

# Self-Organizing of the Reactionary Zones of the Energetic Materials and Concept of the Smart Solid Micro-Propulsion System

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## **Abstract**

The micro/nano- structures arising in the energetic material reactionary zones has a large influence on physical and chemical processes and on controllability of ignition and combustion processes. The analysis of experimental data shows that in a number of cases, the macro-scale phenomena at the energetic material combustion are result of self-synchronization of the magneto-dipole micro/nano-structures in the reactionary zones. Actually, self-synchronization of the micro/nano- structures provides the mechanism of interactions between micro- and macro- scale levels in the reactionary zones - the inter-scale interaction. The new concept of the smart solid micro-propulsion system includes integration of the propellant reactionary zones both into the control system by combustion mode, and into the general control system of the small-sized orbital maneuvering vehicle.

## **1. Introduction**

For more than ten years, solid micro-propulsion has been an active world-wide field of research. The cheap, reliable, and versatile clusters of micro-spacecraft have more advantages than a conventional spacecraft in fabrication, launch, and operation. The level of thrust and the precise impulse required for micro-satellite maneuvers cannot be achieved with conventional solid propulsion systems. One of the major technical drawbacks to solid rocket propellants has always been lack of throttle control and restarting motors once ignited. Once ignited, conventional solid propellants cannot be controlled, easily extinguished or restarted, limiting the function and increasing the cost of smart weapon systems. In the combustion chambers of the micro-propulsion systems of the small-sized orbital maneuvering vehicles (Fig. 1), the inter-scale interaction (the scale factor) has the significant influence.

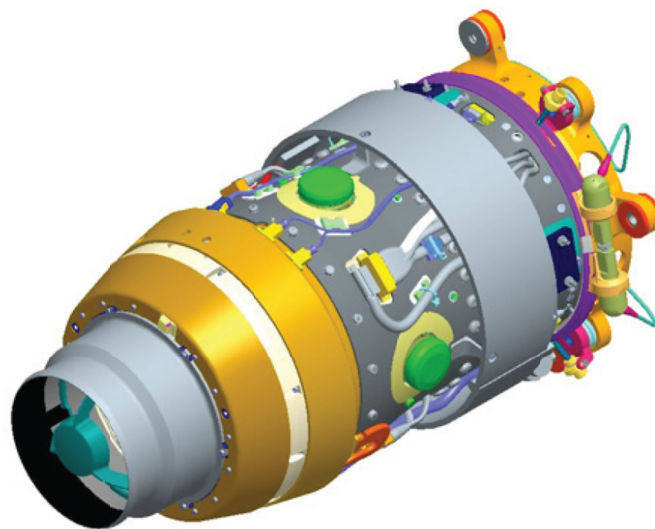


Figure 1: Solid throttling divert and attitude control system of the orbital maneuvering vehicle.

In this connection, the micro/nano- structures arising in the energetic material (EM) reactionary zones has a large influence on physical and chemical processes and on controllability of ignition and combustion processes. The analysis of experimental data shows that in a number of cases, the macro-scale phenomena at the EM combustion are result of self-synchronization of the magneto-dipole micro/nano- structures in the EM reactionary zones. We propose a new hypothesis of excitation of some combustion instabilities that are connected with self-synchronization of the magneto-dipole micro-structures in the EM reactionary zones. For the best understanding of the phenomenon of self-synchronization of the magneto-dipole micro/nano- structures in the EM reactionary zones, let's consider the oscillatory systems, existing in the EM reactionary zones.

## 2. The oscillatory systems in the reactionary zones

As noted by Novozhilov, B.V., the solid propellant burning surface represents the oscillatory system with infinite number of freedom degrees [1]. In 1949 Zhukov, B.P., (Scientific-Research Institute № 125 - Scientific-Research Chemical-Technological Institute, Dzerjinskiy, Moscow Region, Russia) has shown, that at the EM burning on the boundary between of solid and gas phases there is a liquid-viscous layer (LVL) [2]. Later, the existence of a melt layer was proposed by several researchers (Beckstead & Hightower, 1967, [3]), (Tanaka & Beckstead, 1996, [4]), (Jeppson, Beckstead and Jing, 1998, [5]); they made reference to the melt layer and estimated its thickness. Accordingly, the burning is accompanied by the growth of the melt layer front between the condensed and the gaseous regions of the propellant. The melt layer maintains uniform thickness as it propagates after the initiation and growth steps [6]. The known thickness of the entire melt layer is approximately 1  $\mu\text{m}$  at 105 Pa and 0.1  $\mu\text{m}$  at approximately 107 Pa for ammonium-perchlorate/hydroxy-terminated polybuta-diene propellant. In solid rocket-propellant combustion, the dynamic phase change from condensed to gas occurs across the melt layer (Fig. 2).

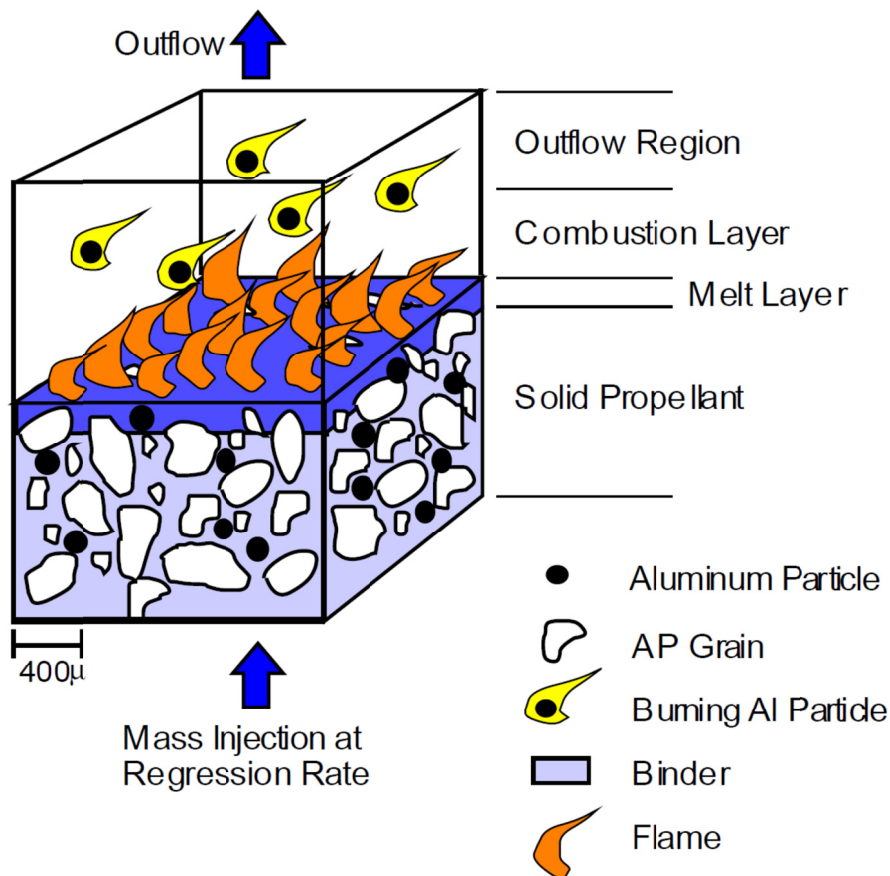


Figure 2: The liquid-viscous layer (melt layer) in the energetic material reactionary zone.

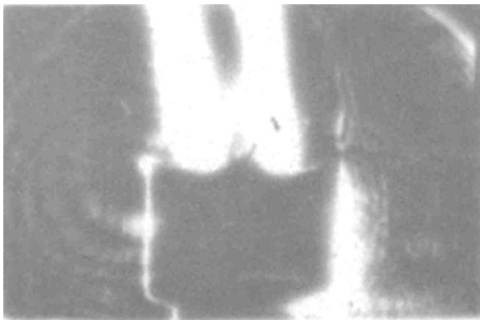
The melt-layer initiation occurs upon ignition of the solid-state propellant. Across the melt-layer front, density experiences a sharp gradient, going from the condensed to the gaseous side. Following the initiation, the thickness of

the hot melt-layer front grows until reaching a uniform thickness. Because the melt-layer thickness depends on pressure, the thickness during the growth step is much thicker than that observed during the propagation step. When the ambient pressure is high, the melt-layer thickness is thin; when the ambient pressure is low, the melt-layer thickness is thick.

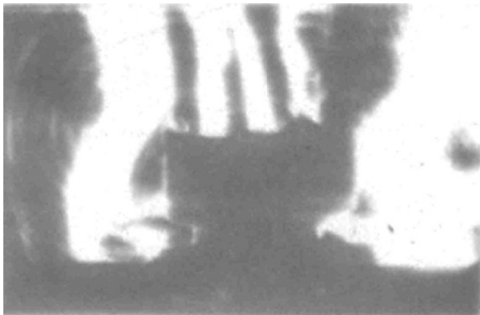
In the last years, researchers have observed the excitation of spatial periodic micro-structures and the presence of micro-torches over the burning surface of the EM with well pronounced exothermic reactions in the condensed phase and evaporation on the burning surface [7, 8].

It can be stated now that such local unstable behavior is typical for the EM with well pronounced exothermic reactions in the condensed phase and evaporation on the burning surface. Both experiments and theory confirm that the spatial periodic micro-structures excitation is a rather universal phenomenon [9].

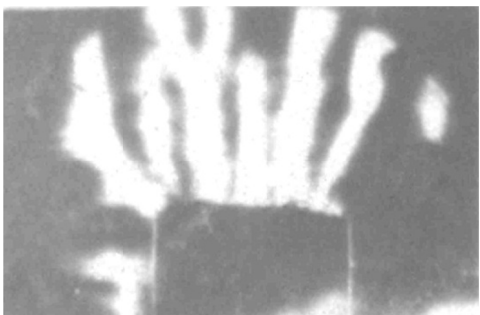
The typical example of the cellular oscillatory systems in the EM reactionary zone is presented in Figure 3.



Burning of the ballistite gun-powder "N" in the nitrogen atmosphere at the pressure 0.4 MPa. Two torch micro-structures on the burning surface are observed.



Burning of the ballistite gun-powder "N" in the nitrogen atmosphere at the pressure 0.6 MPa. Four torch micro-structures on the burning surface are observed.



Burning of the ballistite gun-powder "N" in the nitrogen atmosphere at the pressure 0.8 MPa. Six torch micro-structures on the burning surface are observed.

Figure 3: The shadowgraph photos (obtained by the Toepler's method) of the torch micro-structures at burning of the ballistite gun-powder "N" in the nitrogen atmosphere.

Self-organization of the micro/nano- structures in the EM reactionary zones is a fundamental property of the matter. The key to understanding of self-organization of the micro/nano- structures is the electro-chemical phenomena in the EM reactionary zones. The electric field cellular structures are the original structures or the centers of self-organization at the formation of the burning cells in the EM LVL.

In accordance with experimental researches connected with studying of electrical structure of the flame [10], the flame of composite solid propellants and hybrid rocket propellants possesses own electric field of a complex structure with localization of zones of positive and negative electric charges.

Presence of distributed electric charge in the flame allows to control by shape of the flame by means of external electric field, and, hence, by distribution of the heat sources, by the heat flow into the condensed phase and, at last, by burning rate.

For the first time the representation regarding excitation of the magneto-dipole micro-structures in the LVL of a burning EM was suggested in the paper [11].

### **3. Universal phenomena of self-synchronization in the reactionary zones**

Many natural and human-made nonlinear oscillators exhibit the ability to adjust their rhythms due to weak interaction: two lasers, being coupled, start to generate with a common frequency; cardiac pacemaker cells fire simultaneously; violinists in an orchestra play in unison. These phenomena are universal and can be understood within a common framework based on modern nonlinear dynamics.

The existence of self-synchronization in nature may seem almost miraculous. However, the main “secret” behind this phenomenon is that there exists a communication channel, called coupling, such that the entities/systems can influence each other. This coupling can be, for instance, in the form of a physical interconnection or a certain chemical process. The history of synchronization goes back to the 17th century when the famous Dutch scientist Christiaan Huygens reported on his observation of synchronization of two pendulum clocks which he had invented shortly before.

Many interesting synchronization phenomena have been observed and reported in the literature. More importantly, it gradually became clear that diverse effects which at first sight have nothing in common, obey some universal laws [12].

The phenomenon of self-synchronization of the torch structures in the simple model nonlinear oscillatory experimental system, containing a set of paraffin candles has been examined by Japanese research team [13]. In this study has been experimentally analyzed the characteristics of the oscillation of candle flames. It was found that the two oscillators composed of a set of candles can couple with each other in a synchronous manner. Both in- and anti-phase synchronization can be observed depending on the distance between the two oscillators. The stable combustion has been noticed when a single candle burned, while oscillatory combustion has been observed when three candles burn together.

Actually, this simple experimental example shows a role of the phenomenon of self-synchronization in the excitation of oscillatory burning.

In accordance with the concept of reasons of synchronization of the candle flames, suggested by the Japanese research team, the universal phenomenon of Huygens' self-synchronization of the oscillatory torch structures was not accepted in consideration.

### **4. Influence of an electric field and electric discharges on the reactionary zones**

The idea of using electric fields to manipulate propellant burning rates is not new. In fact, this concept was proposed at least as far back as the 1960's. In general, the application of electric fields to a combusting solid propellant has shown to increase the burning rate of the propellant, and even under certain conditions can decrease the burning rate as well [14]. In particular, application of an electric field changes the burning surface roughness, i.e. modifies the process of excitation of the micro/nano- structures in the reactionary zones.

Use of the electric fields and electric discharges for control by the magneto-dipole micro/nano- structures in the EM reactionary zones gives possibility for control by local curvature of the burning cells surface and to control by origin of vortex micro-structures over the burning surface roughness and to change localization of zones of a heat release over the burning surface. As a result of local change of the burning cells surface curvature, the stability conditions of burning process also will change. There is a limiting value of local curvature of the burning surface in each cell, above which self-sustained combustion is impossible.

The kinetic singing flames can be considered as a simplified model of the torch micro-structures observed in the experiments over the EM burning surface. Optical techniques have shown that the excitation of thermo-acoustic oscillations in singing flames is associated with periodic vortex formation in the boundary layer and the interactions of these vortices with the flame front [15].

It has been shown experimentally that when a constant current discharge is applied to the combustion zone, an internal negative feedback suppresses vortex formation in the thermal boundary layer and the pressure oscillations at all harmonics, simultaneously [15]. On the other hand, when a constant voltage discharge is applied, excitation and amplification of unstable combustion are observed. This method can be used for controlling unstable combustion in thermally stressed combustion chambers at higher discharge currents. The estimates show that the electrical energy required to suppress the unstable burning of a singing flame by this method is an order of magnitude lower than the chemical energy release [15]. In addition, preliminary experiments on controlling combustion stability in more

thermally stressed combustion chambers, for example, in a model of a ramjet engine, have shown that the required electrical energy is two or more orders lower.

At stabilization of the discharge by high-frequency current, the degree of turbulence decreases, and at stabilization of discharge by voltage the degree of turbulence is increased. Use of controlled electric discharge allows to slow or accelerate motion of a wave of combustion front. This method for controlling combustion instability is realized through an "internal" feedback. In this case, the combustion itself regulates the controlling discharge without using the sensors, amplifiers, phase inversion devices, etc., required for external feedback. This sort of feedback, either negative or positive, is the fastest and is essentially instantaneous. The control technique described here was tested on a singing flame with premixed propane-air mixtures [15]. If the electric discharge is imposed on the combustion zone, then the total rate of a heat release consist of rate of heat release provided by combustion and rate of Joule heat release in the discharge.

The pressure oscillations are suppressed through an additional parametric negative feedback. This means that the discharge does not affect the pressure oscillations directly, but serves only as the cause of changes in the parameter for the self-oscillatory process, which is coupled to the pressure oscillations through a definite chain.

## **5. The inter-scale interaction: from self-organization of the micro/nano-structures to self-synchronization in the reactionary zones**

In the EM reactionary zones exists necessary conditions for realization of the phenomenon of self-synchronization. First of all this is a set of similar magneto-dipole micro-structures, which have an identical information-algorithmic condition and being in the conditions supposing fast information exchange between them. Fluctuating magneto-dipole micro-structures also are generators of electromagnetic radiation. One of examples of collective interaction and self-synchronization of the micro-structures in the EM reactionary zones are the process of excitation of the burning cells in the reactionary zones of strobes [16]. Strobes are pyrotechnic heterogeneous compositions which show an oscillatory combustion. They have fascinated many scientists since their discovery at the beginning of the 20th century. A few theories have been proposed to explain this phenomenon but the current knowledge of these mechanisms is only based on empirical methods and the physical and chemical processes that trigger the occurrence of flashes is still unclear. Explanation of such phenomenon just as a chemical oscillator is not confirmed by experimental data and detailed chemical mechanisms remain unknown. However, the mechanism of self-synchronization of the micro/nano- structures in the EM reactionary zones was not suggested earlier.

The experimental studying of thermal and electrical structure of the diffusive flames, which models a flame of the composite solid propellant, has shown possibility of control of the burning rate of propellant by change of heat flux to the burning surface by superimposition of a dilatational electric field on the flame [17]. At superimposition of the external electric field on the flame, occurs change of the shape and the height of the flame. It is caused by presence of the distributed electrical charge in a flame. Together with it there is a change of a position of radiants of thermal emission in the flame, a change of heat flow on the burning surface and burning rate.

The EM reactionary zones can be considered as excitable systems. Actually, self-synchronization of the micro/nano-structures provides the mechanism of interactions between micro- and macro- scale levels in the EM reactionary zones (the inter-scale interaction).

According to our hypothesis, self-synchronization of the magneto-dipole micro/nano- structures in the reactionary zones occurs through the electro-magnetic fields interaction. Such interaction of the electric charges and electro-magnetic fields changes the space localization of the reaction zone and the sources of heat release in the burning zone. Self-organizing of the EM reactionary zones is a key link in the control methods by combustion regime. The new possibilities for effective control by ignition and combustion processes opens in connection with possibility of initiation of self-organizing of the reactionary zone by use of the electric fields and the electric discharges.

Self-organizing of the EM reactionary zones is essentially new level of self-organizing which is determined by achievement of critical spacial concentration of the micro/nano- structures - by a bifurcation point. In particular, application of an electric field changes the burning surface roughness, i.e. modifies the process of excitation of the micro/nano- structures in the reactionary zones.

Self-synchronization of oscillations of the torch micro-structures under the influence of external action can excite combustion instabilities in the combustion chambers of solid micro-propulsion systems. In the greatest degree, the effects of self-synchronization will be observed in the area of low pressure, when the micro-structures in the reactionary zone have the maximum size. In the area of reduced pressures the majority of anomalies of ignition and combustion are observed. Self-synchronization of the micro/nano- structures are capable to induce changes of distribution of heat flows and to induce the combustion anomalies.

One of interesting examples is the resonance merging of the shock waves, at combustion of granulated EM in the elongated channels, stimulated by self-organizing of the micro-structures in the reactionary zones. In this

phenomenon, at the approach of a shock wave and intensive increase in pressure, the number of the torch micro-structures over the burning surface sharply increases.

Waves of negative erosion, the phenomenon of rhythmic extinctions of the burning surface and phenomenon of intermittent burning of the EM also can be considered as a result of appearance of the phenomenon of self-synchronization of the magneto-dipole micro/nano- structures.

## 6. Concept of the digital smart solid micro-propulsion system

The solid propulsion systems continuously improve their performances and dependability thanks to more and more enhanced materials, sophisticated modeling tools and optimized architectures. One of the major disadvantages of solid propulsion systems is the inability to throttle. Once ignited, the solid propellant grain continues to deflagrate until all of the reactive material is consumed. Throttling of solid rocket motors to date has mainly been achieved through the use of pintles, which act to change the exit nozzle throat area that effectively alters the chamber pressure. Since propellant burning rates are often characterized by a St. Roberts' burning rate power law, the change in chamber pressure significantly affects the burning rate thereby producing a throttling behavior. However, pintles remain difficult to employ and generally add parasitic weight to the overall system. The ability to actively throttle would substantially increase the flexibility of a solid rocket motor regardless of the mission profile.

The effects, which an electric field exerts on flames, have been observed and reported in the literature for a long time. Burning velocity, flame stability, flame shape, flame luminosity, extinction limit, and soot formation, are among the effects that have been observed. Most of the studies in this field were experimental observations.

The concept of the digital smart solid micro-propulsion system are based on control by self-organization and by self-synchronization of the magneto-dipole micro/nano- structures in the solid propellant reactionary zones. The concept includes integration of the propellant reactionary zones both into the control system by combustion mode, and into the general control system of the small-sized orbital maneuvering vehicle.

Self-organizing of the reactionary zones is essentially new level of self-organizing which is determined by achievement of critical spacial concentration the micro/nano- structures. In particular, application of an electric field, changes the burning surface roughness, i.e. modifies the process of excitation of the micro/nano- structures in the reactionary zones.

The priority in development of technique of control by the EM reactionary zone (liquid-viscous layer), by its heating at the electric current passing belongs to the Swedish inventors [18]. The simple version of the electrode system for control by heat release in the reactionary zone also is presented in the Russian patent [19], completely repeating the invention of the Swedish scientists [18]. The further development of the technique suggested in the patent [19] is the design of the composite solid propellant charge which includes the metal electrode system used as a combustible propellant component [20].

However, the given technique does not give possibility for control by the micro/nano- structures in the reactionary zones of the solid rocket propellant. The new possibilities for effective control by combustion processes opens in connection with possibility of initiation of self-organizing of the reactionary zone by use of the electric fields and electric discharges. Research of self-organizing and self-synchronization of the micro/nano- structures in the EM reactionary zones opens a new possibility for development of the smart solid propellants that allow variable thrust at minimal cost. In the smart solid micro-propulsion system the scale factor has a large influence - the influence of self-organizing of the micro/nano- structures on the physical and chemical processes in the combustion chamber. Besides, the electrical-conducting LVL in the external electro-magnetic field is the micro-oscillator. There are possibility for control by micro-oscillations of the LVL. The thin LVL can be considered as the object for electro-thermal control by ignition and combustion processes, and as a sensor of the pressure oscillations in the combustion chamber.

For example, in some cases, the solid propellant charge together with complex electro-control system (electrodes), being one of the propellant components (for example, in the hybrid propulsion systems) can be manufactured by a method of Additive Manufacturing (3D Printing) [21]. This technique allows to provide as much as possible random distribution of the propellant components in comparison with techniques of mechanical mixing and as result, to provide more complete combustion of components and to increase the solid propellant energy.

In case of use of the electrically controlled solid propellants, the phenomenon of spontaneous excitation of the micro/nano- structures in the reactionary zones will influence also on the processes of ignition, combustion and extinguishing.

Suggested concept also can be applied for development of the solid micro-propulsion systems as a high energy density actuation method for aerial micro robots.

## 7. Conclusion

Studying of the combustion instabilities is a key to understanding of the mechanism of self-organization of the micro/nano- structures at the EM ignition and combustion. In the combustion chambers of the solid micro-propulsion systems of the small-sized orbital maneuvering vehicles, the scale factor has the significant influence. In this connection, the micro/nano- structures arising in the EM reactionary zones has a large influence on physical and chemical processes and on controllability of ignition and combustion processes. Self-organizing of the EM reactionary zones is a key link in the control methods by combustion regime. The concept of the digital smart solid micro-propulsion system are based on control by self-organization and by self-synchronization of the magneto-dipole micro/nano- structures in the EM reactionary zones. This concept includes integration of the propellant reactionary zones both into the control system by combustion mode, and into the general control system of the small-sized orbital maneuvering vehicle. The new possibilities for effective control by combustion processes opens in connection with possibility of initiation of self-organizing of the reactionary zone by use of the electric fields and electric discharges.

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