Fuel Processing Technology 107 (2013) 155–165

Contents lists available at SciVerse ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Self-organizing of the micro-structures in the reactionary zones of the energetic materials and excitation of the phenomenon of waves of negative erosion

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ARTICLE INFO

Article history:
Received 31 March 2012
Accepted 2 August 2012
Available online 24 August 2012

Keywords:
Energetic materials
Combustion instability
Reactionary zones
Electro-chemical phenomena
Micro-structures
Liquid-viscous layer

ABSTRACT

The wavy propagation of the local zones captured by negative erosion along the energetic material burning surface is implied under the phenomenon of waves of negative erosion. The key to the understanding of this effect is the electro-chemical phenomena in the reactionary zone of burning energetic material. It is proposed that the phenomenon of excitation of periodic toroidal vortex micro-structures over the burning surface plays a key role in the realization of the phenomenon of negative erosion. The boundary of existence of the phenomenon of negative erosion is determined by stability of self-organized toroidal-shaped vortex micro-structures in the stream of the combustion products which is blowing the burning surface.

1. Introduction

For more than 10 years, micro-propulsion has been an active world-wide field of research. Propulsion is a key point in the miniaturization of highly-maneuvering micro-satellites because they require very small and very accurate forces to carry out stabilization and large angle attitude maneuvers. The level of thrust and the precise impulse required for micro-satellite maneuvers cannot be achieved with conventional propulsion systems. Improved understanding of the combustion mechanisms of the energetic materials (EM) gives possibilities for the development of new methods and technologies for effective control by varying the parameters of ignition and combustion processes. Active combustion control is one of the most promising approaches to further optimize the size–weight–power relationship in solid propulsion systems.

The wavy propagation of the local zones captured by negative erosion along the EM burning surface is implied under the phenomenon of waves of negative erosion. Usually, appearance of this phenomenon is connected with propagation of the pressure waves over the burning surface. The waves of negative erosion may lead to local extinction of the flame on the burning surface and to appearance of the regime of pulsating ignition of the charge channel. The phenomenon of waves of negative erosion will reduce the solid propellant energetic performance. Taking into account of this phenomenon is important at designing of the solid-propellant highly-maneuvering micro-satellites having possibility of deep thrust control.

Understanding the mechanism of excitation of the phenomenon of waves of negative erosion is important from the point of view of formation of correct representations regarding fundamental laws of burning of the EM.

The necessity of revision of the negative erosion models is determined by the fact that the mathematical apparatus of the present-day models does not contain the necessary elements to obtain solutions that adequately describe these phenomena. Recent developments in predicting negative erosive burning do not show and do not take into account the electro-chemical phenomena in the reactionary zone of burning energetic material. They also don't show or take into account the excitation of hydrodynamic micro-structures over the burning surface [1].

It is desirable to base a new negative erosion model on experiments in which the temporal stepwise nature and the spatial non-uniformity of the torch micro-structures on the burning surface are pronounced most clearly.

In the last years, researchers have observed the excitation of spatial periodic micro-structures (SPMS) 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 (Fig. 1) [2–8].

It can be stated now that such local unstable behavior is typical for the EM with well pronounced exothermic reactions in the condensed

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0378-3820/$ – see front matter
http://dx.doi.org/10.1016/j.fuproc.2012.08.009

Nomenclature

C	sound velocity in air
C_x	drag coefficient of a toroidal vortex
F_d	drag force
L	length of the pulsed jet, $L = u_j \Delta t_j$
p_∞	constant pressure of the ambient medium
Q	heat flow onto the burning surface depending on the blowing velocity V
t	time
u_c	propagation velocity of the contact surface
u_j	velocity of plasma ejection at the nozzle edge
V	combustion products blowing velocity
V_r	radial velocity component
$V_{\varphi A}$	rotational speed of the leading part of the spiral
ρ_∞	mass density of the ambient medium
τ_B	high-temperature toroidal vortices formation time
τ_ν	total time of toroidal vortice formation
Δt_j	plasma decay time

phase and evaporation on the burning surface. Both experiments and theory confirm that the SPMS excitation is a rather universal phenomenon [9,10].

It is obvious that the dimension, shape and transient behavior of the glowing objects (spots) on the burning surface are of real importance when approaching the combustion limits, e.g., in combustion near the critical EM diameter.

Existence of pulsating micro-torches over the burning surface induces the small-scale turbulence in the gas phase above the burning surface and it induces the local increase of over-superficial heat-and mass transfer which results in heat feedback rising to the surface. "Wandering" micro-torches on the burning surface cause excitation of the micro-vortex cells (a the periodic toroidal vortex micro-structures).

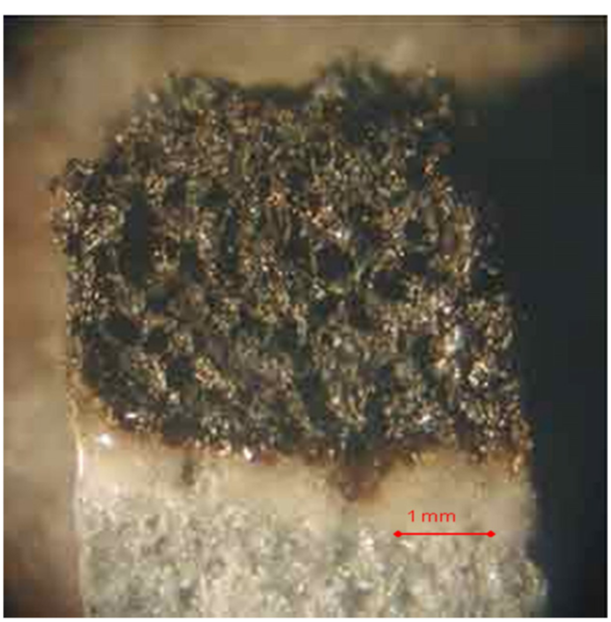

Fig. 1. Superficial layer of the extinguished solid rocket propellant on the basis of the ammonium nitrate (AN) for motors of space systems, (AN — 68%; HTPB — 17%; Al — 15%). As it is possible to observe, this propellant shows presence of the liquid-viscous layer and micro-structures on the burning surface.

A more complex case is when a propellant has a thick liquid-viscous layer (LVL) on the burning surface which is blown over by the combustion products (CP). There is a tendency to use solid propellants with a significant fraction of relatively low-melting [compared to ammonium perchlorate (AP)] EM, such as HMX, RDX, ADN, CL-20, HNF, etc. The surface temperature in this case is controlled primarily by evaporation processes and, in the rocket pressure range, it remains high. Thus, compositions with a thick LVL are being developed, which will lead to the necessity of estimating and describing the generally unsteady behavior of this layer at any site of the blown burning surface, particularly at the site of sudden flow expansion. The similar phenomena are observed at burning of the paraffin-based propellants in hybrid rocket systems.

2. Theoretical concepts of the phenomenon of negative erosion

In the earlier papers, negative erosion was also explained by possible experimental errors. Explanation of the negative erosion was associated with the melting of the fuel binder.

The further possible explanations of the negative erosion effect were connected with a hypothesis that treats negative erosion as a consequence of a decrease in reaction rate in the presence of large-scale turbulence [11,12]. Another possible explanation is the hypothesis that negative erosion can be explained from the standpoint of small-scale turbulence as a consequence of the inequality of the transport coefficients, i.e., the diffusion coefficient and thermal diffusivity (both the laminar values and their turbulent analogues).

The most favorable conditions for negative erosion develop at the laminar–turbulent transition, since loss of stability leads directly to large-scale fluctuations, small-scale turbulence appear only at very large Reynolds numbers [12].

Later, it was proposed that the mechanism, connected with the displacement of the boundary layer, followed by the flame deviation from the solid-phase surface and by decrease of the temperature of this surface [13–16]. The listed authors tried to confirm suggested mechanism of negative erosion only by the results of numerical modeling of the turbulent propellant combustion.

A similar mechanism of occurrence of the negative erosion was proposed in the paper [17]. In accordance with this mechanism, the burning rate decreases during blowing because the boundary layer is displaced, which results in a decrease of the heat flux from the flame zone to the solid-phase decomposition surface.

Earlier executed researches of the phenomenon of negative erosion did not consider characteristic conditions in which this phenomenon could be realized. In particular, the phenomenon of negative erosion is investigated at the pressure level of 10 MPa when the sizes of micro-structures on the burning surface are minimal [13–16,18].

3. The hypotheses of excitation of instability of the reactionary zone

Studying laws excitation micro-structures on the burning surface gives the key for understanding of possibilities of efficient control by the processes in the reactionary zones of the EM.

Several theories have been proposed highlighting different processes as the dominant mechanism of excitation of the micro-structures on the burning surface, but a unifying theory is yet to emerge.

The key to an understanding of these effects is the electro-chemical phenomena in the reactionary zone of the burning EM. The experiments for research amplitude–frequency characteristics of reactionary zones of the model composite solid propellants on basis of the ammonium nitrate and ammonium perchlorate, described in the papers (Refs. [19–21]), have shown, that in the frequency band of the electric current