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Torch Combustion and Low-Frequency Non-Acoustic Combustion Instability Phenomena in Solid Propulsion Physics

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ABSTRACT
Understanding of the mechanism of the low-frequency non-acoustic instability phenomena at the solid rocket propellants combustion - one of the most complicated problems in the solid propulsion physics. The burning process of each specific solid propellant can be characterized by the set of own frequencies of pulsations of the burning surface that appears in the critical burning conditions. Several theories have been proposed highlighting one or other process as the dominant mechanism, but a unifying theory is yet to emerge. The present work focuses on one of the critical events, namely the spatial-periodic micro-structures excitation in the evaporated energetic materials liquid-viscous layer. The low-frequency non-acoustic combustion instability phenomenon, the chuffing phenomenon and the accompanying physics-chemical effects have received a new explanation within the concept based on the data of optical visualization of the physics-chemical processes on the energetic materials burning surface. This concept connected, mainly, with excitation of the synergetic dissipative spatial-periodic micro-structures in the thin liquid-viscous layer and on the energetic materials burning surface. At heating from above in the thin liquid-viscous layer occurs the thermo-electric convection excitation, that induce cellular movement and formation of the synergetic spatial-periodic micro-structures. On the energetic materials burning surface is observed the process of self-organizing of the dynamic dissipative synergetic spatial-periodic micro-structures into the torch macro-structures. Suggested mechanism opens possibilities for understanding the essence of the energetic materials unstable combustion phenomena on the new qualitative level.

Keywords: Evaporated Energetic Materials, Combustion Instability, Torch Macro-Structures, Ionic Fusion, Thermo-Electric Convection Excitation, Carbon Grid

NOMENCLATURE

a	- Thermal diffusivity of the energetic material liquid-viscous layer;
C	- Specific heat capacity of the condensed phase;
E_a	- Activation energy of the condensed phase reactions;
F_L	- Buoyancy (lifting) force (the difference between Archimedean force and the force of gravity), (Rayleigh, 1916);
F_{ST}	- Surface tension force (thermo-capillary force), (G.K.A. Pearson, 1958), (the convection cells arising under influence of this mechanism is known as Maringoni cells);
F_{TE}	- Thermo-electric (electrostatic) force, Coulomb's force, (I.V. Ioffe and E.D. Eidelman, 1976);
g	- Acceleration due to gravity;
h	- Characteristic size of fluctuation movement (the thickness of the energetic material liquid-viscous layer, cross-sectional size of the cell);
k_0	- Pre-exponential factor of chemical reaction rate;
P	- Combustion products pressure;
q_0	- Heat release distribution due to chemical reactions in the solid phase and in the energetic

	material liquid-viscous layer;
Q_0	- Heat flux issuing from the gaseous phase (flame) to the surface of the burning cell;
R	- Gas constant;
t	- Time of the process;
T	- Temperature;
T_0	- Initial temperature;
T_C	- Temperature of the "cold" boundary surface of the energetic material liquid-viscous layer;
T_h	- Temperature of the "hot" boundary surface of the energetic material liquid-viscous layer (on the interface of liquid-viscous layer and gasification zone);
T_R	- Temperature of beginning of the effective exothermic reactions;
T_S	- Temperature on the energetic material burning surface;
u_C	- Linear burning rate of the energetic material sample;
$u_C^{(i,j)}$	- Linear burning rate of the energetic material sample in the cell with number "(i, j)";
z	- Space coordinate, perpendicular to the energetic material liquid-viscous layer;

Greek Symbols

χ_S	- Average thickness of the reaction liquid-viscous layer (the effective thickness of the zone of electric conductivity);
φ_0	- Temperature gradient;
λ_C	- Conductivity;
ρ	- Density of the energetic material liquid-viscous layer, density of the condensed phase;

Subscripts and Superscripts

c	- Condensed phase;
g	- Gas phase;
s	- Surface;
0	- Parameters of equilibrium state.

1.0 INTRODUCTION

The problem of combustion instability and anomalies of burning of the energetic materials (EM) traditionally remains one of actual problems in the theory of combustion [1]. The evolutionary history of the EM reflects to some extent the history of investigation of combustion instability and methods for its removal.

The principles of the EM combustion anomalies theory were established by outstanding Russian scientist Ya.B. Zel'dovich [2]. Prediction of ignition transients and low-frequency non-acoustic combustion instability in the solid propulsions systems (SPS) has remained a topic of active research for several decades, yet there appears to be no model that can describe the roles played by all the complex physics-chemical processes. The development of larger and more sophisticated SPS have emphasized the need to model the ignition transients accurately as they do not lend themselves to costly trial and error development techniques. The radical difference in size and technology of these SPS defy extrapolation of the empirical knowledge gained in the development of earlier, more conventional SPS.

With regard to the physical mechanisms of the solid rocket propellant combustion, the combustion zone is quite complicated even under steady state conditions, with multiple flamelets attached to different parts of the burning surface. The complications are, in part, due to the statistically random nature of the distribution of the reactants in the condensed phase, and, in part, due to poor understanding of the combustion zone owing primarily to its microscopic nature and the hostility of the environment to clear investigation. Understanding of the mechanism of the low-frequency non-acoustic instability phenomena at the solid rocket propellants combustion - one of the most complicated problems in the solid propulsion physics. Several theories have been proposed highlighting one or other process as the dominant mechanism, but a unifying theory is yet to emerge. The present work focuses on one of the critical events, namely the spatial-periodic micro-structures (SPMS) excitation in the evaporated EM liquid-viscous layer (LVL).

2.0 THE LOW-FREQUENCY NON-ACOUSTIC INSTABILITY IS THE CHARACTERISTIC PROPERTY OF COMBUSTION PROCESS OF THE SOLID ROCKET PROPELLANTS

SPS with a small characteristic length of the chamber L* may exhibit spontaneous oscillations in the chamber pressure. If the oscillations occur simultaneously in the bulk of the chamber, such an instability has been variously called the L*, bulk mode or non-acoustic type. The phenomenon is typically characterized by the amplifying low-frequency pressure oscillations of below some 300 Hz, leading to the extinction of the SPS. In extreme cases, when the L* is very small, extinction occurs almost immediately after ignition, followed by a sequence of periodic pressure build-up and extinction: such a process has been called chuffing.

The phenomenon of chuffing involves large pressure fluctuations, sometimes with widely varying frequencies. Although the order of magnitude of chuffing frequencies suggests a dominant solid-phase energy release mechanism at low pressures, the underlying process is not convincingly explained yet. Such kind of combustion instability in the combustion chamber is most frequently observed for the end-burning solid propellant charges and for channel-shaped propellant grains. According to the data presented in the paper [3], for the channel-shaped charges the boundary of low-frequency combustion instability depends not from the channel volume and the chamber volume, but is determined, mainly, by the pre-nozzle volume. Therefore, if the volume of the SPS combustion chamber with end-burning charge coincides with the pre-nozzle volume of the SPS with a channel-shaped charge, the boundaries of their low-frequency stability coincide.

In the paper [4] on the basis of large number of the fire stand tests has been made conclusion that periodic processes - the chuffing processes and the low-frequency non-acoustic combustion instability are the characteristic properties of combustion process of the solid rocket propellants. Usually, these properties appears in the conditions of low pressure in the combustion chamber and (or) in the conditions of the low ambient temperatures. As a matter of fact, for the first time has been suggested assumption that the burning process of each specific solid propellant can be characterized by the set of own frequencies of pulsations of the burning surface that appears in the critical burning conditions. And also has been mentioned the existence of some universal law connected with unstable processes on the burning surface of the solid propellants.

However how it is possible to explain this universal property and what physical phenomena appears here not enough clearly till now.

Existence of such problems has been indicated in the recent dissertations [3], [5]. The hypothesis that the determining mechanism of excitation of the low-frequency combustion instability and chuffing are the reactions in the gas phase has been suggested in the paper [6]. The similar hypothesis about existence of the gas-phase oscillatory chemical reactions which excite low-frequency combustion instability and chuffing has been suggested again in 2003, in the dissertation [5]. However the papers [4], [7] have convincingly shown that the determining mechanism of excitation of the chuffing processes and the EM low-frequency combustion instability are the reactions in the condensed phase (the mechanism of thermal explosion of the condensed phase), but not the reactions in the gas phase. Frequency of pulsations at the burning process of the propellant laboratory samples in the air appeared same as at burning of the samples in the conditions of the nitrogen flow above the propellant burning surface. At the same time, the heat feedback from the hot gases trapped in the chamber when the chamber and ambient pressure equalized due to extinction, could not cause re-ignition of the propellant. Re-ignition after extinction, and hence chuffing, could not be obtained with a surface reaction model.

3.0 TORCH COMBUSTION PHENOMENON – ONE OF THE MOST COMPLICATED PROBLEM IN THE SOLID PROPULSION PHYSICS

For successful solution of the problems, connected with suppression of the SPS combustion instability are necessary to have detailed understanding about essence of mechanisms of the EM unstable burning on the new qualitative level. Obviously the possibilities of understanding of laws of this complex phenomenon are closely connected with excitation and formation of the cellular micro-structures on the EM burning surface.

Certainly, the new level in understanding of the fundamental laws of the EM low-frequency non-acoustic combustion instability can be provided on the basis of use of the newest technologies of visualization of zones of burning of the EM. Recently with use of new interferometric and shadow technologies of optical visualization of the zones of burning of the EM, the unique results overturning traditional representations about the mechanisms of cellular-pulsating burning and low-frequency non-acoustic instability at the solid rocket propellants combustion have been received [8] – [10].

Understanding of the mechanism of the torch (cellular-pulsating) combustion phenomenon of the solid rocket propellants - one of the most complicated problems in the solid propulsion physics. The torch macro-structures on the EM burning surface can be considered as independent synergetic structures. This phenomenon reflects universal law of the SPMS excitation on the EM burning surface.

The experimental data have shown that torch (cellular-pulsating) combustion phenomenon develops irrespective of properties and structure of the specific EM. At realization of this burning mode the sizes of torches (burning cells) are not connected with sizes of components and the sizes and structure of researched EM. Besides, according to the experimental data, ignition of long propellant channels occurs in the cellular or in the torch (cellular-pulsating) mode [11].

Also the experimental data has shown that active (reaction-capable) SPMS (the burning cells) on the burning surface are united into the more large-scale structures - into the torch macro-structures. By other words, on the EM burning surface is observed the process of self-organizing of the dynamic dissipative synergetic SPMS into the torch macro-structures. The torch macro-structures on the EM burning surface can be considered as independent synergetic structures. This phenomenon reflects universal law of the SPMS excitation on the burning surface of the EM. In this connection, on the burning surface the process of moving (wandering) of the torches is observed.

Figure 1 shows dynamics of two torch macro-structures on the burning surface of the standard ballistite propellant. The processes in each of the burning cells develops independently from each other. The torch structures on the burning surface can exist steadily in the event that they form a pair of two torches. This phenomenon is observed also on the shadow photos of torches on the burning surface.

Figure 1 (1) shows a luminescence of gaseous products of reaction in the one torch. At this time occurs formation of the carbon grid on the burning surface. After formation of the carbon grid on the burning surface the luminescence of the torch disappears. Further the process starts to develop on the burning surface and appears luminescence of the carbon grid on the burning surface (Fig. 1 (2)). The combustion products flowing from the burning surface throw away a carbon grid from the burning surface (Fig. 1 (3)). After throwing away of the carbon grid the luminescence of the torch above the burning surface appears again (Fig. 1 (4)).

Separate researches of the torch structures were executed, with use of shadow method, both for the gun-powder "N" and for standard gun-powders on the basis of nitrocellulose with the lead oxide [8] – [10]. In the researches were used the gun-powder plates with thickness of 3 mm (on the course of the light beam) and with width of 12 mm.

Fig. 2 - Fig. 4 contain the information only of two categories. Firstly, this is jet streams of the gasification products from the burning surface and secondly, the dependence of the sizes (and accordingly, the numbers) of the burning cells from the pressure.

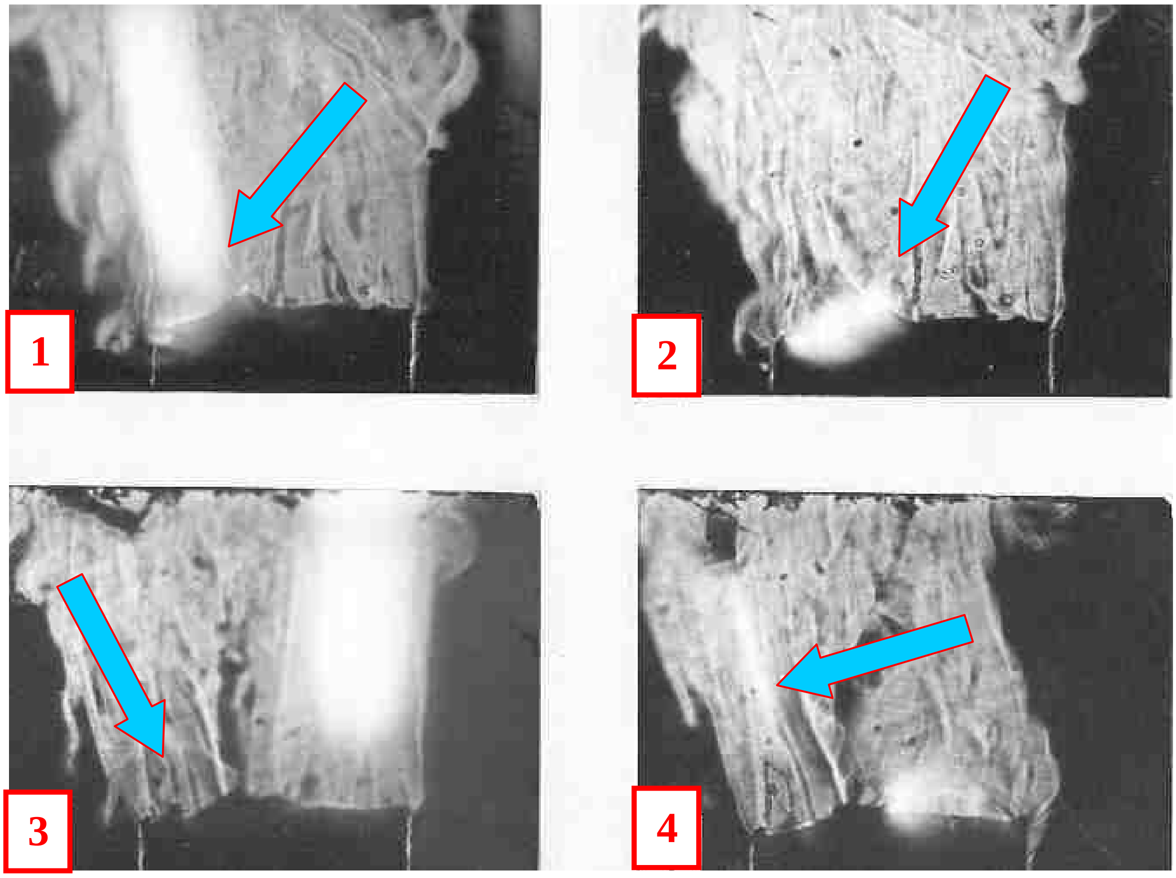


Figure 1. The Effect of Formation of the Pair of Torch Macro-Structures. Sequential Images of Dynamics of Two Torch Macro-Structures on the Burning Surface of the Standard Ballistite Propellant.

At execution of the researches in the field of high pressures it was impossible to differentiate the cells on the burning surface. In these conditions on the burning surface there was so many burning cells, that at transverse passing of the light beam through the several jets it was impossible to differentiate behavior of the separate burning cell on the background of others.

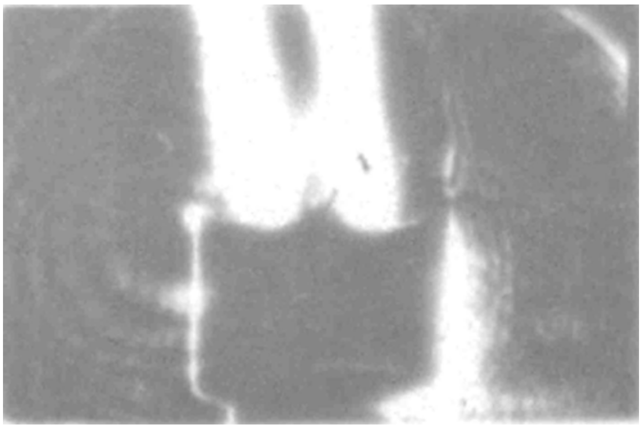


Figure 2. Burning of the Ballistite Gun-Powder "N" in the Nitrogen Atmosphere at the Pressure 0.4 MPa. Two Torch Macro-Structures on the Burning Surface are Observed.

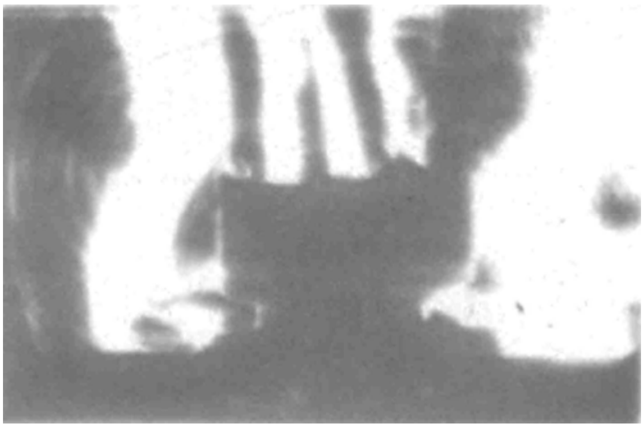


Figure 3. Burning of the Ballistite Gun-Powder "N" in the Nitrogen Atmosphere at the Pressure 0.6 MPa. Four Torch Macro-Structures on the Burning Surface are Observed.

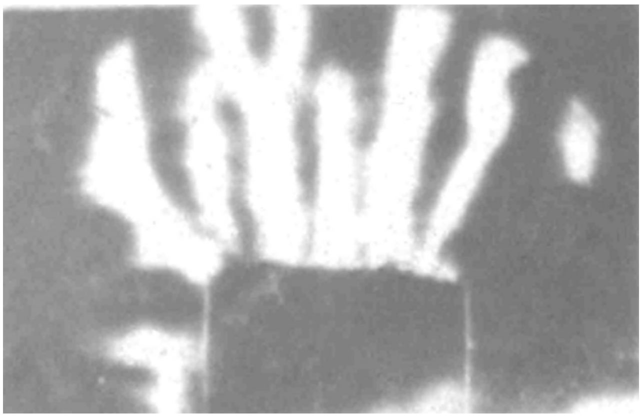


Figure 4. Burning of the Ballistite Gun-Powder "N" in the Nitrogen Atmosphere at the Pressure 0.8 MPa. Six Torch Macro-Structures on the Burning Surface are Observed.

4.0 PRESENT-DAY THEORETICAL CONCEPTS OF THE ENERGETIC MATERIALS TORCH COMBUSTION PHENOMENON

Analysis of micro-pulsations on the EM burning surface are presented in paper [12]. As the reason for appearance of micro-pulsations on the burning surface, the non-simultaneous burning out of the EM components was considered. The idea of non-simultaneous burning out of the EM components was suggested at the end of 19th century by D.I. Mendeleyev [13]. Authors of paper [12] have shown that each specific solid propellant has its intrinsic (own) frequencies of micro-oscillations in the combustion zones. Thus, the new “universal” integrated parameter ("intrinsic frequencies of micro-oscillations on the burning surface of propellant") was entered. This parameter allows characterize the most probable range of the acoustic oscillations, radiating from the burning surface of each specific propellant, from the point of view of the phenomenon of the non-simultaneous burning out of the components.

The results, obtained in paper [12] shows that in case of coincidence of the "propellant intrinsic frequencies" with the acoustic frequencies of the charge channel cavity (combustion chamber cavity), are observed the oscillations of the combustion products pressure and combustion instability. However, these experimental results and the theory [13] have not allowed explain the reason of the SPMS excitation on the burning surface and all other mechanisms of the torch combustion phenomena. At the same time, the "propellant intrinsic frequencies of micro-oscillations" are the unique property that shows the existence of some universal mechanism.

Present-day theoretical concepts of the energetic materials torch combustion phenomenon are based, mainly, on ideas generated under influence of investigations of the processes of self-propagating high-temperature synthesis (SHS) – on the models of spinning combustion processes developed for description of dynamics of the SHS front structure [14]. Spinning waves at the SHS represent a spiral-helix motion of a localized combustion center, which occurs along the lateral surface of a cylindrical sample. In particular, theoretical explanation of the torch (cellular-pulsating) combustion phenomenon suggested by V.N. Marshakov is based on this concept. V.N. Marshakov has suggested theoretical model of the burning wave thermal instability [15], [16], [17]. In accordance with this model, on the burning surface there is a mobile system (grid) of burning transverse waves, which is the waves, spreading on the heated-up layer, in the transverse direction to the burning propagation. Between these transverse waves burning stops. In accordance with theoretical scheme of V.N. Marshakov, the transverse burning waves are propagating one after another.

These theoretical model is very similar to theoretical model of spiral propagation of the burning wave, which for the first time was suggested by V.N. Fomenko, in 1990 (The Federal Centre of Dual-Use Technologies "SOYUZ", Dzerzhinsky, Moscow Region, Russia). V.N. Fomenko has used this model for description of the end-burning solid propellant charges rhythmic extinctions phenomenon.

Nevertheless, such theoretical explanation of the phenomenon do not correspond to other results of researches. Figure 5 shows the images of the video film of burning of the ballistite powder with various curvature of the burning front.

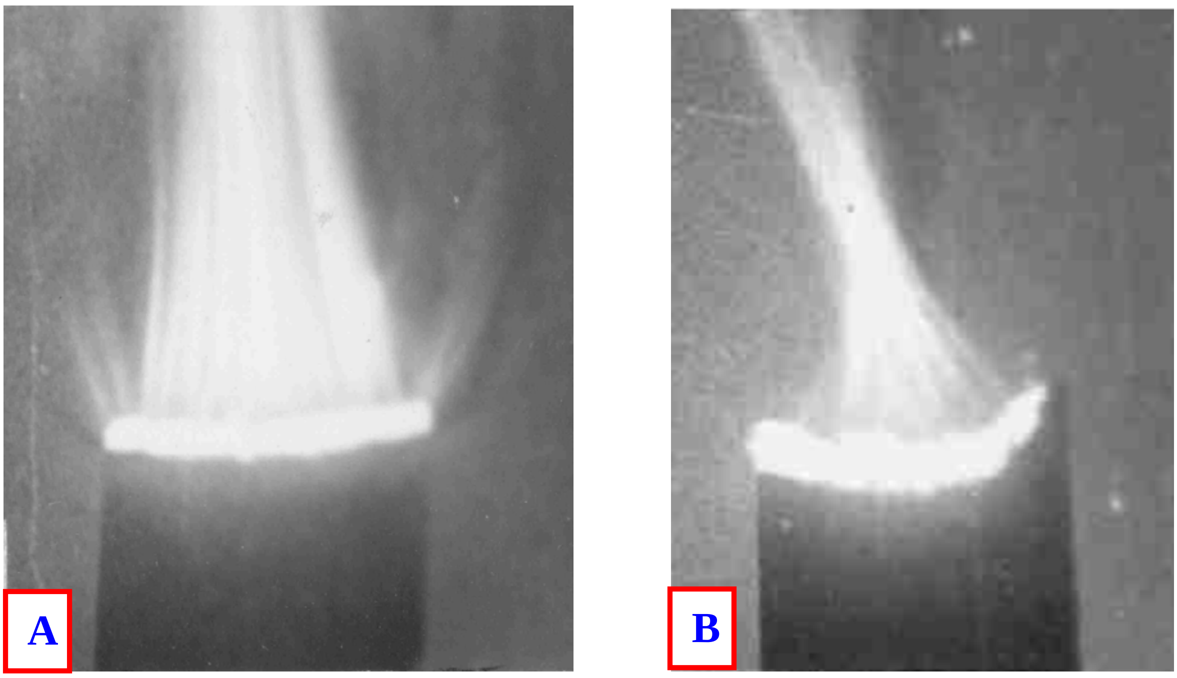


Figure 5. The Images of the Video Film of Burning of the Ballistite Powder with Various Curvature of the Burning Front.

As it is possible to see from the images of video film of burning of the ballistite powder with various curvature of the burning front, the products of gasification flow out from the burning surface in perpendicular direction. From presented fragments (Fig. 5) it is possible to see, the heat transfer along the burning surface is not observed, as there is no the temperature gradient. Therefore the theoretical model, suggested by V.N. Marshakov, according to which, "the burning wave of the gun-powders represents the system (the grid) of burning transverse waves, which is the waves, spreading on the heated-up layer, in the transverse direction to the burning propagation, and forming the mobile cells (torches) on the burning surface" [17], does not correspond to the experimental data.

Use of theoretical concepts from the area of SHS does not allow explain the mechanism of formation of the burning cells on the burning surface of the EM and solid rocket propellants. Firs of all there is no full analogy between the burning processes of the solid rocket propellants and the SHS-systems. At the SHS the condensed reaction products continue produce essential influence on further development of the burning process. The solid-flame combustion [14] is an self-wave chemical process in the system of solid-phase reagents. This process leads to formation of the intermediate and finished products in the solid-phase. The solid-flame combustion is only solid-phase process, not connected with formation of liquid and gaseous phases. For example, in the reaction zone there is no LVL. After the burning wave propagation, in the material develops the volumetric physics-chemical processes that not connected with burning. In these conditions, considerable influence on the process development is provided by significant heterogeneity of the EM structure. For example, for the SHS-systems, the transverse burning waves may exist at various ratios between propagation velocities of the transverse and longitudinal burning waves. However, at the gun-powders and solid propellants burning, the transverse burning waves can be considered only if their propagation velocity considerably exceeds the longitudinal burning wave propagation velocity. The transverse burning waves exist, but only for SHS-systems.

For analysis of system of the burning cells on the burning surface, G.V. Melik-Gaiykazov (Semenov Institute of Chemical Physics of the Russian Academy of Sciences, Moscow, Russia) has suggested to use the theory of clusters [18]. In particular, was suggested to consider the system of burning cells as infinite cluster that disintegrates at the time of the cells extinction. However, the mechanism of formation of the burning cells on the burning surface was not explained.

On the other hand, behavior of the complex micro-structures, developing on the EM burning surface is un-analyzable by traditional methods. V.N. Marshakov's theoretical model of the burning wave thermal instability, considers only separate components and connections between them. As noted by B.V. Novozhilov [19], the solid propellant burning surface represents the oscillatory system with infinite number of freedom degrees. However, such composite systems cannot be understood, analyzing their parts separately.

A lot of efforts has been put into development of models for transient burning of solid propellants.
In B.V. Novozhilov's recent paper [20] was suggested synergetic approach for consideration of the problem of combustion instability - the anomalies of the EM burning and the phenomenon of non-acoustic instability (the "chuffing" phenomenon) in the combustion chambers. In particular, was suggested consider the processes on the solid propellant burning surface as a chaotic process. However the torch combustion phenomenon was not considered.

The torch combustion phenomenon is similar to the phenomenon of hydrodynamic instability at transition of laminar flow into the turbulent flow, connected with self-organizing of dynamic dissipative spatial-periodic vortex micro-structures. In this case some part of energy of the system will be transformed in the organized eddy movement. Until recently such hydrodynamic instability was identified as transition to chaos. However last investigations have shown that in this case, vice versa, takes place transition to the order, i.e. to formation of the self-ordering vortex structures.

5.0 EXCITATION OF THE SPATIAL-PERIODIC MICRO-STRUCTURES IN THE IONIC FUSION WITH THERMO-ELECTRIC PROPERTIES ON THE BURNING SURFACE

In accordance with extensive experimental data [21] – [23] burning of the evaporated EM is accompanied by occurrence of electric conductivity of the burning surface (of the EM liquid-viscous layer) and by chemical ionization of the gas layers adjoining to the burning surface. In conditions of burning wave, where the temperature in the condensed phase increasing by exponential law, the thin reactionary LVL can be considered as the molten mass with ionic properties. Concentration of the ions increases with the burning rate and determines electric conductivity of the burning surface. At burning in conditions of threshold-low pressures, periodic pulsations of the electric conductivity are observed. In connection with existence of the ionic properties of the LVL and electric conductivity of the LVL, the new technologies of regulation of the burning rate of the solid rocket propellants have been developed [24] – [26].

Detailed analysis and mutual comparison of the researches executed in this area (K.I. Synayev, V.D. Kochakov, B.V. Novozhilov, Merrill W.Beckstead, Kenneth K.Kuo, Herman F.R. Schoyer, Fred E.C. Culick, Luigi T. De Luca, Vigor Yang, B.P. Zhukov, A.D. Margolin, P.F. Pohil, V.N. Marshakov, A.G. Istratov, N.M. Pivkin, G.V. Melik-Gaykazov, I.G. Assovskii, V.Ye. Zarko, V.N. Fomenko, O.Ya. Romanov, V.A. Babuk, S.G. Yiarushin, S.A. Rashkovskii, O.P. Korobeynichev), and also detailed analysis of experimental data, obtained in adjacent areas of science and engineering has allowed suggesting the new mechanism of occurrence of the torch (cellular-pulsating) combustion phenomenon.

The low-frequency non-acoustic combustion instability phenomenon, the chuffing phenomenon and the accompanying physical-chemical effects also have received a new explanation within mentioned new mechanism that bases on the unique data of optical visualization of physics-chemical processes on the EM burning surface.

This concept connected, mainly, with excitation of the synergetic dissipative SPMS in the thin LVL and on the EM burning surface and determining the burning wave spatial instability. Obviously, it is possible to speak about the fundamental law determining the processes of the EM burning: phenomenon of the SPMS formation has universal nature. As the system becomes complicated (during heating up), it gets such phenomenological features that are difficult for finding out, at studying of more simple subsystems. On the EM burning surface occurs transition from the isotropic medium to the medium with existential structure.

At heating from above in the thin LVL occurs interaction of hydrodynamic, electric and thermal subsystems of disordered system - the thermo-electric convection excitation, that induce cellular movement and formation of the synergetic SPMS [27]. Thermo-electric mechanism can induce instability of the LVL and excitation of cellular movement and formation of synergetic SPMS. Excitation is possible at any direction of heating, including heating of the LVL from above. Besides the velocity (convection) cells, in the LVL arise the electric field cellular structures.
Figure 6 schematically shows distribution of the physics-chemical processes in the thin LVL in the EM reaction zone.

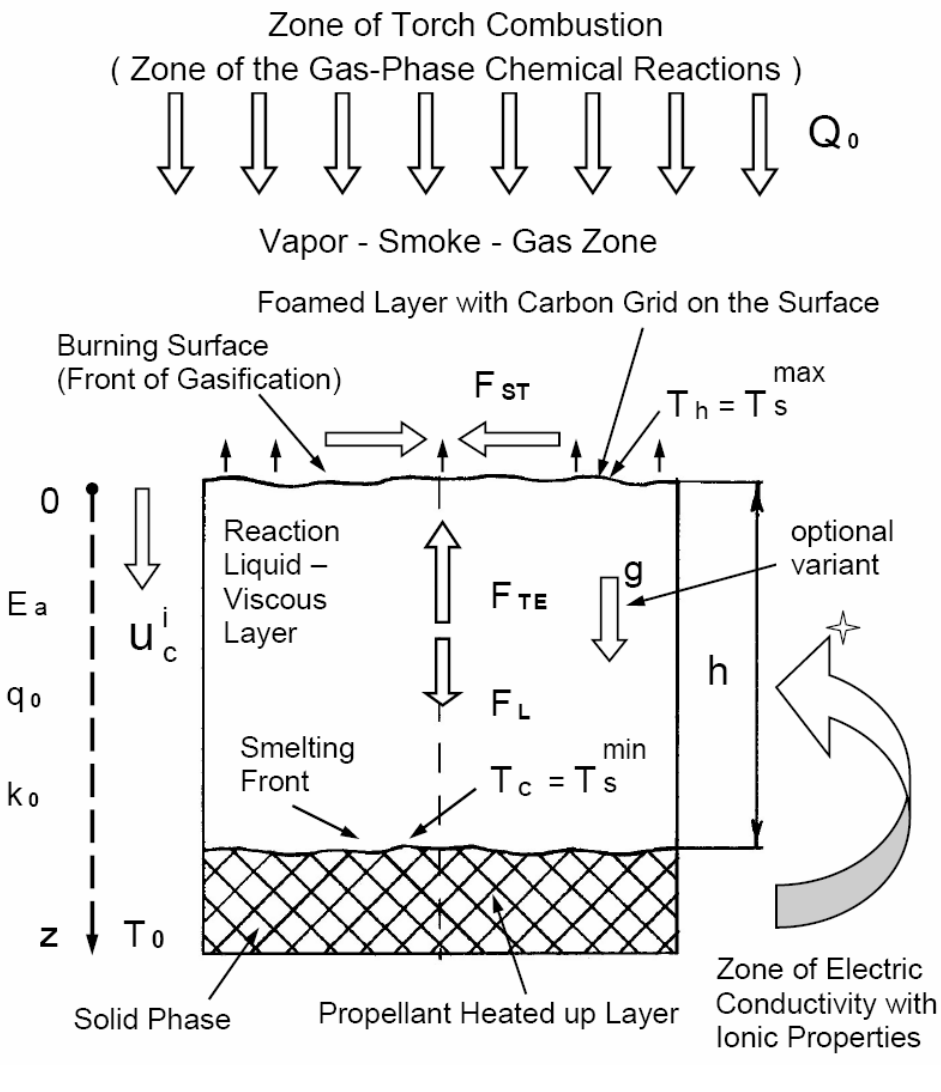


Figure 6. Thin Liquid-Viscous Layer in the EM Reaction Zone, Having Thermo-Electric Properties at Heating From Above.

In accordance with the experimental data, the ratio of the longitudinal and cross-sectional sizes of the elementary SPMS is the most stable characteristic of the cellular movement excitation. Change of the boundary conditions practically does not influence this parameter. The reason of stability of the sizes of the SPMS is connected with the thermo-electric mechanism of excitation of such structures.
In other words, stability of the SPMS is provided by the electro-magnetic field cellular structures in the LVL. The experimental data shows the boundaries of the electric field structures coincide with the boundaries of the convection cells (“the structures of velocity”). And on the LVL surface under influence of thermo-electric field is excited the electric charge.

6.0 TWO SCALES OF THE SPATIAL-PERIODIC STRUCTURES ON THE ENERGETIC MATERIAL BURNING SURFACE

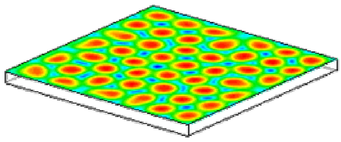
Comparison of the scales of zones of the EM torch (cellular-pulsating) burning shows that reaction-capable SPMS, excited in the LVL, are the initial existential structures that are united in the set of aggregates. Each of such aggregates represents a torch or the burning cell on the burning surface.

The burning process localized in each of the SPMS, is supported by the process of self-organizing of the SPMS into the groups. In other words, each of such aggregates, formed from two and more SPMS with identical properties it is possible to consider as a cluster.

TORCH (CELLULAR) SPATIAL-PERIODIC MACRO-STRUCTURES ON THE BURNING SURFACE

Scale of the torch (the burning cell) on the burning surface - (10 - 15) h

(Diameter of the torch - (1 - 2) mm)



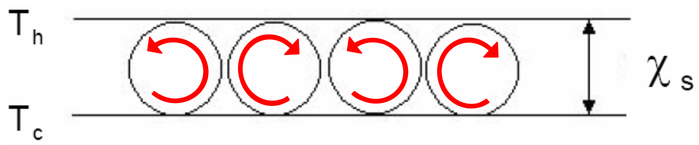
CARBON GRID (CARBON SPATIAL-PERIODIC MICRO-STRUCTURES) ON THE BURNING SURFACE

HEATED-UP LAYER OF THE ENERGETIC MATERIAL

The Thickness of the Heated-up Layer (The Conductive Size)

$$h \approx a \ / \ u_C$$

h ~ (0.010 – 0.070) mm



Reaction Liquid-Viscous Layer

The thickness of the reaction liquid-viscous layer determines scale of the SPMS (cells) of the thermo-electric convection.

For estimation of the average thickness of the reaction liquid-viscous layer (the effective thickness of the zone of electric conductivity) in the EM heated-up layer can be used the following expression:

$$\chi_S \approx a \ / \ (10 \cdot u_C)$$

The thickness of the reaction liquid-viscous layer - (0.0010 – 0.0035) mm

The Inert Heated-up Layer of the Energetic Material

Figure 7. Two Scales of the Spatial-Periodic Structures on the Burning Surface.

The torch structures on the burning surface forms the non-uniform burning front: on the burning surface appears the local discontinuity.

In the conditions of low pressures the sizes of the SPMS and the cluster structures (torches) will increase, but the total number of the torch structures on the burning surface will decrease. And vice versa, in the conditions of high pressures the sizes of the SPMS and the cluster structures (torches) will decrease, but the total number of the torch structures on the burning surface will increase.

Besides for estimation of the average thickness of the reaction LVL (the effective thickness of the zone of electric conductivity) in the EM heated-up layer, the χ_S value, can be used D.A. Frank-Kamenetskii's characteristic temperature interval [28]. Let's consider that the main part of reactions takes place within the limits of the quadruple specified temperature interval:

$$\chi_S = \frac{4 \cdot R \cdot T_S^2}{E_a \cdot \varphi_0} . \qquad (1)$$

With taking into account equality for the temperature gradient:

$$\varphi_0 = \frac{C \cdot \rho \cdot u_C}{\lambda} \cdot \left(T_R - T_0\right). \qquad (2)$$

we can write down:

$$\chi_S = \frac{4 \cdot R \cdot T_S^2 \cdot \lambda}{E_a \cdot C \cdot \rho \cdot u_C \cdot \left(T_R - T_0\right)} = \frac{a}{u_C} \cdot \frac{4 \cdot R \cdot T_S^2}{E_a \cdot \left(T_R - T_0\right)} \approx h \cdot \frac{4 \cdot R \cdot T_S^2}{E_a \cdot \left(T_R - T_0\right)}. \qquad (3)$$

For example, at T_0 = 293 K and P = 4 MPa, χ_S = 0.0035 mm; and at T_0 = 293 K and P = 10 MPa, χ_S = 0.0022 mm.

7.0 THE PHENOMENON OF THE SPATIAL-PERIODIC MICRO-STRUCTURES EXCITATION ON THE ENERGETIC MATERIAL BURNING SURFACE AT THE INFLUENCE OF THE LASER RADIATION ENERGY

The experimental data have shown that the SPMS develops on the EM burning surface under influence of the laser radiation energy. Both the experiment, and the theory confirm, that the SPMS formation is rather universal phenomenon.

In the researches, executed by Dr. Valery D. Kochakov, was used radiation of the CO_2 - laser with power of 60 watt and with wave length of 10.6 micrometers. The time of influence of the laser radiation energy on the gun-powder surface gradually increased up to the moment of ignition of the burning surface of the sample. It has allowed to observe development of the micro-structures on the burning surface in various phases of the process. Figure 8 shows the image of the burning surface of the standard ballistite propellant under influence of the laser radiation energy in the nitrogen atmosphere at the pressure of 0.4 MPa.

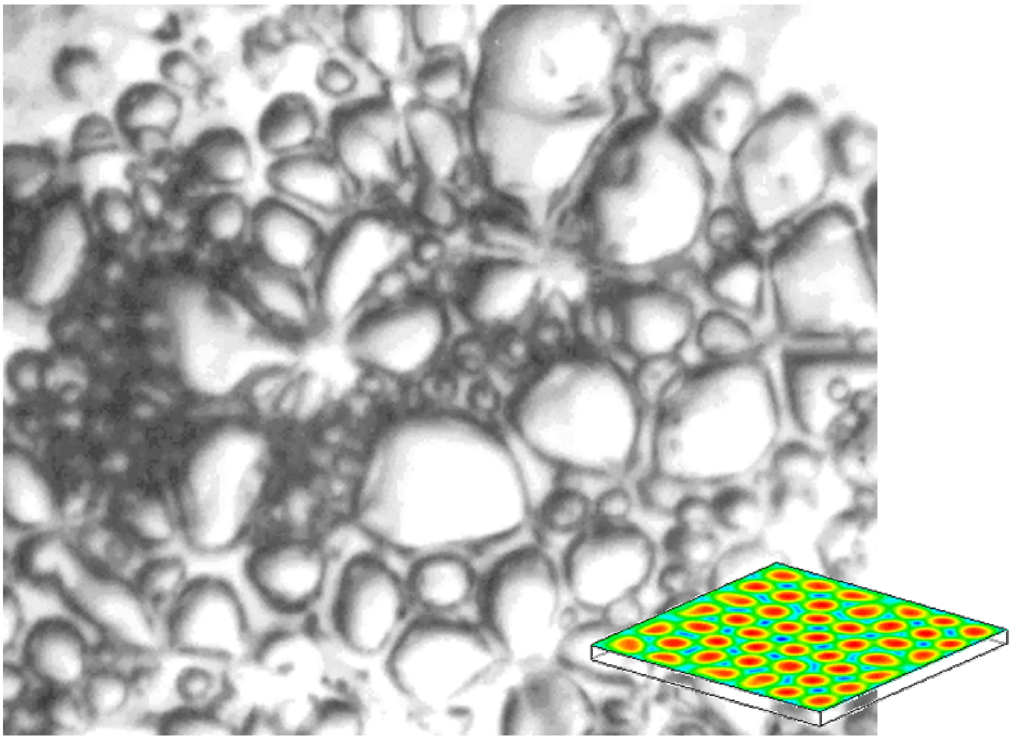


Figure 8. The Structure of the Surface of the Sample After Influence of the Laser Radiation During 120 Milliseconds.

Excitation and formation of the SPMS on the burning surface is accompanied by separation of the LVL on the local zones with different viscosity and density. Local zones with the increased viscosity are formed on the boundaries between cellular micro-structures. In such zones with increased viscosity occurs formation of the carbon micro-structures (Fig. 9).

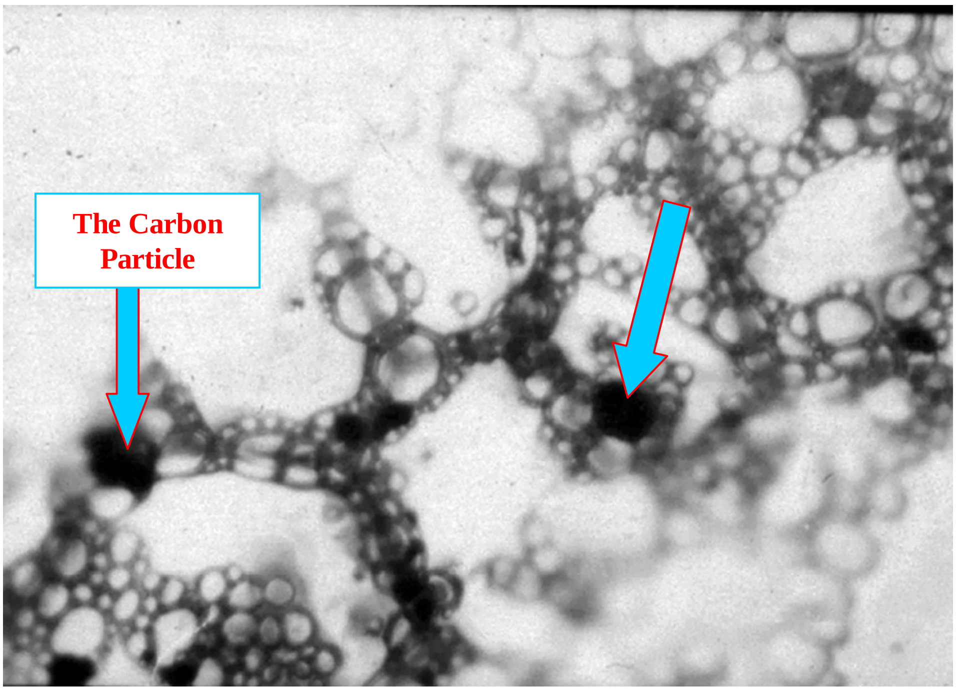


Figure 9. Formation of the Carbon Micro-Structures on the Burning Surface.

Actually, the carbon grid reflects one of sequential stages of development of the cellular micro-structures on the EM burning surface. In this case, excitation of the thermo-electric convection in the layer is a main structures-forming factor. At further increase of the duration of influence of the laser radiation energy on the surface of the sample, the carbon structures will unite with each other and will cover all a greater and greater surface. Figure 10 show gradual increase in quantity of carbon structures on the burning surface.

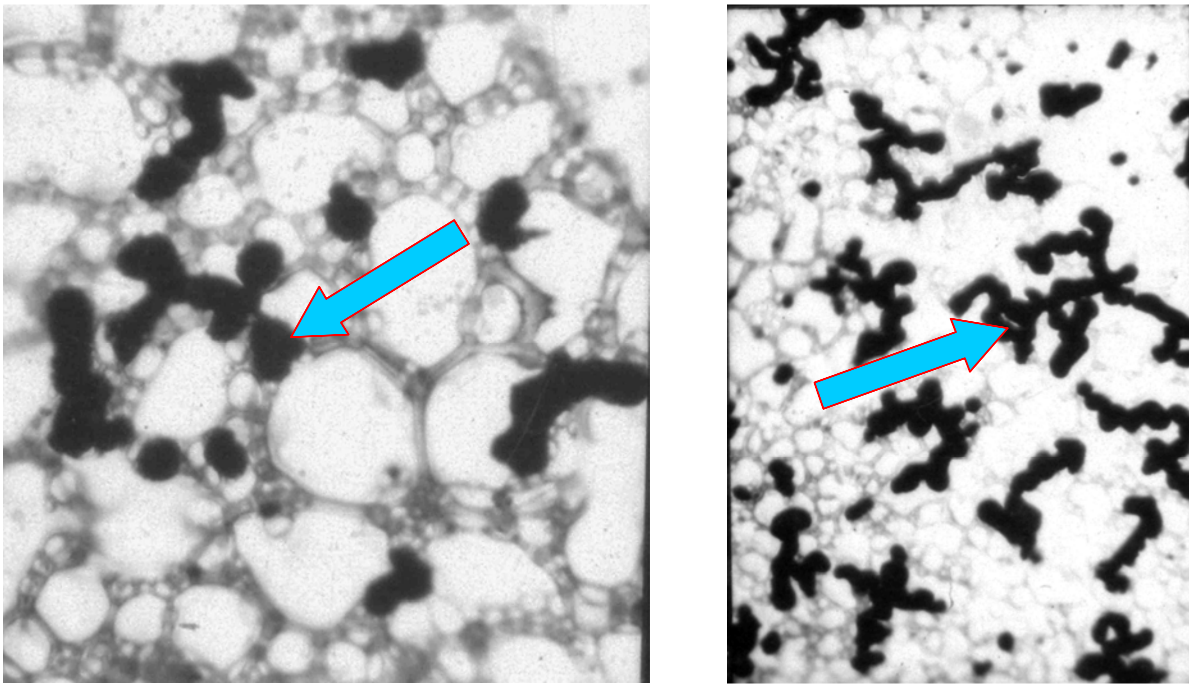


Figure 10. Increase in Quantity of the Carbon Micro-Structures on the EM Burning Surface.

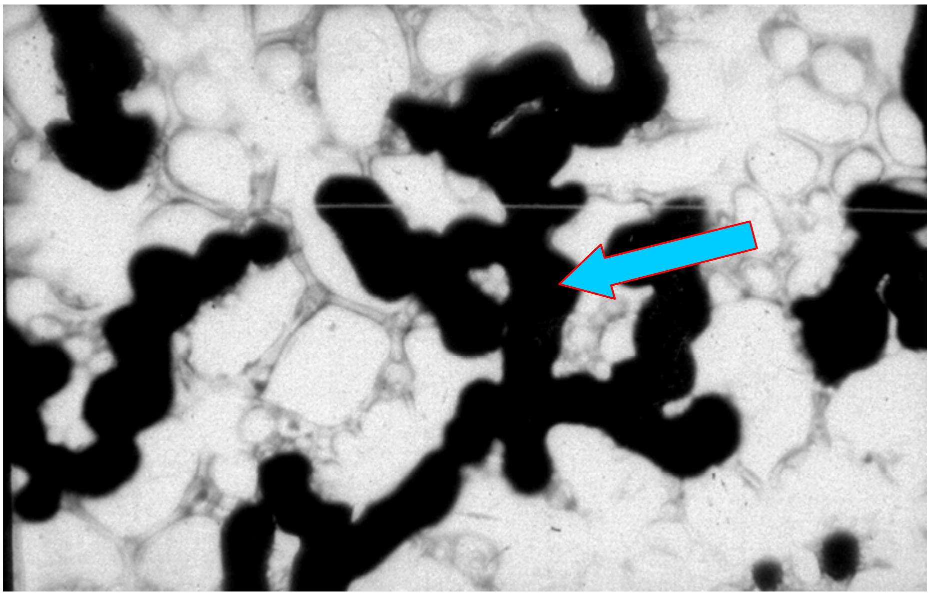


Figure 11. Formation of the Carbon Micro-Structures on the Burning Surface.

When the carbon micro-structures cover the surface of the sample approximately on 60 %, transition from ignition to burning will be observed. Figure 11 shows the threshold time moment, after which the surface of the sample will be ignited.

The EM burning surface gradually becomes covered by a carbon grid. During formation of the carbon grid on the burning surface the burning process is gradually reduced and eventually the torch luminescence disappears. At this stage of the process the luminescence of the carbon grid is observed only (Fig. 1, (2)). Further, the combustion products flowing from the burning surface throw away a carbon grid from the burning surface. After throwing away of a carbon grid the luminescence of the torch above the burning surface appears again. Formation of the carbon grid are determined by formation of the cellular micro-structures on the EM burning surface.

8.0 THE PROCESS OF SELF-ORGANIZING OF THE DYNAMIC DISSIPATIVE SYNERGETIC SPATIAL-PERIODIC MICRO-STRUCTURES INTO THE TORCH MACRO-STRUCTURES

On the EM burning surface is observed the process of self-organizing of the dynamic dissipative synergetic SPMS into the torch macro-structures. In this connection, on the burning surface the process of moving (wandering) of the torches is observed. Besides, the torch structures on the burning surface can exist steadily in the event that they form a pair of two torches.

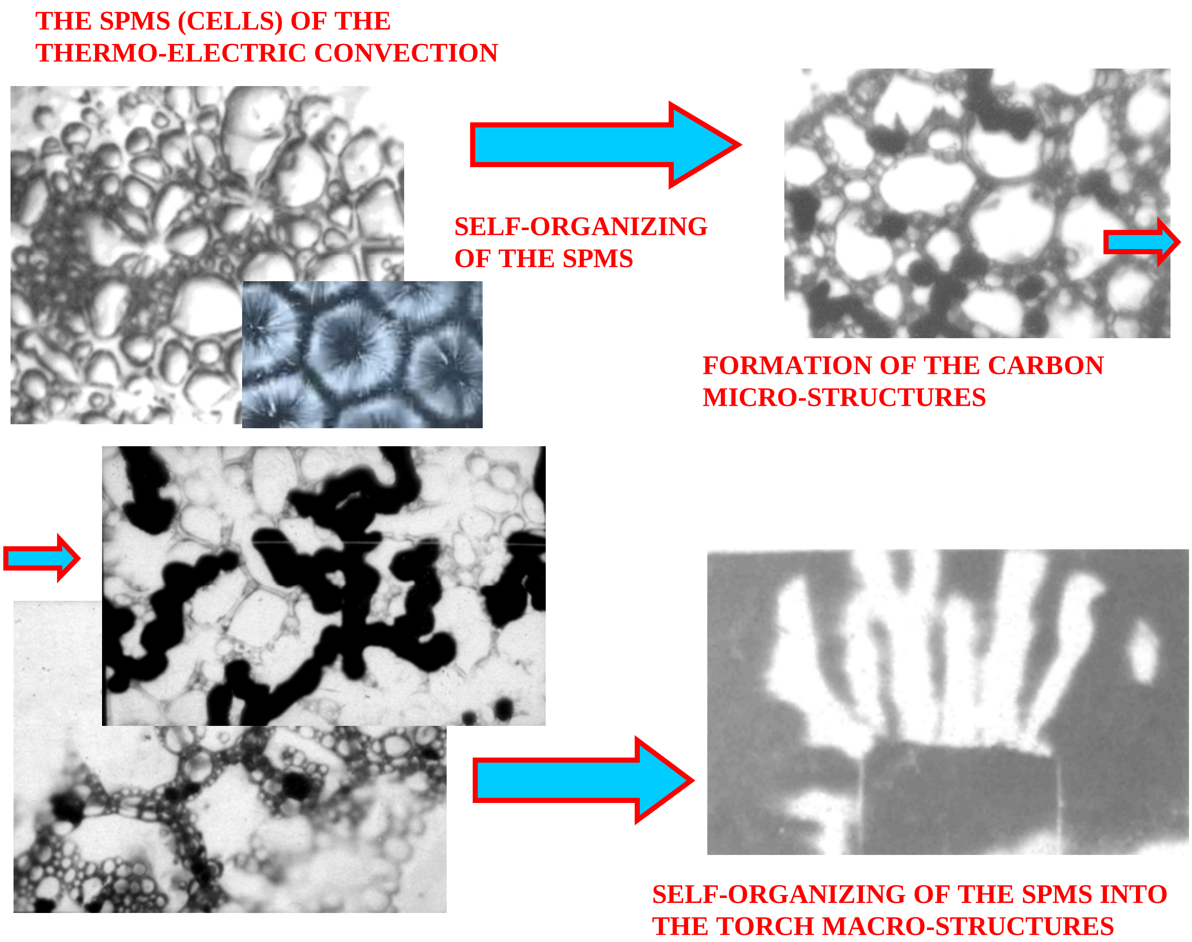


Figure 12. Self-Organizing of the SPMS Into the Torch Macro-Structures.

It is important to note, that in the majority of theoretical models of the low-frequency non-acoustic combustion instability phenomenon in the SPS, the processes of excitation of the SPMS on the burning surface are not taken into account. Thus, suggested mechanism and theoretical model opens possibilities for understanding the essence of the EM unstable burning phenomena on the new qualitative level. Such an improved model will be a step towards detailed interpretation of the large amount of experimental data on L* instability that is available.

9.0 PROBLEMS OF CONTROLLING OF THE ABNORMAL PHYSICS-CHEMICAL PROCESSES AT THE ENERGETIC MATERIALS BURNING

Actuality of the researches connected with controlling of the abnormal physics-chemical processes at the EM burning is evidently demonstrated by continuous perfection of the designing-technological development in the given scientific-technical area.

For suppression of the combustion instability can be used various mechanical devices installed in the combustion chamber or in the charge channel: the resonant rods of various forms; longitudinal and cross perforated plates and diaphragms; various screens. Other versions of technologies for suppression of combustion instability are purposeful change or regulation of form and geometrical characteristics of the combustion chamber; exact tuning of geometrical characteristics of the chamber or its separation on several volumes; creation of resonant acoustic cavities in the combustion chamber; installation of damping rings (diaphragms) and also internal and external acoustic (gas dynamics) dampers (Helmholtz resonators). Besides, in some cases for suppression of the combustion instability there may be used high-porosity cellular materials in the form of disks installed in the combustion chamber. Such disks are usually manufactured by means of powder metallurgy.

At the same time there are deficiencies of these technologies. The efficiency of the mechanical damper decreases after burning out a portion of the propellant charge, in connection with change of the cavity sizes, because the mechanical means of suppression of unstable burning operates in a narrow frequencies band. Also, damper design elements induce the energy losses due to braking of the combustion products flow. Use of mechanical dampers leads to increase of the engine inert weight. In some cases there may be damper destruction and ejection of its separate elements from the engine. Absorbers of resonant type - the acoustic dampers (Helmholtz resonators) operates effectively in a narrow frequencies band and can induce transition of unstable mode to other frequency or lead to destabilization of steady burning process in the engine.

The main source of instability is the solid propellant pulsating burning surface. However, the existing technologies for suppression of the solid propellant combustion instability do not take into account the influence of the synergetic spatial-periodic micro-structures on the propellant burning surface. Further progress in this vital area may be connected with understanding of mechanisms of formation and destruction of the synergetic micro-structures on the EM burning surface.

In the SPS of a new generation with high energy and mass characteristics, the problem of prevention of development of combustion instability and anomalies of burning have extreme importance. Solution of this problem can be provided with using of suggested mechanism and with using of plasma physics technologies for control of the process of excitation of the SPMS on the burning surface. And the selective sensitivity of the SPMS can be controlled by influence on the thermo-electric convection in the LVL.

In particular, for control of the process of the SPMS excitation on the EM burning surface the effect of acoustic cavitation in the LVL can be used. This effect can be organized in the LVL under influence of the acoustic field with certain frequency.

10.0 CONCLUSIONS

The low-frequency non-acoustic combustion instability phenomenon, the chuffing phenomenon and the accompanying physics-chemical effects have received a new explanation within the concept based on the data of optical visualization of the physics-chemical processes on the EM burning surface. On the EM burning surface is observed the process of self-organizing of the dynamic dissipative synergetic spatial-periodic micro-structures into the torch macro-structures. The torch macro-structures on the EM burning surface can be considered as independent synergetic structures and can exist steadily in the event that they form a pair of two torches. Excitation of the spatial-periodic micro-structures in the ionic fusion with thermo-electric properties on the burning surface is a main source of development of the synergetic phenomena in the EM burning zone. The existing technologies for suppression of the solid propellant combustion instability do not take into account the influence of the synergetic micro-structures on the propellant burning surface. Further progress in this vital area may be connected with understanding of mechanisms of formation and destruction of the synergetic micro-structures on the EM burning surface.

Design community and quality assurance people should continue to give due importance to the above problem of controlling low-frequency non-acoustic combustion instability of the energetic materials in practical applications so that their guidelines will be realistic for safety.

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