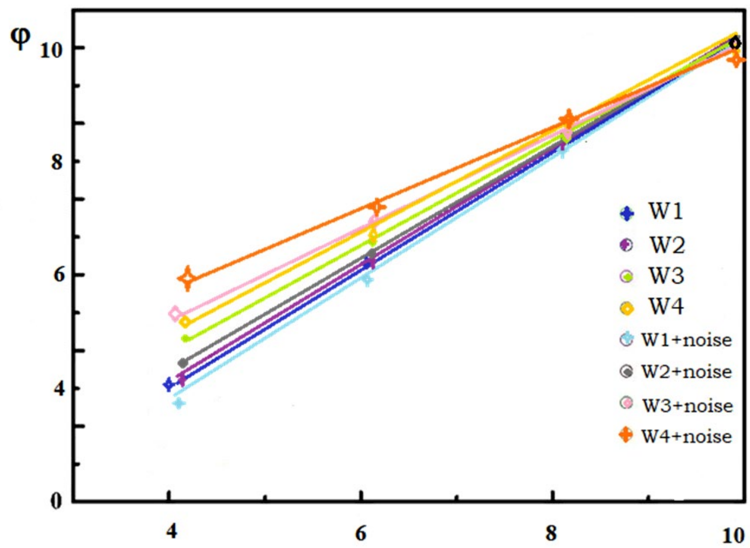
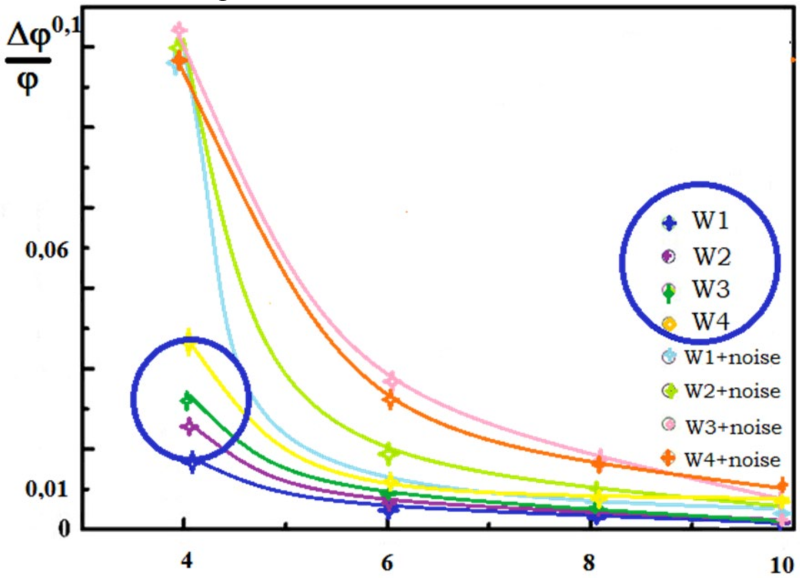


Figure 8. Verification of the Scale Invariance Properties of the Spin Instability Trace Criterion.

The scale invariance has a multiplicative error that is a multiple of the magnification factor of the optical field of view: $\Delta\varphi = k\,\Delta\varphi_0$

The influence of the random nature of the formation of the combustion front was taken into account by introducing additive geometric noise at the level of -20 dB into the chronogram model, as can be seen in Figure 9.



Scale of analysis windows when zooming:

W_1 (512x512) k= 1:1

W_2 (256x256) k= 1:2

W_3 (128x128) k= 1:4

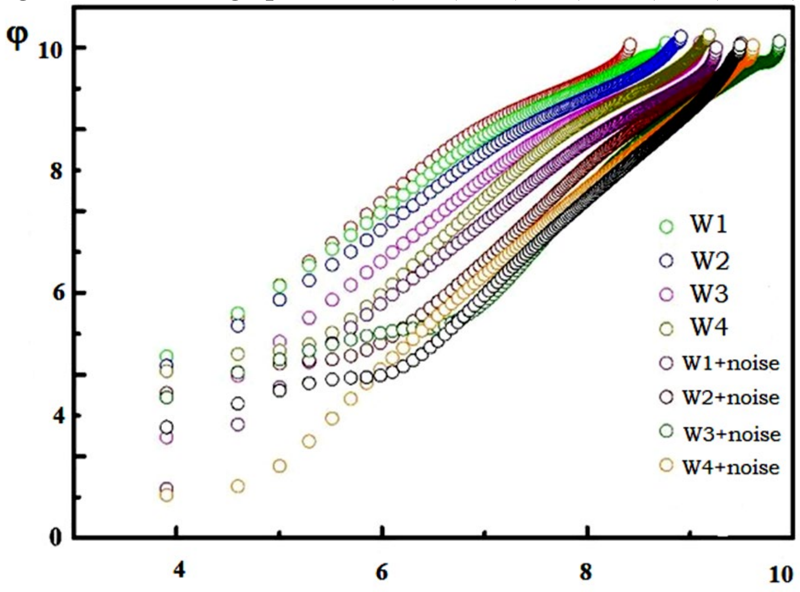
W_4 (64x64) k= 1:8

Noise

±12 pixel

Figure 9. The value of the relative error in measuring the angle of inclination of the DCS isoclines

Time shift invariance was tested at four chronogram delay intervals or shifts by the corresponding number of image pixels: 4 (2 ms), 8 (4 ms), 16 (8 ms), 32 (16 ms), as seen in Figure 10.



DCS shift amount:

W_1 (512x512) Δ= 32 (16ms)

W_2 (256x256) Δ= 16 (8ms)

W_3 (128x128) Δ= 8 (4ms)

W_4 (64x64) Δ=4 (2ms),

The shift invariance has a constant additive error in the analysis window W_i:

$\Delta\varphi = const\,(W_i)$

Figure 10. Verification of the Shift Invariance Properties of the Spin Instability Trace Criterion

A high degree of shift invariance of trace-transformation nodes is shown, which is limited only by the presence of additive geometric noise in the original image of the combustion wave.

Conclusions

1. A high degree of invariance to the shift of the Trace-transformation nodes is shown, the error in determining the coordinates of which is limited only by the presence of the initial additive geometric noise $\Delta\varphi_0$ in the image of the differential chronogram of the combustion wave (provided: $\Delta\varphi_0$ = const) [24, 26, 28].

2. The scale invariance of the Trace-features with a change in k (the magnification factor of the optical system) remains on the average ($<\varphi>$), and the error in determining the angular coordinates of the nodal points of the Trace transform increases with a scale increase: $\Delta\varphi = k{\cdot}\Delta\varphi_0$, where $\Delta\varphi_0$ is the error at $k = 1$.

3. Scaling is possible up to the limiting value of the optical magnification factor of the microscope $k = <\varphi>/\Delta\varphi_0$, where $<\varphi>$ is the average tilt angle of the DCS isocline, which in practice provides a dynamic magnification range of 40 dB.

Acknowledgments

This study was partially funded by a scholarship from the Novosibirsk City Hall (by the City Hall resolution of August 24, 2020 N 2587).

References

1. Effect of plasma spraying regimes on structure and properties of Ni_3Al coatings / E. E. Kornienko, D. O. Mul', O. A. Rubtsova [et al.]. – DOI 10.1134/S0869864316060147 // Thermophysics and Aeromechanics. – 2016. – Vol. 23. – № 6. – P. 919–927.

2. Cold spraying of aluminum bronze on profiled submillimeter cermet structures formed by laser cladding / N. S. Ryashin, A. G. Malikov, V. S. Shikalov [et al.]. – DOI 10.1063/1.5007495 // Proceedings of the XXV Conference on High-Energy Processes in Condensed Matter (HEPCM 2017) : Dedicated to the 60th anniversary of the Khristianovich Institute of Theoretical and Applied Mechanics SB RAS (Electronic resource): AIP Conference Proceedings, Novosibirsk, 05-09.06.2017 / editors V. Fomin. – Novosibirsk : AIP Publishing, 2017. – P. 030037.

3. Development prospects of SHS technologies in Altai state technical university / V. V. Evstigneev, P. J. Guljaev, I. V. Miljukova [et al.] // International Journal of Self-Propagating High-Temperature Synthesis. – 2006. – Vol. 15, № 1. – P. 99–104.

4. Thermal analysis of reaction producing K_XTiO_2 / K. Borodina, S. Sorokina, N. Blinova [et al.]. – DOI 10.1007/s10973-017-6840-0 // Journal of Thermal Analysis and Calorimetry. – 2018. – Vol. 131, № 1. – P. 561–566.

5. Cui, H. Z. Influence of micropores on structural instability of the combustion wave / H. Z. Cui, A. A. Grigoryevskaya, P. Yu. Gulyaev. – DOI 10.17816/byusu20190433-40 // Yugra State University Bulletin. – 2019. – № 4 (55). – P. 33–40.

6. Dolmatov, A. V. Thermal imaging complex with tracking function for joint research of microheterogeneous processes and macrokinetics of SHS phenomenon / A. V. Dolmatov, P. Y. Gulyaev. – DOI 10.1088/1742-6596/1333/6/062006 // Journal of Physics: Conference Series : International Conference «Information Technologies in Business and Industry», Novosibirsk, 13-15.02.2019. – Novosibirsk : Institute of Physics Publishing, 2019. – P. 062006.

7. Бороненко, М. П. Телевизионная измерительная система наносекундного разрешения / М. П. Бороненко, П. Ю. Гуляев. – Текст : непосредственный // Доклады Томского государственного университета систем управления и радиоэлектроники. – 2014. – № 1(31). – С. 60–64.

8. Increasing the noise immunity of optical-electronic systems based on video cameras with an optical converter / M. P. Boronenko, P. Yu. Gulyaev, A. E. Seregin, K. G. Poluhina. – DOI 10.1088/1742-6596/643/1/012028 // Journal of Physics: Conference Series. – 2015. – Vol. 643. – P. 012028.

9. Экспериментальное исследование характеристик топливных струй / А. Е. Свистула, Д. Д. Матиевский, П. Ю. Гуляев, А. В. Еськов. – Текст : непосредственный // Двигателестроение. – 1999. – № 1. – С. 29–31.

10. Измерение скорости и температуры частиц в потоке низкотемпературной плазмы / М. П. Бороненко, И. П. Гуляев, П. Ю. Гуляев, А. Е. Серегин. – Текст : непосредственный // Известия высших учебных заведений. Физика. – 2014. – Т. 57, № 3-2. – С. 70–73.

11. Gulyaev, P. Instability of the Ni-Al combustion wave in the Zeldovich-Barenblatt parameters / P. Gulyaev, A. Dolmatov, V. Jordan. – DOI 10.1088/1742-6596/1353/1/012036 // Journal of Physics: Conference Series : International Conference «High-Tech and Innovations in Research and Manufacturing» HIRM 2019, Krasnoyarsk, 06.05.2019. – Krasnoyarsk : Institute of Physics Publishing, 2019. – P. 012036.

12. Boronenko, M. High-speed visualization of combustion synthesis discrete reaction waves: Coherent heat microstructures / M. Boronenko, P. Gulyaev, A. Dolmatov. – DOI 10.1088/1742-6596/1115/4/042021 // Journal of Physics: Conference Series, Tomsk, 16-22.09.2018. – Tomsk : Institute of Physics Publishing, 2018. – P. 042021.

13. Optical-ectronic system for diagnostics of two-phase flows by dynamic particles count method / P.Yu. Gulyaev, V.I. Iordan, I.P. Gulyaev [et al.] // Russian Physics Journal. – 2008. – Vol. 51. – № 9-3. – P. 79–87.

14. Analysis and optimization of gas-thermal spray process in terms of condensed phase velocity and temperature / A. V. Dolmatov, I. P. Gulyaev, E.A. Lyskov [et al.]. – DOI: 10.1134/S0869864317010097 // Thermophysics and Aeromechanics. – 2017. – Vol. 24 (1). – P. 83–94.

15. Limit of inert functional admixtures depending on the dispersion in the combustion synthesis of nickel aluminides / P. Gulyaev, A. Dolmatov, V. Jordan, Y. Panchenko. – DOI: 10.1088/1742-6596/1134/1/012018 // Journal of Physics: Conference Series. – 2018. – Vol. 1134. – P. 012018.

16. Wien"s criterion for choosing the parameters for reducingtion of the temperature distribution of particles by their total thermal spectrum / P. Yu. Gulyaev, V. I. Iordan, I. P. Gulyaev [et al.] // Russian Physics Journal. – 2008. – Vol. 51, № 9-3. – P. 69–76.

17. Иордан, В.И. Разрешающая способность виртуальных приборов контроля температуры частиц в плазменных потоках по суммарному спектру / В. И. Иордан. – Текст : непосредственный // Ползуновский альманах. – 2008. – № 2. –С. 13–14.

18. Ivleva, T. P. Three-dimensional modes of unsteady solid-flame combustion / T. P. Ivleva, A. G. Merzhanov. – DOI 10.1063/1.1540772 // Chaos (Woodbury, N.Y.). – 2003. – Vol. 13, № 1. – P. 80–86.

19. Гуляев, П. Ю. Моделирование технологических процессов плазменного напыления покрытий наноразмерной толщины / П. Ю. Гуляев, И. П. Гуляев. – Текст : непосредственный // Системы управления и информационные технологии. – 2009. – Т. 35, № 1.1. – С. 144–148.

20. Моделирование фрактальных структур упаковок порошковых СВС-материалов / И. В. Милюкова, А. Л. Трифонов, С. А. Ширяев [и др.]. – Текст : непосредственный // Ползуновский альманах. – 2007. – № 3. – С. 39–41.

21. Гуляев, П. Ю. Байесовское восстановление цвета цифровых изображений / П. Ю. Гуляев, Ю. П. Гуляев, А. В. Долматов. – Текст : непосредственный // Вестник СГУГиТ. – 1997. – № 2. – С. 114–115.

22. Dolmatov, A. V. Investigation of structure formation in thin films by means of optical pyrometry / A. V. Dolmatov, I. V. Milyukova, P. Y. Gulyaev. – DOI: 10.1088/1742-6596/1281/1/012010 // Journal of Physics: Conference Series. – 2019. – Vol. 1281. – P. 012010.

23. Gulyaev, P. Trace-Analysis of Images of the Differential Chronogram of the Combustion Wave for Recognition of Transitional Modes of SHS / P. Gulyaev, V. Jordan // CEUR Workshop Proceedings: Optoelectronic equipment and devices in systems of pattern recognition, image and symbol information processing. Recognition. – 2017. – Vol. 1940. – P. 37–44.

24. Gulyaev, P. Experimental Observation of the Instability Mode in the Combustion Wave by the Differential Chronoscopy Method / P. Gulyaev, A. Grigoryevskaya, V. Jordan. – DOI:

10.1109/EFRE47760.2020.9241952 // 7th International Congress on Energy Fluxes and Radiation Effects (EFRE 2020). – 2020. – P. 1227–1231.

25. Григорьевская, А. А. Компьютерная визуализация радиационного теплопереноса в волне горения СВС / А. А. Григорьевская, П. Ю. Гуляев. – Текст : непосредственный // Ползуновский альманах. – 2019. – № 4. – С. 5–9.

26. Григорьевская, А. А. Компьютерный эксперимент верификации инвариантных свойств Trace-критерия спиновой неустойчивости движения фронта горения / А. А. Григорьевская. – Текст : непосредственный // Математика : материалы LIX Международной научной студенческой конференции. – Новосибирск : ИПУ НГУ, 2021. – С. 94–95.

27. Зельдович, Я. Б. Теория горения и детонации газов / Я. Б. Зельдович. – Москва ; Ленинград : АН СССР, 1944. 71 с. – Текст : непосредственный.

28. Grigoryevskaya A., Jordan V., Shmakov I., Gulyaev P. Criteria for spin instability based on the node distribution in Trace-transform of the SHS combustion wave chronogram //Journal of Physics:Conference Series.- 2021.- Vol. 1745.- С. 012065.

29. Kadyrov, A. The Trace transform and its applications / A. Kadyrov, M. Petrou // IEEE Transactions on Pattern Analysis and Machine Intelligence. – 2001. – Vol. 23. – P. 811–828.

30. Barenblatt, G. I. On thermal-diffusive stability of a laminar flame / G. I. Barenblatt, Ya. B. Zel'Dovich, A. G. Istratov // Journal of Applied Mechanics and Technical Physics. – 1962. – Vol. 4. – P. 21–26.

31. Lam, F. Front roughening of flames in discrete media / F. Lam, X.C. Mi, A. J. Higgins. – DOI: 10.1103/PhysRevE.96.013107 // Physical Review E. – 2017. – Vol. 96. – Iss. 1. – P. 013107.

32. Micro-heterogeneous regimes for gasless combustion of composite materials / J. M. Pauls, C. E. Shuck, A. S. Mukasyan, A. S. Rogachev. – DOI 10.1080/00102202.2017.1417269 // Combustion Science and Technology. – 2018. – Vol. 190, № 5. – P. 893–908.

33. Bharat, N. T. Effect of Heat Loss on Propagation Limits of Combustion Fronts / N. T. Bharat, D. P. Mishra, M. K. Gundawar // Combustion Science and Technology. – 2020. – Vol. 192 (3). – P. 391–415.

34. Мержанов, А. Г. Новые явления при горении конденсированных систем / А. Г. Мержанов, А. К. Филоненко, И. П. Боровинская. – Текст : непосредственный // Доклады Академии наук СССР. – 1973. – Т. 208. – С. 829.