INFLUENCE OF THE SOLID PROPELLANT GRAINS PROCESSING ON BURNING RATE OF DOUBLE BASE ROCKET PROPELLANTS

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Abstract

Besides a basic value of burning rate measured in standard test rocket motors, actual burning rate within a real rocket motor includes other influences as rocket motor dimensions, combustion gases flow within the chamber, chamber pressure, environmental temperature, angular acceleration, processing technology etc. The basic burning rate of solid rocket propellants is measured by standard ballistic test motor and is expressed by Saint Robert's law in form of $r = a \cdot p^n$*. Actual burning rate can be greater or less than the basic burning rate. Determination of different impacts on the actual burning rate is a complex task, which includes introduction of several assumptions in order to estimate an influence of each factor on the total burning rate.*

Impacts of geometric shape of propellant grains (star grain and hollow cylindrical grain with interior burning surface) and grain processing technology on variance of the basic burning law have been considered. Propellant grains, which were used in this research, had been manufactured by pressing and extrusion.

Significant deviation between burning rate measured in standard ballistic test rocket motors and the actual burning rate within the real rocket motors has been observed.

Key words: *rocket motors, double base propellant, burning rat, HUMP effect, pressing, extrusion manufacturing, radial acceleration*

1. BURNING RATE

Propellant burning rate is mostly influenced by the combustion chamber pressure and is expressed by Saint Robert's or Vielle's law within a limited pressure range:

$$r = a \cdot p^n \tag{1}$$

The pressure exponent n and the burn rate coefficient a are dependent on chemical composition of a solid propellant and initial temperature of the propellant grain. These coefficients are usually determined by ballistic evaluation motors [1,5,6,11,13].

Applied shapes of solid propellant grains for standard ballistic evaluation motors should ensure a low flow velocity over the burning surface, or mass flux of combustion products through the internal flow channel. The pressure exponent n should be independent on the combustion chamber pressure at a defined pressure range, and should be valid for a defined initial grain temperature.

Burning rate measured by ballistic evaluation motors must be corrected for real rocket motors, which depends on rocket motor size and conditions of its application. In order to obtain real values of burning rates within a rocket motor, previous measured values should

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be fitted for a real rocket motor. Typical fitting coefficient of burning rates, which is applicable to real rocket motors, lies between values of 1.01 to 1.05 [1].

For typical rocket propellants, at a pressure range of 3 to 15 MPa, pressure exponent is usually from 0.2 to 0.7 [2]. At double base rocket propellants, which contain burning rate catalysts, the pressure exponent is an indicator for catalytic efficiency to be obtained "plateau" and "mesa" effects (Fig. 1). If the pressure exponent approximates zero, "plateau" effect appears, and for a negative one, "mesa" effect. The pressure exponent n at extreme high burning rates, "plateau" or "mesa" effects, depends on physical and chemical properties of lead catalysts and their particle properties, as well as chemical composition of a double base propellant.

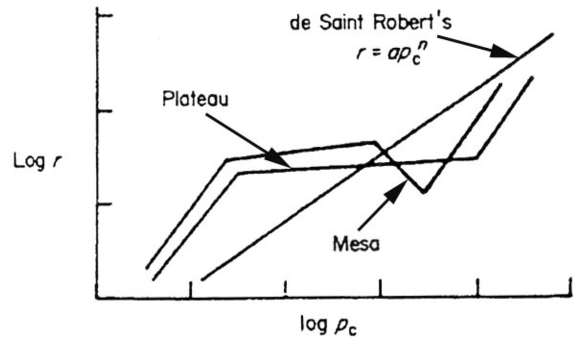

Fig. 1. Dependence of burning rate as a function of combustion chamber pressure[5,6]

Actual burning rate within real rocket motors is under other influences and because of that the burning rate is one of ballistic properties, which is determined with difficulty.

An actual burning rate in a rocket motor, except the basic value measured in standard ballistic evaluation motors, consists of several components. Determination of these components is a very complex task so many assumptions must be included, in order to be estimated their influence on the total actual burning rate.

Actual burning rate can be expressed as:

$$r_i = a \cdot p_c^n \cdot \sum \delta r_i \qquad (2)$$

where: δr_i i-th component of influence on a basic burning rate, *a* and *n* burn rate coefficient and pressure exponent measured in ballistic evaluation motors.

From the equation of mass conservation, which establishes balance between mass generation rate generated from the propellant burning and the sum of the gaseous mass rates accumulated in the chamber *dM/dt* and exhausted gases rate through the nozzle $\dot{m}_n$, actual burning rate can be determined [13,14,15]:

$$r = \frac{1}{\rho_p \cdot A_b} \cdot \left(\frac{p_c}{R \cdot T_c} \cdot \frac{dV}{dt} + \frac{V}{R \cdot T_c} \cdot \frac{dp_c}{dt} + \frac{p_c \cdot A_{th}}{c^*} \right) \qquad (3)$$

where: ρ_p – solid propellant mass density [kg/m^3]; A_b – grain burning area [m^2]; r – solid propellant burning rate [m/s], ρ_g – instantaneous gas density in the chamber; V – free volume within the chamber [m^3]; p_c – chamber pressure [Pa]; R – combustion gas constant; Tc – combustion chamber temperature [K], A_{th} – cross-sectional throat area [m^2] and c^* – characteristic velocity.

Estimation of variation of the basic burning rate due to influence of several factors can be made by appropriate separation each of influence components. Research of the influence of gaseous mass flux on the basic burning rate, which were performed by many authors [9,1], has shown that combustion products flow over the burning surface affects the effect of erosive burning.

When a solid propellant burning takes place under conditions of high radial acceleration, variation of the basic burning rate rises more intensive [13]. The newest research shows that the solid propellant grain processing affects the variation of basic burning rate [10], which has been confirmed through author's research work [13].

1.1 Influence of the solid propellant grain processing

Influence of the solid propellant grain processing, which is called effect the HUMP [4], consider a radial variation of burning rate as a function of the web burned. This effect has been noted when chamber pressure-time and thrust-time curves, for simple standardized propellant grains, were analyzed.

The greatest influence of the HUMP effect appears at the half of the web thickness, and calculations have shown the burning rates were increased in 3 to 7% [2], compared to the basic burning rate. Analysis of burning rates, obtained as a consequence of the HUMP effect, has shown that the burning rate varied with web burned. This influence is caused by rheology of the solid propellant grain processing, or actually by propellant mass flow during the pressing determined by pressing tool. The HUMP effect can be taken into consideration for internal ballistic prediction, if an empirical dependence of the burning rate of the web burned being established. Such dependence can be established for cylindrical and star grains, while a finocyl grain (with burning direction in different directions) this dependence has a sinusoidal character [5,6].

According to **[7]**, participation of the HUMP effect in variation of the burning rate is about 5% and it can be reflected on the burning rate increase or decrease. Fig. 2 shows the HUMP factor as a function of the relative web ratio burned for different rocket motors.

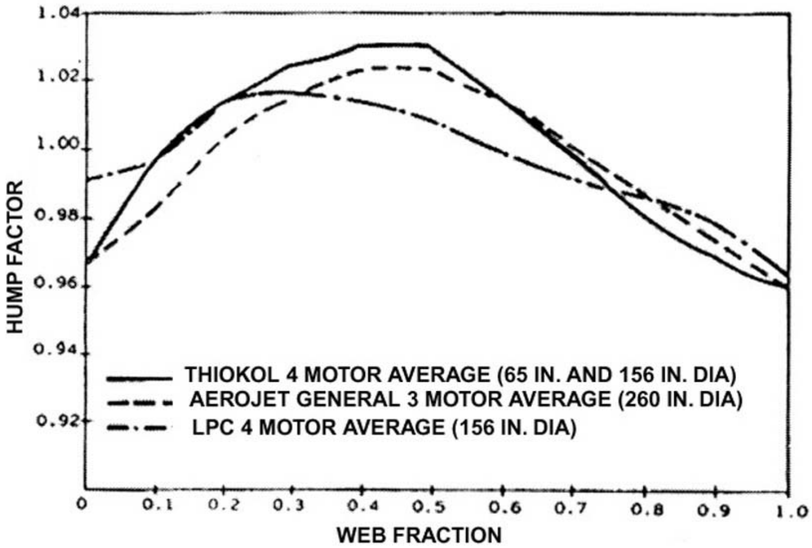

Fig. 2. HUMP factor as a function of the relative web for different rocket motors[10]

1.2 Influence of solid propellant grain processing method

A standardized production method for double base propellant grains is discontinuous process (pressing technology). High rate serial production of limited size solid propellant grains requires a different way of solid propellant processing –continuous process (extrusion). Differences between these two processing methods, lies in way of moisture separation from the "strong mixture", gelatinization procedure and forming processing of solid propellant grains. As a consequence of these technological procedures, percent ingredients of some additives and ballistic catalysts in the "tough mixture" are changed. These ingredients variations should not affect the character of the burning process essentially (curve "pressure-time" should be approximate same).

2. EXPERIMENTAL RESEARCH

Basic burning rate law for solid propellants manufactured by the discontinuous process has been determined for three initial grain temperatures 243 K, 293 K and 323 K. The burning rate law was determined by means of the standard ballistic evaluation motor 32/16 (cylindrical solid propellant grain with external diameter of 32 mm, internal diameter of 15.9 mm and length of 125 mm). The solid propellant grain ensures a neutral burning character. Each point of the burning rate plot corresponds to the test, which is determined by the nozzle throat diameter of the test motor. Burning rate laws for double base propellant NGR-A, at three different grain temperatures, are shown in Fig. 3.

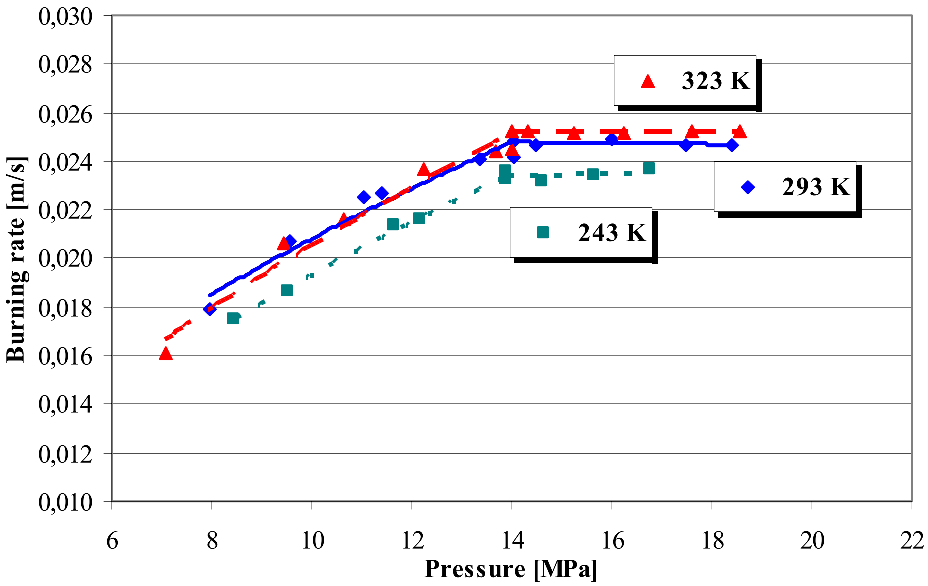

Fig. 3. Kinetic characteristics of the solid propellant NGR-A

2.1 Research of the Hump effect influence

Experimental research with two types of double base solid propellant rocket motor was performed. Fourteen rocket motors of 57 mm (*RM-3*) diameter with cylindrical (CP) grain and rocket motors with 128 mm diameter with star grain and two types of nozzles (two motors with a central nozzle *RM-2* and five motors with multiple peripheral nozzles *RM-1*). The basic burning rate laws for both DB solid propellants were measured in the ballistic evaluation motor *32/16* previously.

During testing of the rocket motors *RM-2* with the central nozzle and star grains (Fig.4), combustion chamber pressure were measured at both ends of the combustion chamber (Fig.5).

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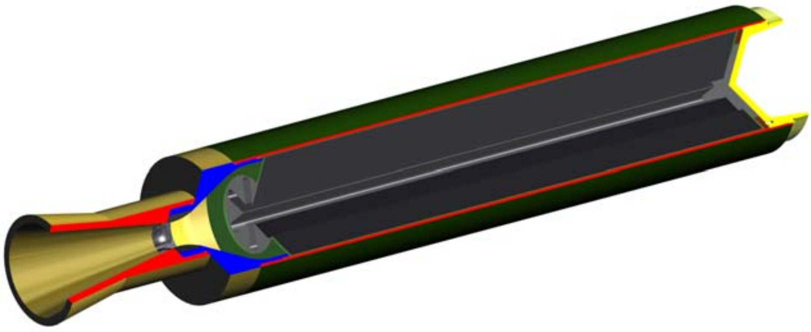

Fig. 4. Test rocket motor *RM-2*

The pressure-time curve measured by piezo-transducer system, and another one, which was determined by means of the computer program *SPPMEF* [12], deviate from each other. This deviation was caused by variation of the burning rate measured in standardized ballistic evaluation motors from the actual burning rate within a real rocket motor. Burning rate in a real rocket motor comprises a component of the HUMP effect.

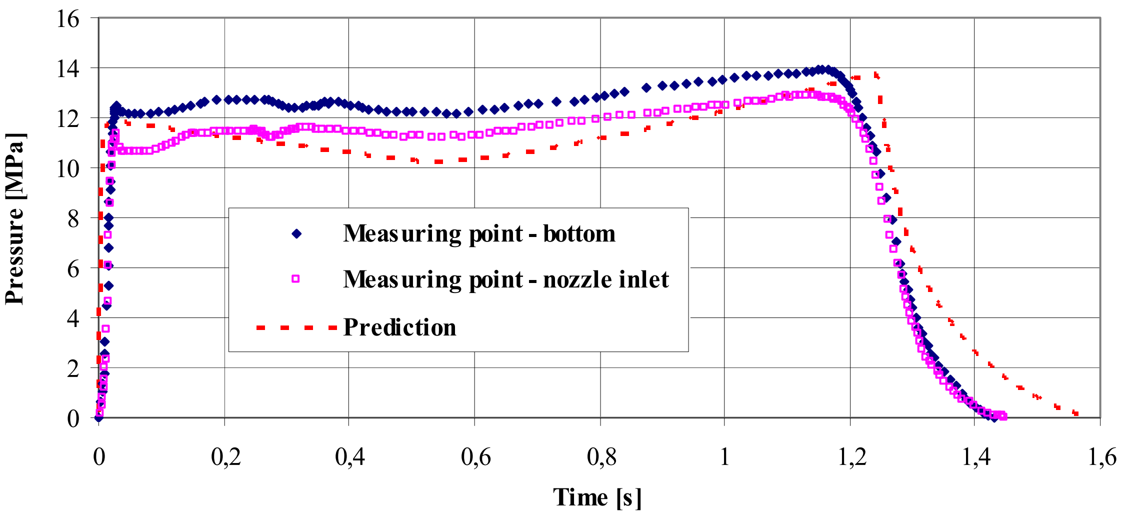

Fig. 5. Pressure-time curve for the test rocket motor *RM-2* [12]

Variation of the basic burning rate, caused by HUMP effect, is defined as a ratio of actual burning rate (within a real rocket motor) to the basic burning rate (measured by standardized ballistic evaluation rocket motor) under same chamber pressures and the definite web thickness burned (w). Influence of gaseous mass flux to the actual burning rate is neglected [12]:

$$\delta_{HUMP}(w) = r_i(p_c, w)/r_0(p_c) \quad (4)$$

Actual burning rate is determined by the relation (3), and the basic burning rate law was determined by tests with standardized ballistic evaluation rocket motors (Fig. 3).

Component of the burning rate caused by the HUMP effect for the rocket motor *RM-2*, was determined by analysis of the pressure-time curve, and it is shown in Fig. 6 as a function of relative web thickness.

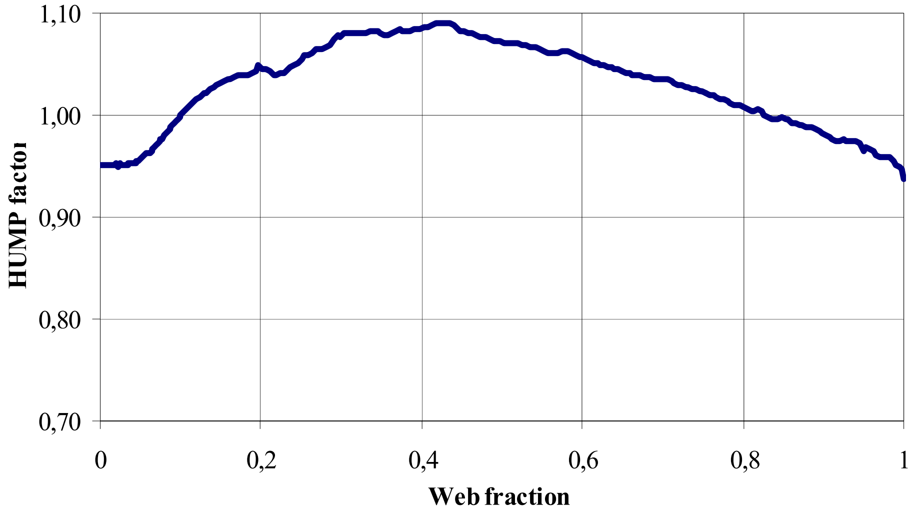

Fig. 6. Influence of the HUMP effect for the rocket motor *RM-2* [12]

Basic burning rate was corrected by HUMP effect influence, and the pressure-time curve was predicted by means of the computer program *SPPMEF*. The prediction has shown a good agreement with test results (Fig. 7).

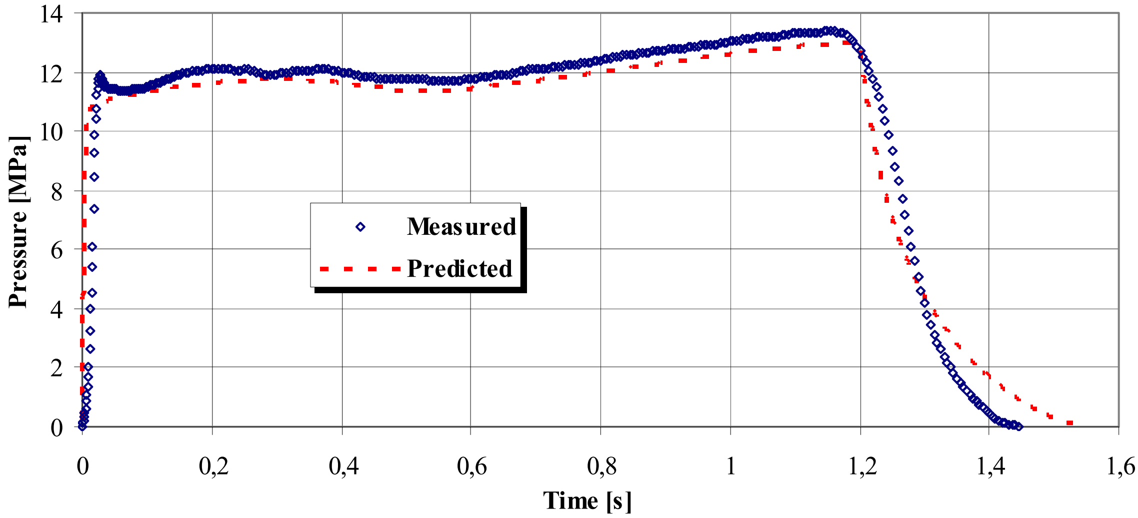

Fig. 7. Pressure-time curve for the motor *RM-2*, after correction due to HUMP effect [12]

Rocket motors *RM-1* with multiple peripheral nozzles were tested in order to be evaluated an influence of nozzle configuration on the actual burning rate. Character of variation of the component due to HUMP effect, as a function of web thickness, is shown in Fig. 8.

Variation of the component due to HUMP effect for rocket motors RM-3 (57 mm) is also shown in Fig. 8, where a significant variance can be noted. This fact points to the assumption, in which mass flux influence was neglected, is not correct. Results of calculations of the mass flux variation within the rocket motors 57 mm and *RM-2*, obtained from the computer program *SPPMEF*, is shown in Fig. 9. It can be seen that the mass flux in the rocket motor 57mm is considerable greater, and its influence on the basic burning rate is essential.

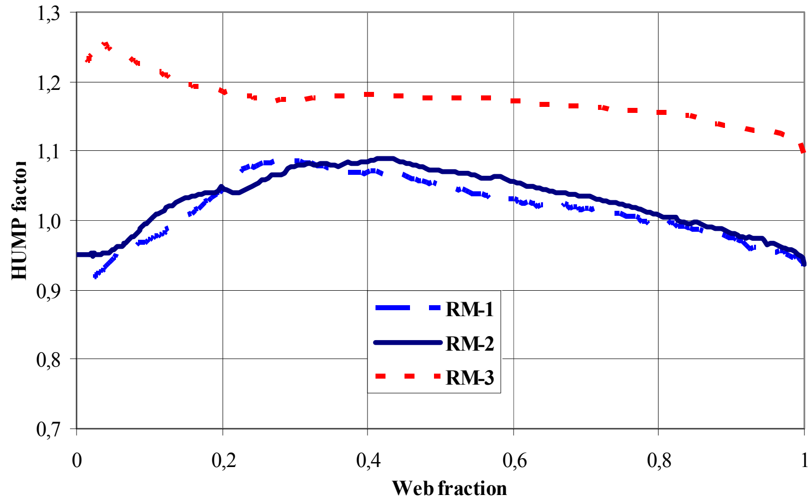

Fig. 8. Variation of the basic burning rate under influence of HUMP effect as a function of web thickness for rocket motors 57 mm, *RM-1* and *RM-2* (with central and multiple peripheral nozzles)

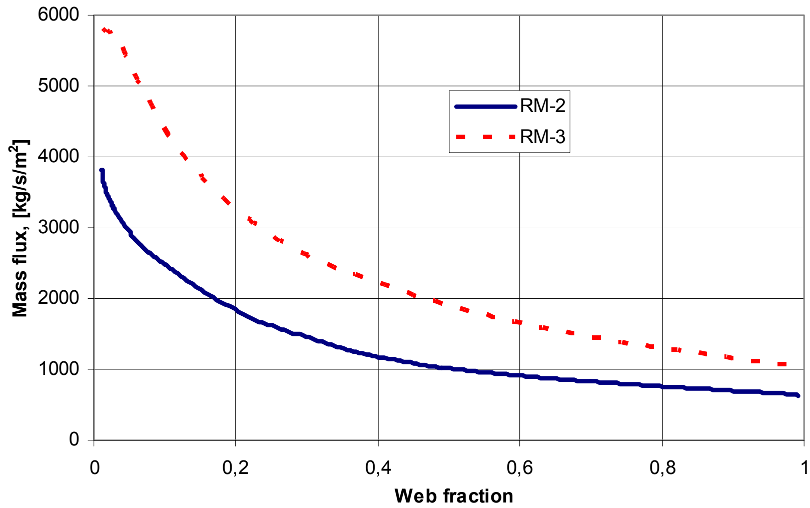

Fig. 9. Variation of the mass flux as a function of the web thickness for rocket motors 57 mm and RM-2

Character of variation and values of the burning rate component caused by HUMP effect is agreed with results obtained from other authors [5,6,10], and so that method, which was used in this paper, can be considered as correct. However, results obtained for 57 mm rocket motors, has shown a considerable influence of mass flux, so it should be careful when an assumption of its neglect being introduced.

2.2 Research of an influence of the solid propellant processing method

In order to raise the productivity, Vitezit- company (Bosnia and Herzegovina) introduced a continuous method of DB rocket propellant manufacturing. This production procedure comprises a process of gelatinization nitrocellulose by nitroglycerin and addition ballistic catalysts [3, 8] during the production sequences. Gelatinized mixture, which is used in this manufacturing process, has viscosity of 8-15 mPas, while discontinuous process requires (pressing) requires a mixture with greater viscosities of 25-35 mPas.

Ballistic evaluation rocket motors 32/16 with solid propellant grains manufactured by continuous and discontinuous process were tested at initial grain temperatures 293 K, 243 K and 323 K (Fig. 10. to Fig. 12.).

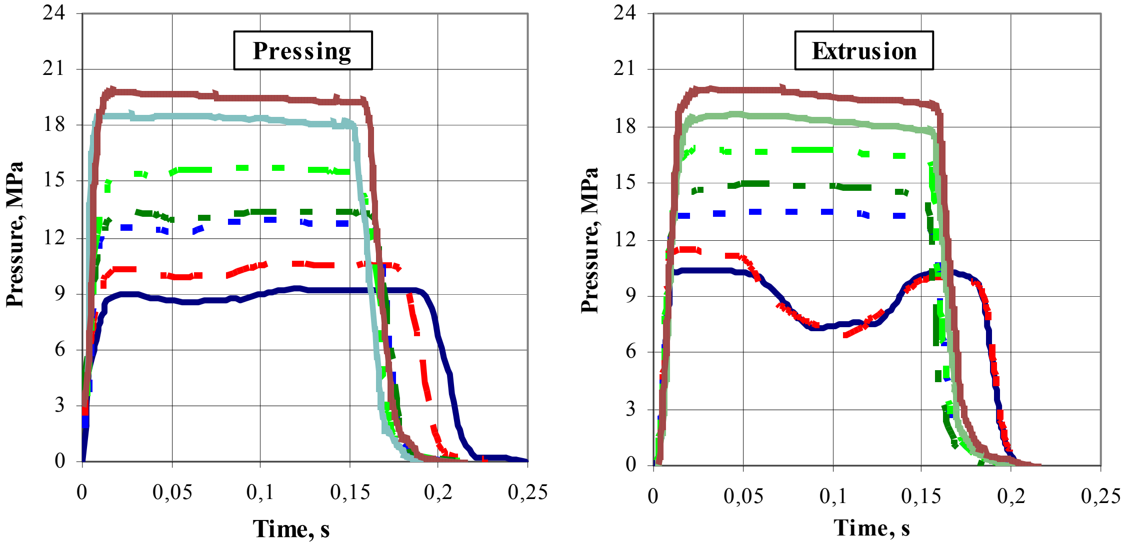

Fig. 10. Standardized ballistic evaluation motor 32/16 at temperature of 293 K, propellant NGR-A manufactured by pressing and manufactured by extrusion [13]

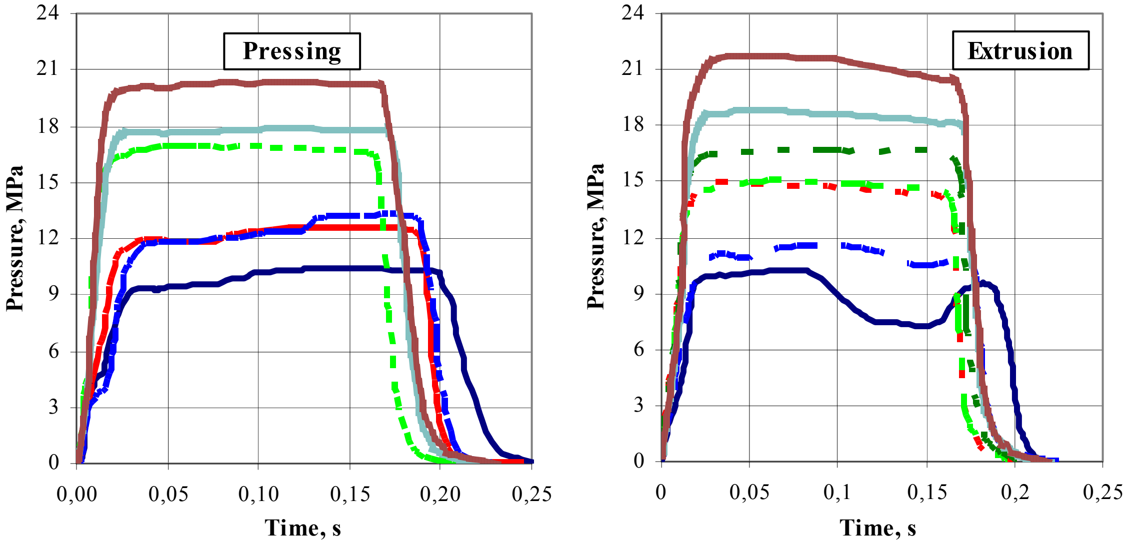

Fig. 11. Standardized ballistic evaluation motor 32/16 at temperature of 243 K, propellant NGR-A manufactured by pressing and manufactured by extrusion [13]

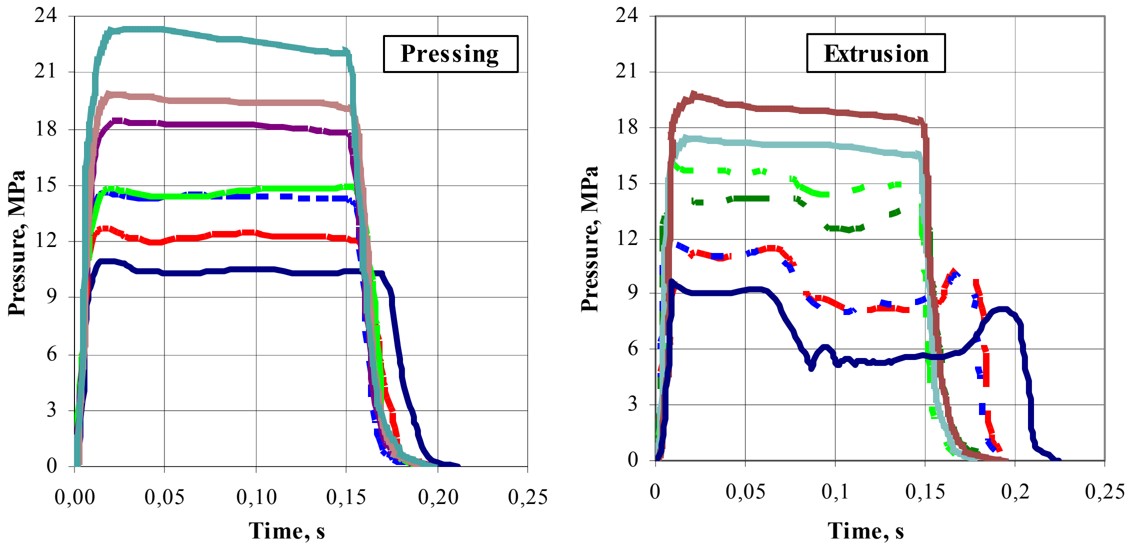

Fig. 12. Standardized ballistic evaluation motor 32/16 at temperature of 323 K, propellant NGR-A manufactured by pressing and manufactured by extrusion [13]

The basic burning rate for DB propellants manufactured by extrusion (Fig. 13) was determined on the basis of plots shown in Fig. 10 to Fig. 12.

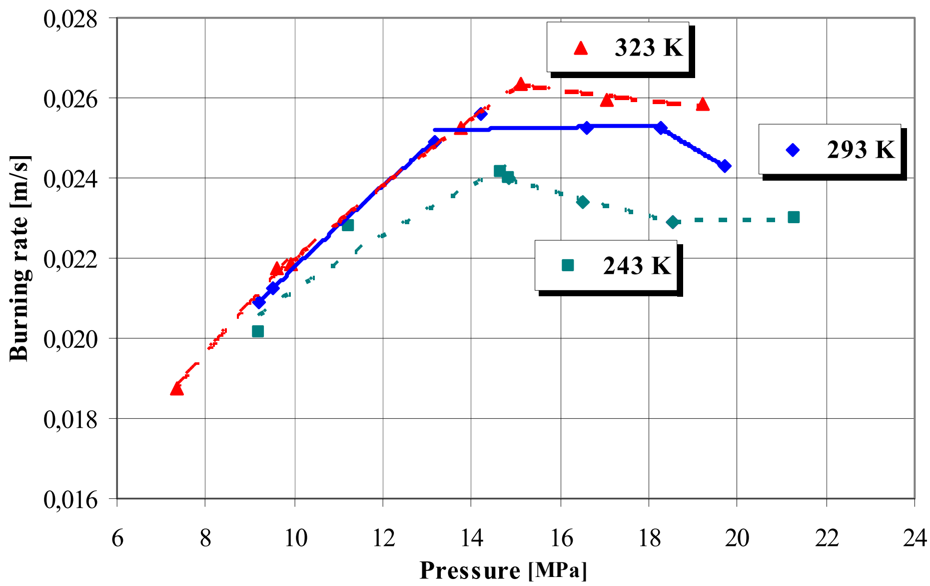

Fig. 13. Kinetic characteristics of the propellant NGR-A (manufactured by continuous process)

Unstable burning of solid propellant grains manufactured by continuous process, at low combustion chamber pressures, was observed. It was particularly distinguished at temperature of 323 K. Character of the basic burning rate law, for all three initial test temperatures (Fig. 13), is significantly different than in case of the rocket propellant manufactured by discontinuous process (Fig. 3). At initial temperatures of 323 K and 243K, the “mesa” effect appeared, while “plateau” effect disappeared. It was also observed that the start point of the “plateau” effect moved in 0,5 MPa to the left direction, at initial grain temperature of 293 K [13].

Real rocket motors with DB rocket propellants NGR-A, manufactured by continuous process, were tested at initial grain temperatures of 243 K and 323 K in order to research an influence of manufacturing process variation, composition and conditions of high radial acceleration, on the burning process (Fig. 14).

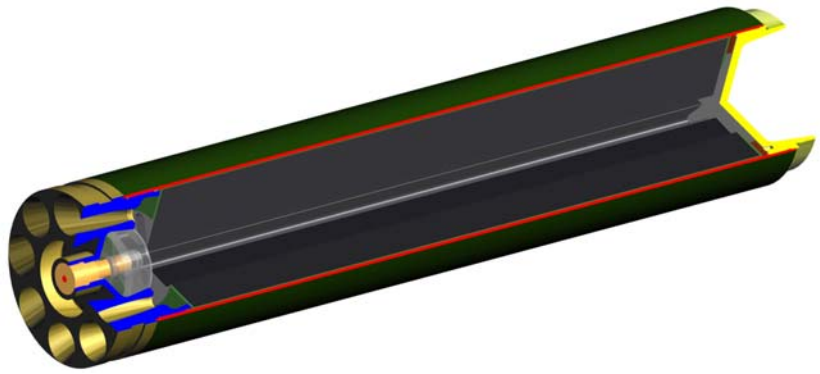

Fig. 14. Test rocket motor *RM-1*

Unstable burning was observed in standardized ballistic evaluation motor 32/16 at initial temperature of 323 K and at combustion chamber pressure less than 15 MPa (which determines a zone of super burning rate). There was no unstable burning when real rocket motors were tested, at same initial temperature and under variable radial acceleration (Fig. 15).

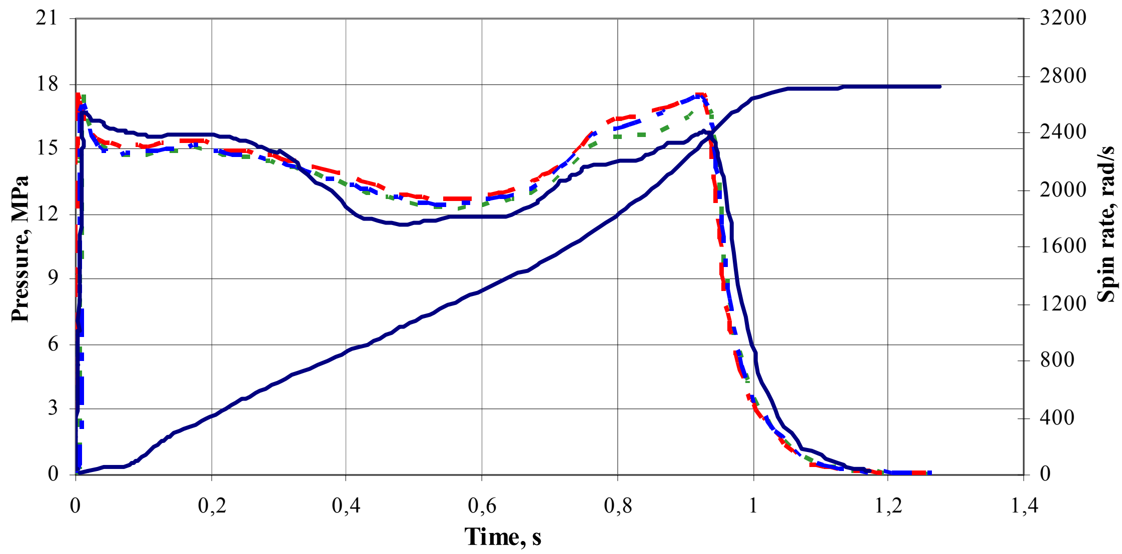

Fig. 15. Influence of variation of solid propellant processing on the curve pressure-time form for DB propellant NGR-A tested at temperature of 323 K [13]

A distinguished unstable burning was observed when real rocket motors were tested at initial temperature of 243 K (Fig. 16). It was more intensive while rocket motors were approaching to maximum radial acceleration.

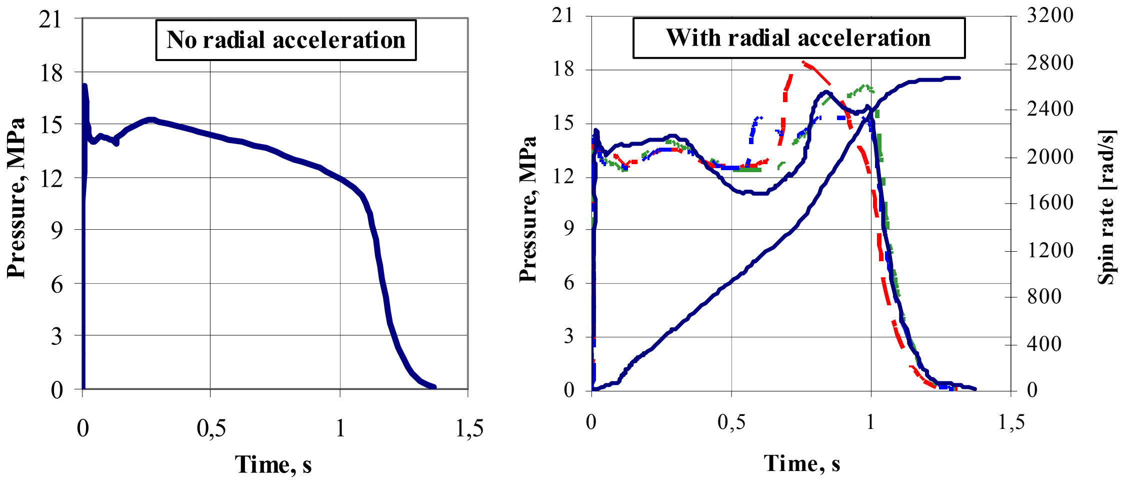

Fig. 16. Influence of variation of solid propellant processing on the curve pressure-time form for DB propellant NGR-A tested at temperature of 243K, without and with radial acceleration [13]

Pressure-time curves of two groups real rocket motors, which were exposed to influence of variable radial acceleration, are shown in Fig. 15 and Fig. 16. Continuous line refers to solid propellant grain, manufactured by discontinuous process (pressing), while other dashed or dash dot lines refer to solid propellant grains manufactured by continuous process (extrusion).

Unstable burning, observed at extruded DB propellants in standardized ballistic evaluation motors 32/16, becomes more distinguished at real rocket motors, which are exposed to variable radial acceleration.

3. CONCLUSION

The presented method enables determination of the HUMP effect influence on the basic burning rate.

Accuracy of the method depends on mass flux intensity, which flows over the burning surface. For extreme intensities of mass flux, this method is not applicable.

Measured components of burning rates caused by HUMP effect, obtained for different types of rocket motors during the presented research, are agreed with results obtained from other authors.

Comparative analysis of the pressure-time plots points to conclusion that variation of solid propellant processing has an influence on DB propellant burning process, but also that burning behavior depends on radial acceleration.

The most distinguished unstable burnings were observed for propellant grains tested in standardized ballistic evaluation motors 32/16 at initial grain temperature of 323 K. However, the most intensive unstable burning at real rocket motors, which were exposed to variable radial acceleration, appeared at initial grain temperature of 243 K.

Burning instability caused by variation of solid propellant grain processing, corresponding percentage ingredients and types of additives has shown that burning mechanism had been changed.

Dispersion of ballistic additives within the basic DB propellant structure, manufactured by extrusion, is different than dispersion from structure obtained by pressing. This affects catalytic effects of different additives, which cause the “mesa” effect in the basic burning rate law of the extruded solid propellant NGR-A.

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