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EFFECT OF EROSIVE BURNING IN ROCKET MOTOR ON THE BALLISTICS OF ROCKET FLIGHT

SRĐAN STOJKOVIĆ
Military Technical Institute, Rocket Armament Sector, Belgrade, ssrdjanvti@gmail.com

NIKOLA GLIGORIJEVIĆ
Institute Vlatacom, Belgrade, nikola.gligorijevic@vlatacom.com

Abstract: *Erosive burning in solid rocket motor is a phenomenon that occurs at the beginning of the motor operation and represents an increase in the burning rate in the motor compared to the designed rate. The result of increased burning rate is an unwanted pressure increase in the motor, and thus thrust, which changes the designed flight parameters of the rocket. During development of the rocket motor, this problem should be solved constructively, if possible, by changing the shape and dimensions of the propellant grain and motor elements. If it is not possible, the designer tries to make the system capable enough to withstand pressure and thrust jumps without major disturbances, and to provide to achieve the reproducibility of this phenomenon. The paper presents examples of the impact of erosive burning onto the flight of some small-caliber unguided rockets, and also for one short-range guided missile, where this phenomenon is clearly expressed, but reproducible and acceptable. In this paper, the results obtained on the basis of measurements carried out by researchers from MTI, HK Krusik, MB-Lucani and the Vlatacom Institute were used. Measurements were made in static and dynamic conditions, in the laboratories of the mentioned companies. For the analysed guided missile, the shape of the propellant grain was reconstructed to avoid guidance and structural problems. Some examples of design solutions of the rocket propellant grain in order to reduce the occurrence of erosive burning are also presented.*

Keywords: *Propellant, Grain, Erosive burning, Port/throat ratio, Thrust, Burning surface*

INTRODUCTION

In a solid rocket motor high-velocity flow of gaseous combustion products over the burning surface in the propellant grain channel, on their way towards the nozzle, causes an undesirable increase in the burning rate. The phenomenon is called erosive burning [1]. The increased burning rate affects the pressure increase in the motor, (Fig.1) and thus also the thrust increase, which can significantly affect the rocket cinematic and dynamic performances.

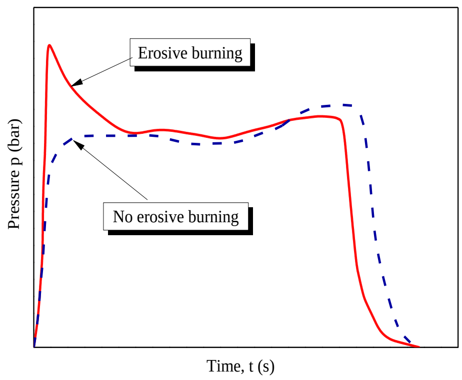

Figure 1 – Erosive burning

Erosive burning is well known and much discussed in the literature [2,3], but in addition there is no clear pattern for defining the boundary conditions at which it occurs. Each case is different [4,5] and only some similar forms of propellant grains can be compared under recommended criteria.

There are various methods of preventing or reducing erosive burning, and some of them are mentioned here. In addition, this paper discusses the possible effects of erosive burning on rocket flight.

Erosive burning occurs mainly at the start of rocket motor operation, most often in the central channel of the grain, but also in the gaps and perforations through which the combustion products flow towards the nozzle. This phenomenon usually lasts for a short time, until a certain layer of the propellant is burned out and until the channel for the passage of the gases are expanded. Sometimes this phenomenon can last even longer [6,7], depending on the design of the propellant grain and other motor elements.

Erosive burning is most reflected in the parts of the grain where the highest concentration of gases flowing towards the nozzle is present, in the rear portion of the channel, because the grain port is too small to accept a large amount of gases [8]. This happens when the port to throat ratio is less than 2, but the pressure overshoots of 100 % have been observed even with higher ratios of 4 to 6 [9].

This case often occurs with smaller-caliber rocket motors, which require a large thrust but the smallest possible mass, which implies a high propellant volumetric loading fraction [10] in the motor chamber. This is achieved by means of long propellant grain, usually with complex port shape. Designers often project propellant grain with low port-to-throat ratio, partially neglecting erosive burning or “controlling it to be reproducible from one motor to the next” [1].

Corresponding author: S.Stojković;
E-mail: ssrdjanvti@gmail.com
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In this paper some examples of the controlled erosive burning are shown, as well as some design details that prevent the high intensity of this phenomenon.

The influence of erosive burning process on the ballistic characteristics of the several well known rockets was also analysed. A few own-made softwares, developed in Military Technical Institute (MTI) were used for the analysis. Aerodynamic derivatives were calculated using the DMAC program [11]. On the basis of thrust distribution vs time curves and mathematical models of missile motions, the trimmed (equilibrium) trajectories in vertical plane were calculated using the GMTC-3D program [12]. Ballistic parameters of the rockets were used for calculation of their trajectory parameters using the program UMTC 3D [13].

AN OVERVIEW OF INDIVIDUAL EXAMPLES

The S-8 is a rocket weapon cal.80 mm, developed by the Soviet Air Force in the 1970's for use by military aircraft [14]. There are two versions of this rocket, S-8 KO and S-8 KOM. Their motors are good examples of fairly strong but controlled erosive burning that is reproducible under the same conditions. Static tests in MB-Lucani, MTI and HK Krušik showed that during the design of these propellant grains the erosive burning was accepted, fully reproductive at elevated temperatures, but so that the system can withstand this without major disturbances.

The port to throat ratio of the propellant grain is generally a good criterion for the occurrence of erosive burning. If this ratio is greater than 4, it is considered that the basic construction of the propellant grain is good. This ratio also can be less than 2, if the propellant burning rate in standard conditions is less than 7-8 mm/s. However, with the S-8 KO and S-8 KOM motors, burning rates are around 11 mm/s and port to throat ratios are less than 2 [15]. It means that erosive burning could be predicted even in design phase. The only question was, which was later proven by experiments, whether the level of erosive burning was acceptable from the point of view of the motor elements safety factor, as well as from the point of view of external ballistics.

In the case of the WS-15, 122 mm Chinese-made rocket motor, which was tested by the Vlatacom Institute at the test laboratory in Egypt, this level of erosive burning should have been higher, but the designers prevented this by the grain shape. Similar logic was also applied for the Russian rocket motors Grad 122 mm and BUK 400 mm.

It is difficult to define the final rules during the design and development of a rocket motor, because each motor is a case for itself. In the case of special design, like for the sustainer for "Bumbar" ATGM guided missile [6,7], this port-to-throat ratio was even higher, about 4.50, which is a condition for less pronounced erosive burning, and yet this phenomenon was very high.

The reason for this was the specific design of the rocket motor with a central pipe, as a result of which there was a high turbulence in the gas flow towards the nozzle, causing a strong phenomenon of erosive burning. System "Bumbar" could not accept this level of erosive burning, so a redesign of the propellant grain and nozzle was carried out.

The port-to-throat ratio is only one in a series of different parameters for assessment for the occurrence of erosive burning. In the case of long propellant grains, like in the motors for unguided rockets S-8 KO and S-8 KOM, the ratio of the burning surface (A_b) in the grain channel to the cross section of the channel (A_{port}) is one of the very good parameters. In the examples given, this ratio ranges from 235 to 270. Preliminary calculations [15] show that erosive burning can be avoided if this ratio is reduced below 200 or even lower. Such is the case with the Chinese rocket WS-15, tested by Vlatacom institute. For the motors of this type, this parameter seems to be much better, because it takes into account the influence of the grain length. All gases produced by combustion, along the entire channel, go towards the nozzle and their highest concentration is at the rear end of the grain, where the greatest heat transfer from the gases to the surface of the propellant grain occurs. That means the greatest increase in burning rate, and thus the pressure and thrust.

In this paper, we analyzed the phenomena of erosive burning in the rocket motors of the unguided rockets "S-8 KO" and "S-8 KOM" with a diameter of 80 mm, the guided rocket "Bumbar", with a diameter of 136 mm, and their effects on the flight of these rockets. The examples are shown of solving the erosive burning problems in the motors of the rockets "Grad" and "WS-15" with a caliber of 122 mm, and BUK rockets with a diameter of 400 mm.

The S-8 KO rocket motor has a 7-wedges star perforated grain (Fig.2) with burning surface web-distribution like in Fig.3.

Figure 2 – Propellant grain S-8 KO

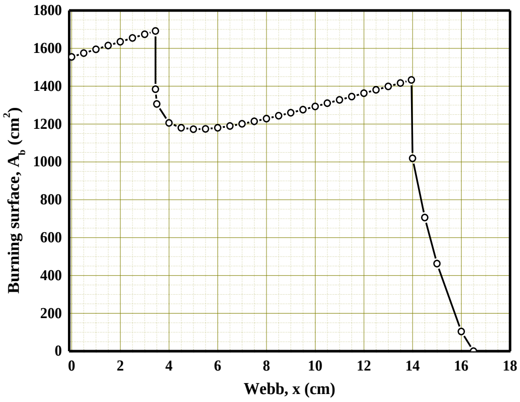

Figure 3 - Burning surface

It is known that the burning rate increases along with temperature, but erosive burning is also more pronounced at elevated temperatures.

Figure 4 shows the diagrams of the pressure vs. time in the S-8 KO rocket motor at characteristic temperatures.

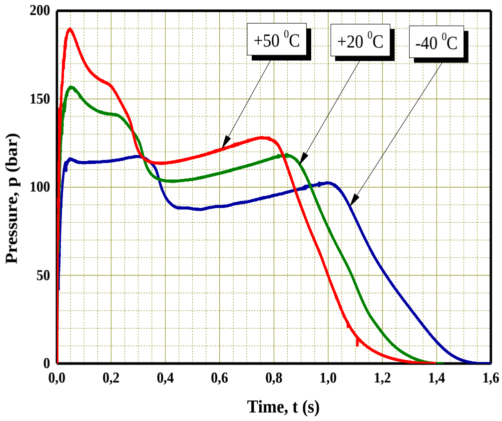

Figure 4 – Pressure distribution in the motor S-8 KO

By comparing the test diagrams (Fig.4) with the burning surface distribution (Fig.3), it is seen that the shape of the pressure curve at low temperature is very similar to the surface distribution. Considering the direct dependence of these two features, this correlation was expected at all temperatures.

However, with the increase in temperature, there is an obvious pressure augmentation in the initial period of motor operation, due to the erosive burning. An increase in pressure can already be seen at standard temperature. During a large number of static tests, it was determined that this phenomenon is reproducible in this motor.

How does it affect the missile's ballistic parameters? We analyzed the case when a rocket is launched from an aircraft that is at a height of 500 m, with an initial speed 200 m/s, and a launch angle of -10^{0}C.

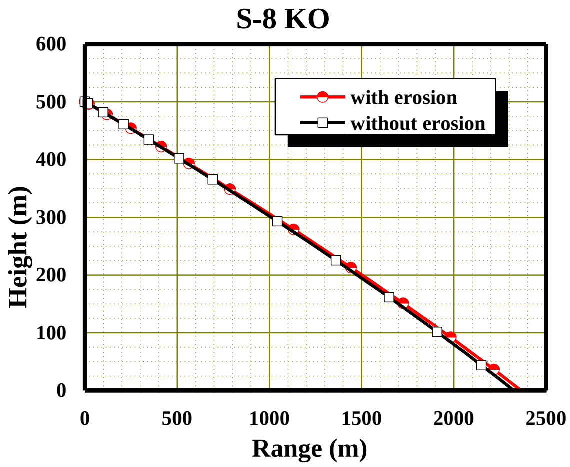

Figure 5 – Effect of erosive burning on missile range

Fig.5 shows two different cases of rocket trajectories, with and without erosive burning. Figs 6 and 7 compare the Range vs Time and Speed vs Time curves for the two cases. There is a big difference between the two operating modes of the motor, but there is no way to avoid this. The rocket designers considered that this impact can be ignored, because the calculation results have shown that the dispersion of hits is very close to the prescribed standards.

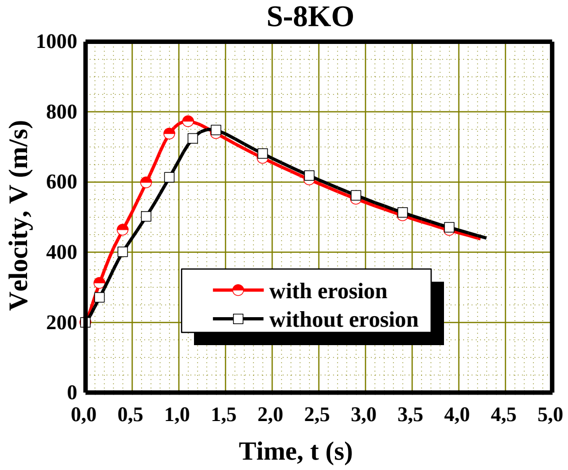

Figure 6 – Effect of erosive burning on rocket velocity

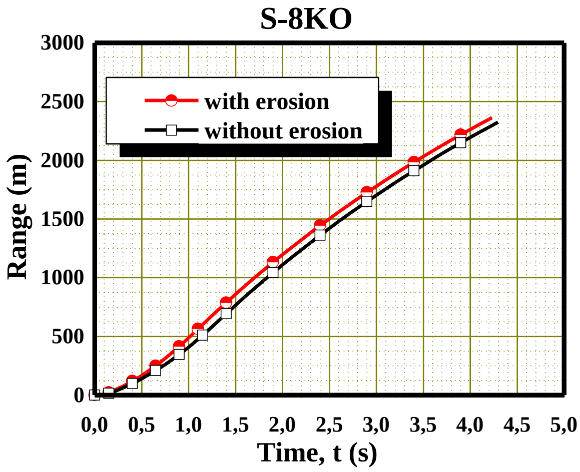

Figure 7 – The effect of erosive burning on the time of reaching the target

Big difference in the motor operating modes at different temperatures looks rather strange, but in this example it has no great effect on the missile's ballistic parameters. It is obvious that the rocket motor designer had experience how these differences affect the ballistic properties or he has solved this problem during development, through the tests, accepting a permissible level of erosive burning. Of course, each development is different and every assumption must be proven in experiments.

A similar analysis was done for the S-8 KOM missile. Propellant grain in the rocket motor, with three arms, burns radially from the outside and inside (Fig. 8).

Figure 8 - Propellant grain S-8 KOM

The propellant grain is very long (fig. 9), and during design it was immediately clear that there are conditions for the erosive burning occurrence.

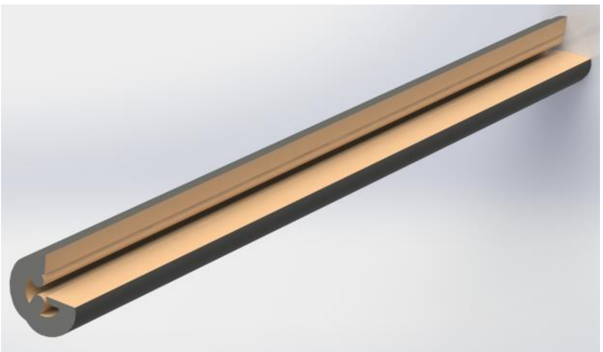

Figure 9 - S-8 KOM propellant grain

During most of the combustion process, the calculated burning surface is neutral, except at the end (Fig. 10).

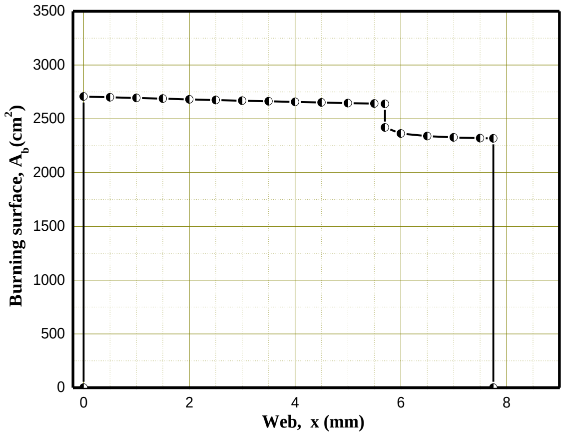

Figure 10 – S-8 KOM burning surface

However, since a large amount of gases hardly passes through the channel, erosive burning occurs in the rear part of the propellant grain, so the initial pressure at +60^{0}C (225 bar) is much higher than the pressure at -60^{0}C (90 bar). The pressure diagram at the extreme low temperature (-60 ^{0}C) completely follows the burning surface distribution. At higher temperatures, starting from standard one (+20 ^{0}C), pressure diagrams show pronounced erosive burning (Fig.11).

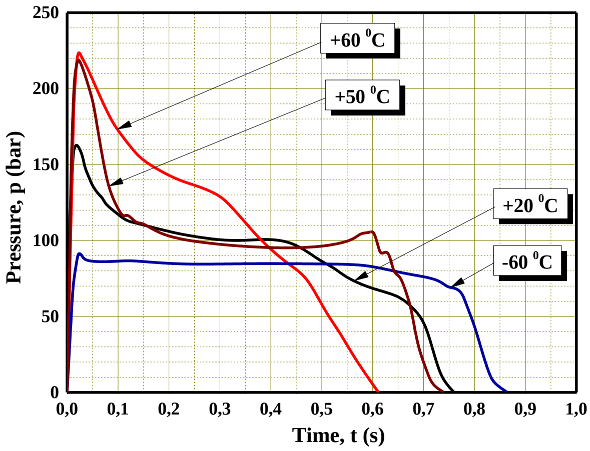

Figure 11 - Pressure distribution in the motor S-8 KOM

One gets the impression that the pressure difference between extreme temperatures is unacceptable. But we know following the practice that this rocket is reliable and in widespread use.

That's why we performed an analysis from the point of view of ballistics of the projectile, to make sure that this is still acceptable. It only means that the designer was able to accept this phenomenon when he achieved its reproducibility during the motor development.

As in the previous case, rocket trajectories were checked for two different cases, with and without erosive burning (Fig. 12). Figures 13 and 14 compare the Range vs Time and Speed vs Time curves for these two cases, in a similar way as for the S-8 KO rocket.

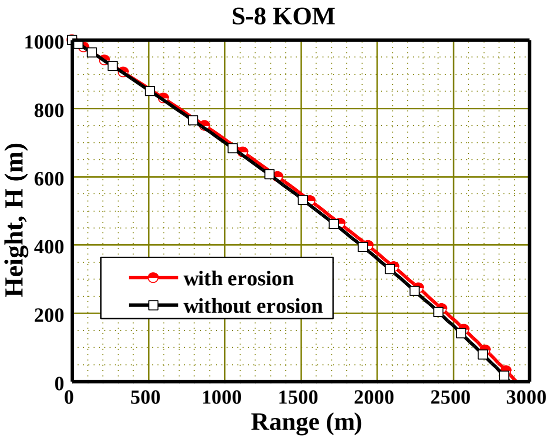

Figure 12- Effect of erosive burning on missile range

Here, the influence of erosive burning on ballistic parameters is also almost negligible, although there is a big difference in the motor operating modes (pressure vs time) with and without erosion (Fig. 11).

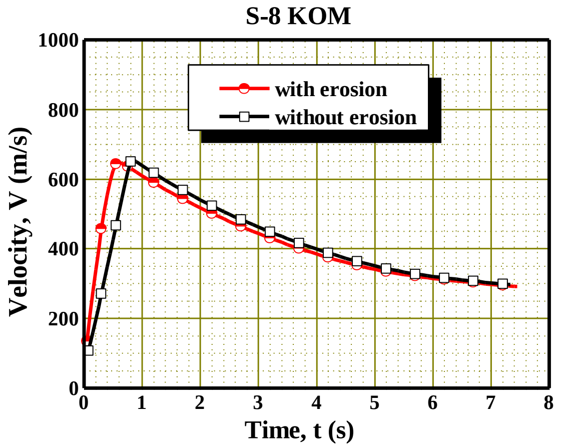

Figure 13- Effect of erosive burning on rocket velocity

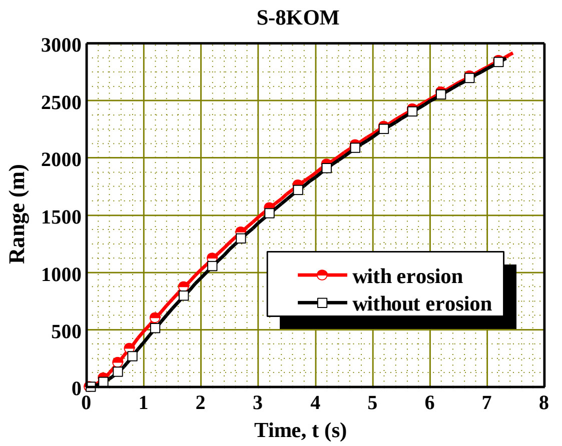

Figure 14 – The effect of erosive burning on the time of reaching the target

If it was determined during the motor development that the phenomenon is reproducible and acceptable from the ballistics point of view, then the pressure increase affects only the mechanical resistance of the motor elements, primarily the propellant grain itself and the motor case.

In the case of the aforementioned S-8 KO and S-8 KOM motors, the designer concluded that pressure increase due to erosive burning does not affect the final mission of the rocket, but the thickness of the motor chamber had to be increased, which affected the entire mass of the rocket. It was estimated that the mass increase was acceptable.

A special case is an example of erosive burning in the sustainer of Serbian-made "Bumbar" ATG missile.

Thrust vector control system is applied with interceptors that are going into and out of the stream of gaseous products at the exit of the nozzle (Fig.15 and 16).

Figure 15 – ATGM Bumbar

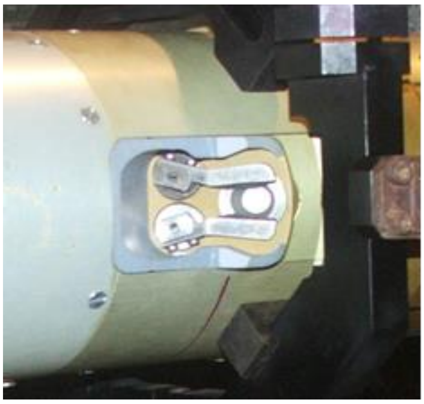

Figure 16 - Thrust vector control system with interceptors

A double based propellant grain in the simple form of internal-burning tube (Fig.17) have been designed for the use in the motor. The grain combines internal and double-end burning [1,8] with outer surface inhibited.

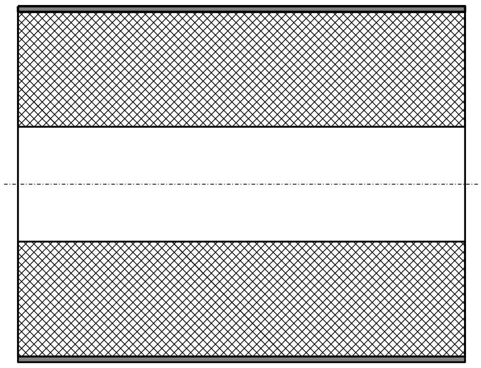

Figure 17- Propellant grain

With the small length to diameter ratio (L/D<2), a mildly progressive-degressive burning surface was expected with a quite high degree of neutrality, in accordance with the calculations (Fig.18).

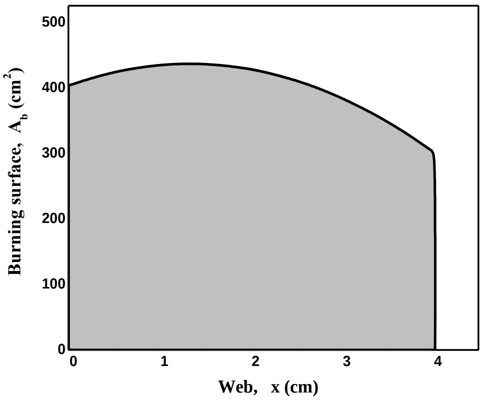

Figure 18 – Burning surface

It could be expected, during design, that both pressure and thrust curves have a slight increase in the central part of the motor operation, proportional to the burning area. Unfortunately, during the initial static tests of the propellant grain in experimental motor, in the temperature range between -30^{0}C and +50^{0}C, erosive burning as expected [4,5,9,16] appeared on higher temperatures (Fig. 19).

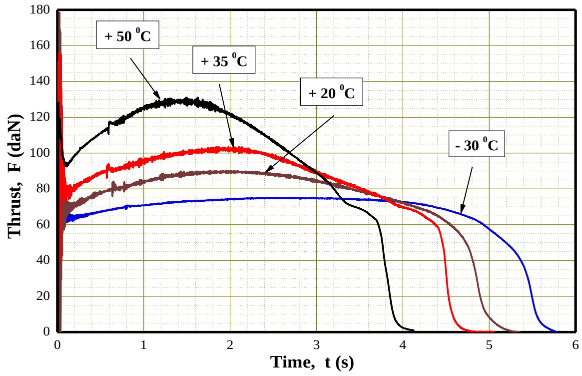

Figure 19 – Thrust vs. time

The main reason is central tube that passes through the grain channel reducing its cross section (Fig.21). Burning products are passing through significantly reduced channel port, in the form of a ring between the outer surface of the central tube and the inner surface of propellant grain. The small passage for the gases created conditions for increasing the flow-rate through the channel.

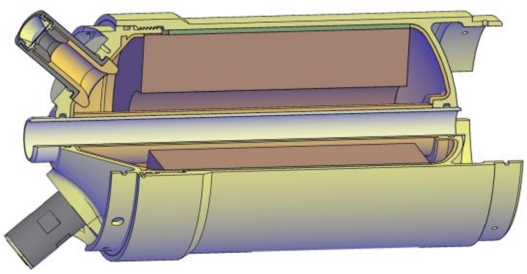

Figure 20 - Test motor intersection

A very good solution to this phenomenon was achieved by a relatively simple change of the propellant grain, by opening a part of the inhibited outer surface of the grain, (Fig 21), which equalized the amount of gases passing through the channel and gases passing from the outside, through the gap between the grain and the chamber wall [6, 7, 17, 18].

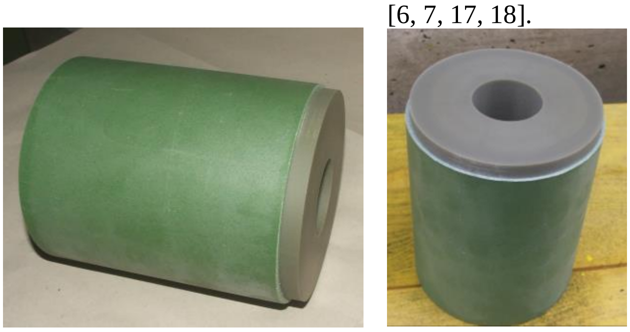

Figure 21 – Modified propellant grain

The tests have now produced the following results (Fig.22):

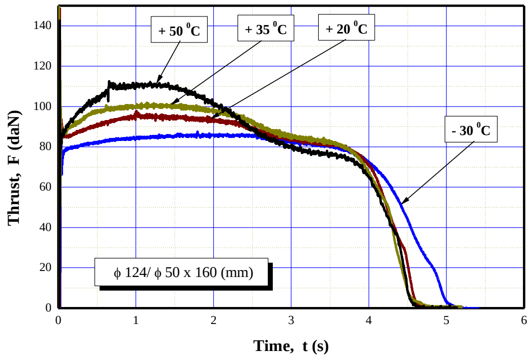

Figure 22 – Reduced thrust after changing the grain shape

Erosive burning is still present at +50 ^{0}C, but the thrust increase is much smaller than with the basic solution. This difference is best seen by comparing the two solutions at the same, upper extreme temperature (Fig 23).

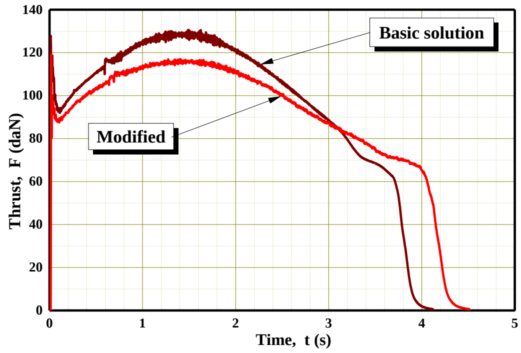

Figure 23 - Comparison of the test results at + 50 ^{0}C for two different solutions

These two solutions were considered by ballistic analysis. As a consequence of the guidance system with thrust vector control, in the case with highly pronounced erosive burning, the rocket has a smaller effective range (Fig. 24).

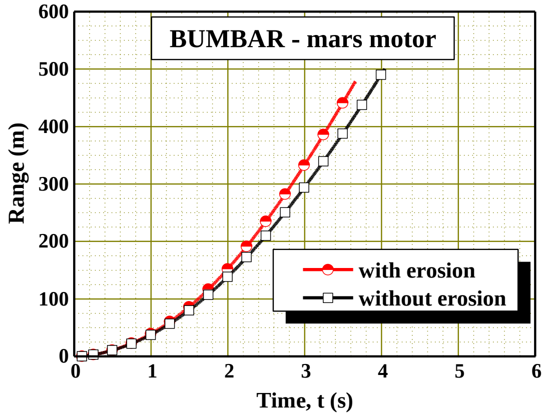

Figure 24 – Range vs Time

At the same time, a higher speed is not enough to reach the required range (Fig. 25).

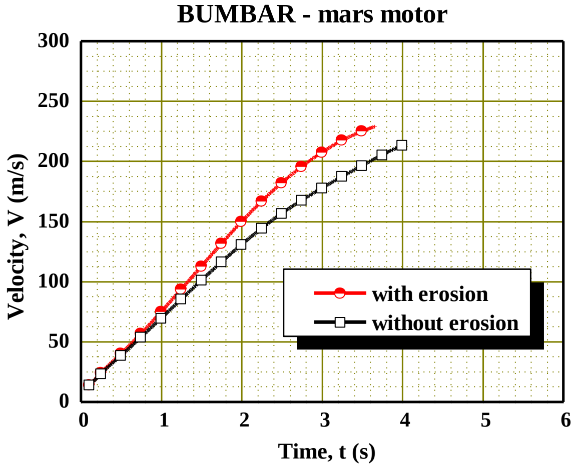

Figure 25 – Velocity vs Time

In the case of nonerosive (or less erosive) burning, in order to maintain trimmed horizontal flight we need 10% more command in pitch (η) in the first phase of flight, but in the second phase, after 3.5 s, when it is much more convenient, we need 12% less command to achieve horizontal flight Fig.26)

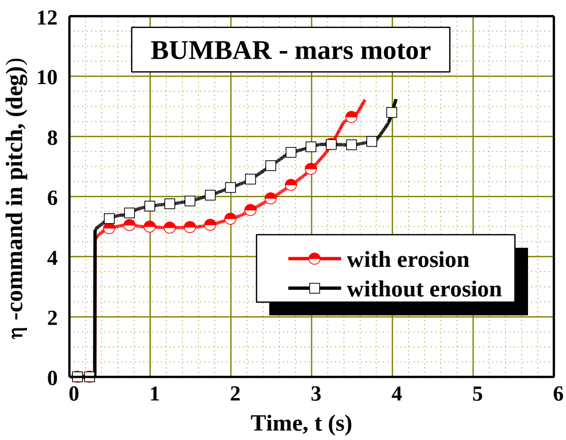

Figure 26 – Command in pitch

And finally, when there is no erosive burning in the motor, the thrust is lower and in the first phase of the flight, the maneuverability is lower. However, in the second phase of the flight, which is much more important, the maneuverability is greater (Fig. 27).

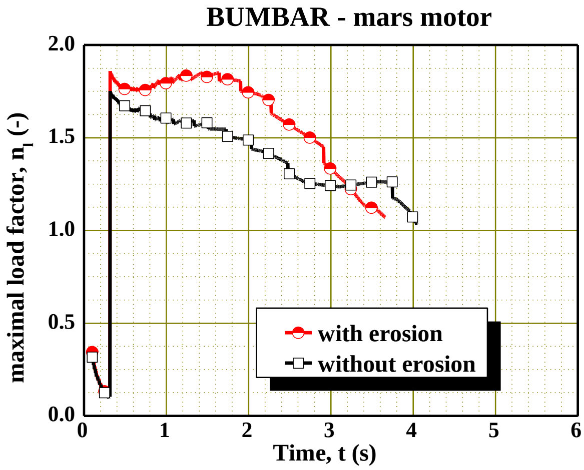

Figure 27 – Maximal load factor

The general conclusion is that in the Bumbar system, erosive burning led to a clearly pronounced weakening of the missile's ballistic properties.

In this particular case, there was another important reason to reduce erosive burning in a constructive way. The increase in pressure at the exit of the nozzle affected the appearance of greater obstacles for the entry of control elements (interceptors) into the stream of combustion products, as a result of which the thrust vector control system was not effective.

When the assumed intensity of erosive burning in the design phase and during development is not acceptable from a ballistic point of view, it is necessary to reduce this phenomenon with a suitable design of the propellant grain.

If neutral burning is desired, which is achieved by radial burning of cylindrical grains, both from the inner and outer side, then the propellant grain may be made in two parts, where the part of the grain that is closer to the nozzle is made with a wider channel that can accept the entire amount of gases from both parts of the grain (Fig. 28).

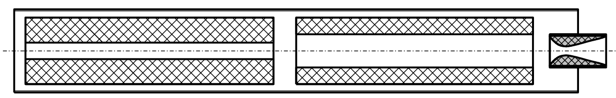

Figure 28 – Propellant grain with two different cylinders

We have such an example with the Grad 122 mm rocket motor, where the required burning surface is achieved by internal-external burning tube. Very high erosive burning is reduced to an acceptable level, although at +50^{0}C the thrust at the start of motor operation is even 80% higher than the thrust in the steady state mode (Fig.29). The diagram shows that the phenomenon is reproductive. These tests were carried out in the laboratories in MB-Lučani and MTI.

Ballistic analysis showed in thgis case, as well, that erosive burning didn't affect the change in the total impulse of the motor, so it didn't have a great impact on the range and the rate of reaching the target.

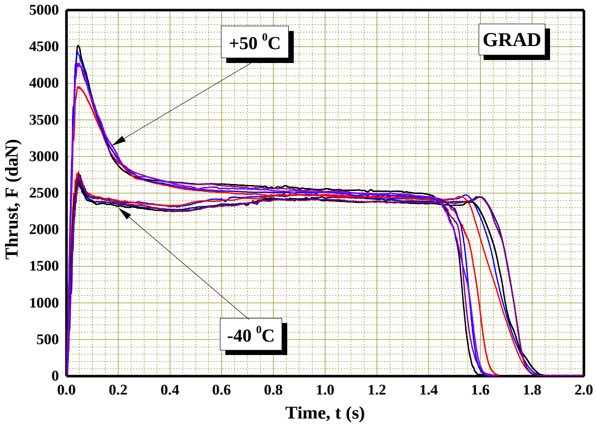

Figure 29 – GRAD, erosive burning

This type of solution is a kind of compromise, because the increase in the diameter of the grain channel reduced the volumetric loading fraction of the grain, and also the two parts of the grain increased the number of additional inert elements in the motor chamber.

Small-caliber motors can achieve high thrust and total impulse only by long propellant grain with radial burning, with a complex-shaped channel that has a large burning surface. This leads to a high production of gases that flow through the channel to the nozzle. The largest amount of gases is at the end of grain channel, where the erosive burning occurs.

This phenomenon is reduced in a similar way as in the previous case, by increasing the cross-section of the grain channel at the rear end. There are several examples in our practice where the front part of the channel is progressive with a small circle shaped cross-section, and the rear part of the channel is star shaped and degressive (Fig.30).

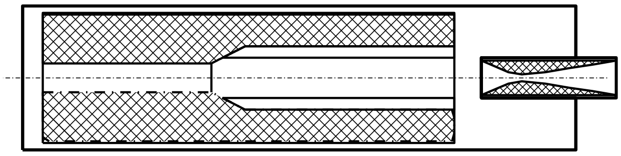
Figure 30 – Circle-Star propellant grain

Such an example is the propellant grain of the Chinese-made WS-15 122 mm rocket. The Vlatacom Institute tested these motors in its laboratory in Egypt. At elevated temperature, 5 motors were tested, whose Thrust vs Time diagrams are shown in Fig. 31.

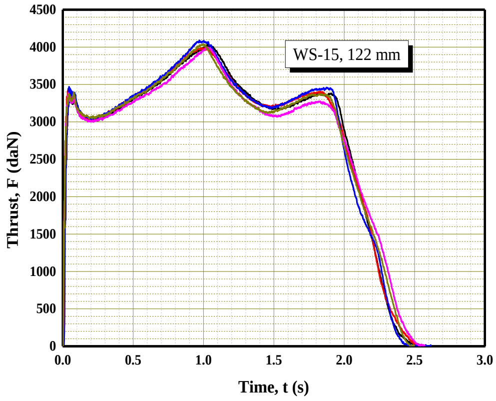

Figure 31 – Thrust vs time, WS-15

On the diagram (Fig. 31), one can recognize a very mild occurrence of erosive burning, which is completely reproducible, and then both progressive and degressive parts of the diagram.

It is important here that complete reproducibility of the erosive burning was achieved in all tested engines.

The Military Technical Institute in Belgrade produced a similar propellant grain (Fig.32) for its RLN rocket, popularly called "Franky", with an even better thrust diagram and with very little erosion at the start of the motor work, although the propellant grain is quite long.

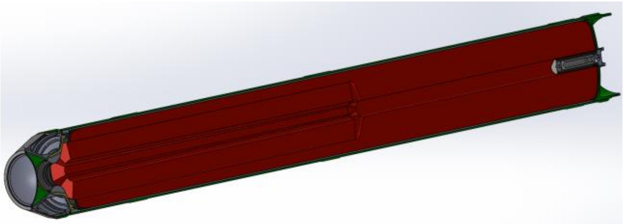
Figure 32 – RLN propellant grain

A similar principle of avoiding erosive burning was also applied to the Russian BUK motor 400 mm (Fig.33).

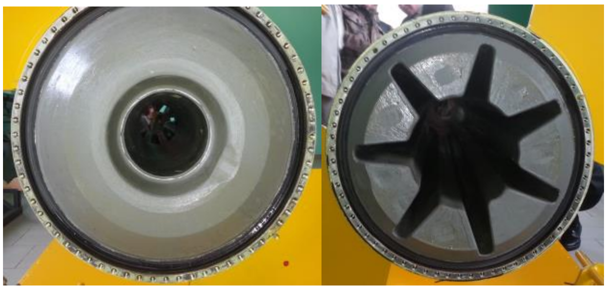
Figure 33 – BUK, The front and rear part of the propellant grain

Unfortunately, we did not have the opportunity to determine the operation mode of this motor through an experiment. The shape of the grain with two different channel ports has a double goal, first of all approximately achieving the desired operating mode, and then preventing erosive burning at the start of motor work.

4. CONCLUSSION

Erosive burning is a negative phenomenon in a rocket motor that leads to a change in designed properties.

The basic pressure dependence on the burning rate in rocket motor is usually used for standard ambient temperature. There are many attempts in the literature to theoretically describe erosive burning dependence. A large number of different criteria have been defined, but its true intensity is almost impossible to predict, except following previous experiences with similar solutions.

During this phenomenon, there is a pressure increase in the motor, causing double effects. It affects the strength of motor elements and the safety factor, which requires their increased mass. In addition, the change in the thrust distribution affects the ballistic properties of the rocket.

The experience with small unguided rockets says that this influence is not great until there is no a big difference in total impulse. Sometimes, but rare, this influence may be quite large, due to a big difference in motor operating modes, especially at different temperatures. That is why rocket motor designers for this type of rocket consciously accept the risk of erosive burning, in order to ensure that the volume of the motor chamber is filled with rocket propellant as much as possible. And yet, the intensity of this phenomenon must be controlled, so that it should be acceptable and reproducible.
Erosive combustion has a much greater impact in guided missiles and one such example is shown in this paper for our "Bumbar" missile. Ballistic analysis showed that the impact was not large enough to prevent the missile's mission, but it was enough to reduce its characteristics.

When there are similar experiences, this phenomenon can be included already during the initial design phase. In addition, there are various ways to reduce and control the intensity of this phenomenon. Some of them are presented in this paper.

References

[1] George P. Sutton, Oscar Biblarz. 2010. Rocket Propulsion Elements. Eighth edition. John Wiley&Sons inc. ISBN: 978-0-470-08024-5.

[2] R. Arora, X. Wu, F.X. White and K.K. Kuo, 23 May 2012, „Erosive Burning of Composite Solid Propellants: Mechanism, Correlation, and Grain Design Applications”, Journal of Spacecraft and Rockets.

[3] M. K. King, "Erosive Burning of Solid Propellants," Journal of Propulsion and Power, Vol. 9, No. 6, November-December 1993.

[4] Wimpress, R. N.: 1950. Internal Ballistics of Solid-Fuel Rockets. McGraw-Hill Book Company, New York-Toronto-London.

[5] Marcel Barrere, Andre Jaumotte, Baudouin Fraeijs de Veubeke, Jean Vandenkerckhove. 1960. Rocket Propulsion, Elsevier Publishing Company, Amsterdam-London-New York.

[6] N. Gligorijević, S. Živković, S. Subotić, M. Nikolić, S. Kozomara, M.A. Boulahlib: „Solving an Irregular Burning Problem in a Small Rocket Motor“, Scientific Technical Review, 2014,Vol.64,No.2,pp.

[7] M. A. Boulahlib, T. Radia, S.Živković, S. Subotić, N. Gligorijević: „An Example of a Successful Erosive Burning Reductionof a Small Rocket Motor“, OTEH 2014.

[8] NASA. 1972. Solid propellant grain design and internal ballistics. NASA Space Vehicle Design Criteria SP-8076.

[9] King K. Merrill. 1981. Erosive burning of composite solid propellants. Atlantic Research Corporation. Air Force Office of Scientific Research, AFOSR-TR-81-0395, AD A098088.

[10] NASA Sp-8039: Solid Rocket Motor Analysis and Prediction, Space Vehicle Design Criteria, Monograph, May 1971.

[11] Ćurčin M., Stojković S., Milošević M.: DMAC – Derivatives of Missile Aerodynamic Coeficient, MTI Beograd, 1995.

[12] Ćuk D., Ćurčin M., Mandić S., Stojković S.: GMTC 3D: Guided missile Trajectory Calculation – 3 Degree of freedom motion model, MTI Beograd, 2002.

[13] Ćurčin M.: UMTC 3D – Unguided missile Trajectory Calculation – 3 Degree of freedom Motion Model, MTI Beograd, 1996.

[14] https://en.wikipedia.org/wiki/S-8_(rocket)

[15] N. Gligorijević: Proračun površine sagorevanja za pogonska punjenja S-8, Analiza mogućeg projekta raketnog motora R-70, Krušuk, 2022.

[16] Landsbaum M. Ellis. 2005. Erosive Burning of Solid Rocket Propellants - A Revisit. Journal of Propulsion and Power, Vol. 21, No. 3, pp. 470-477. doi: 10.2514/1.5234.

[17] Tehničko rešenje: Pogonsko punjenje Marš Motora Bumbar, Naučno veće VTI, Int.br.01/94-241, 28.09.2015.

[18] Tehničko rešenje: Marš Motora Bumbar, Naučno veće VTI, Int.br.01/156-79, 18.05.2016.