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The Influence of Magnetic Fields on the Combustion Processes of Heterogeneous Solid Rocket Propellants

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Abstract: The measured variations in burning pressure with time for a heterogeneous solid propellant with added ferromagnetic particles of size 0.2-0.5 mm are presented. The laboratory tests were conducted with and without an applied external magnetic field generated by a neodymium magnet. The magnetic induction inside the ballistic chamber in which the experiments were performed, was calculated. Variations in the recorded operating pressure reached up to 60%. At the same time it was noticed that the linear burning rate increased by 7%.

Keywords: magnetic field, solid heterogeneous propellant, magnetorheological (MR) fluid, burning rate

1 Introduction

Solid rocket propellants, by their nature, burn in a way that prevents any modifying interference in the already initiated combustion process. It is an extremely interesting task to control the ballistic properties of solid rocket fuels. The well known methods of controlling the combustion of solid propellants are based basically on mechanical principles. In [1] the authors tried to provide a required "thrust-time" diagram by applying a static external magnetic field to the ionized gas that is the product of combustion. In this proposal the magnetic field was oriented in such a way that it would induce a ponderomotive force opposite to the flow in the flow region. Paper [2] concluded that an external magnetic field is a suitable tool for controlling both the mass burning rate and the direction of motion of the combustion products. It is worth mentioning that the observed increase in the mass burning rate for relatively low values of magnetic induction reached a factor of 10.

Accurate study of the processes occurring during combustion of solid rocket propellants with ferromagnetic additives is associated with a consideration of the burning gas as a partially ionized system. In general, gases before the ionization process are electrically neutral, whereas ionized gases, a typical example being combustion products, are strongly affected by electric and magnetic fields [3, 4]. The electrical resistance of a plasma (ionized gas) decreases with increasing temperature and at high temperatures a plasma is a better conductor than metals.

In paper [2] numerical calculations had revealed that a magnetic field has a strong effect on the burning rate as well as the trajectory of the combustion gases, which could be additionally used in the control process of rocket engines [5]. If the magnetic field is directed perpendicular to the gas flow lines, the magnetic field will cause a local increase in pressure, associated with the slowing down of the molecular movement. For condensed systems where the mass combustion rate is proportional to the ambient pressure, any pressure increase will increase the mass burning rate. Additional information related to the influence of magnetic fields on solid propellants and their burning rates can be found in [6] and [7], respectively.

In the authors' opinion, it is of significant importance to develop non-contact methods for controlling the burning processes of solid propellants. Such methods seem to be especially efficient, taking into consideration the high temperature combustion product flow. The current work is a step forward in the direction of evaluating the impact of external magnetic fields on the ballistic properties of solid rocket fuels.

Heterogeneous solid propellant with added ferrous particles from a magnetorheological (MR) fluid provided by the LORD corporation was investigated in this study. MR fluids are a part of so-called "smart structures". Such liquids are mainly used in the field of semi-active damping of vibrations [8-10]. They are designed to respond to different conditions in a fully controlled way. Suspended in a liquid carrier, ferrous particles are randomly located in a container. When this structure is exposed to an external magnetic field, the ferrous particles form classical chains according to the direction of the field. Such a phenomenon fundamentally changes the global physical properties of the MR fluid and is visible as a solidification process. The biggest advantage of such a system is a reaction time measured in milliseconds. It is worth mentioning that the fluid-solid transition is fully reversible.

The existence of the "solidification" mechanism in MR fluids inspired the authors to develop a new type of heterogeneous solid rocket propellant, enabling them to control the ballistic properties of the investigated materials.

The introduction of suitable substances to the mass of a rocket fuel in a manner that does not change the energy properties in a significant way, enabled the authors to change the recorded ballistic characteristics in a continuous and controlled way. A special laboratory stand equipped with a neodymium magnet integrated with a ballistic chamber, including instrumentation for the continuous recording of pressure changes during the combustion process, was designed. The experimental results obtained encouraged the authors to conduct further work aimed at controlling the combustion process of heterogeneous solid rocket propellants, without changing their geometry, which seems to be a very promising field of research.

2 Experimental

2.1 Materials

Heterogeneous solid propellants were obtained by vacuum casting. They were then thermostated at 60 °C for 4 days. A suitable shape for the test specimens *i.e.* rectangular plates with dimensions 35×20×6 mm [11] was obtained by machining. The mass and density of the test specimens varied slightly, according to the amount of the MR Fluid, and were approximately 8.25 g and 1.75 g/cm^3, respectively. To obtain a constant pressure value during the combustion it was necessary to provide a constant burning surface. This was achieved by inhibiting selected edges of the test samples (Figure 1). Such a process allowed the expected plateau effect to be obtain.

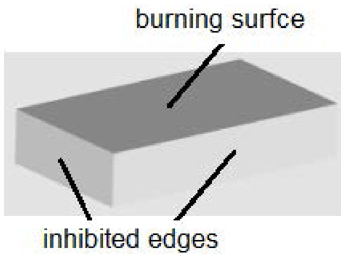

Figure 1. Test sample of the investigated solid propellant.

The fuel compositions examined were as follows:

- carboxylated nitrile rubber (BKN) + epoxy resin (E5) + dioctyl adipate (DOA) = 18%,

- aluminum powder (AG 32/99.8, grain size 32 µm, provided by Brenda-Lutz, Skawina, Poland) = 8%,
- ammonium perchlorate, (size 200-400 µm) = 74%,
- 3, 5 or 10 parts by weight of the magnetorheological fluid over 100% composition.

For reasons of patent protection the exact proportions of the liquid components are not specified here. During the casting of the components in the vacuum system, rigorously measured amounts of MR fluid were added.

The MR fluid applied in the laboratory tests consisted of approximately 80% micron-sized (3-5 µm) ferrous particles (Fe_3O_4) suspended in a carrier liquid (organic oil). More details relating to the MR fluid applied in the laboratory tests can be found in [12]. As was previously mentioned, three different types of test samples having an increasing amount of MR fluid, were investigated (denoted by I, II and III, respectively). The experiments were performed both with and without the presence of a magnetic field. In the preliminary laboratory tests the magnetic field was induced by a single neodymium magnet. Moreover, tests were conducted at three nozzles diameters (2.5, 2.8 and 3.0 mm). Five different burning tests were conducted for each of the considered configurations. In total, 90 various burning probes were performed.

2.2 Measuring methods

The laboratory stand (Figure 2) was equipped with a pressure gauge connected by an analog-digital converter to a computer, and an ignition line connected to an ignition generator. Two types of *Bofors* strain gauges (TDM-1 and TDS-1), with a measuring range up to 30 MPa, were used for the pressure measurements. The test sample, placed in the cylindrical micro-engine having internal diameter 23 mm and length 38 mm (Figure 3), was ignited by a 2mFe ignition system initiated by the ignition generator. Pressure variations with time were acquired during the combustion of the test fuel and were recorded in the data acquisition system *via* the pressure gauge and analog-digital converter. In the first stage of the research laboratory tests, the tests were conducted without an external magnetic field. Then, maintaining the same measurement conditions, the external magnetic field was applied to the test piece. In order to obtain various pressures in the combustion chamber, the nozzle diameter was varied in the range 2.5-3 mm [11]. Cylindrical neodymium magnets NdFeB, having diameter 55 mm and length 20 mm, were applied in the experiments.

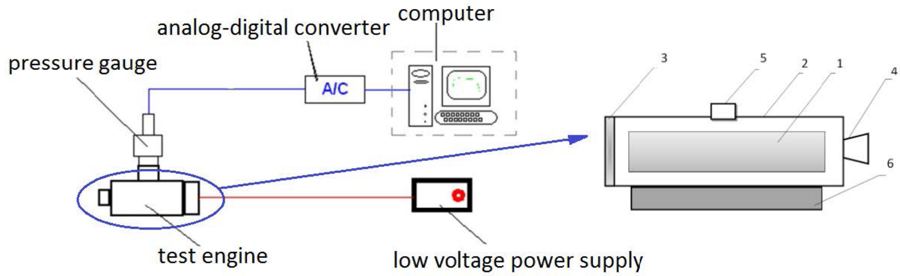

Figure 2. Schematic drawing of the experimental setup: 1 − investigated heterogeneous solid propellant with ferrous particles, 2 − ballistic chamber (micro-engine), 3 − igniter, 4 − nozzle, 5 − pressure gauge, 6 − neodymium magnet.

Even though the authors are generally interested in the variable influence of the magnetic field on the ballistic properties of the heterogeneous solid propellants, in the initial stage of the laboratory tests a permanent magnet was applied (Figure 3). Two positions of the magnet were considered. Additionally, varying numbers of magnets (1 to 4) were applied in the experimental part. As previously mentioned, the main controlling parameter for the ballistic properties of the MR fluid containing solid propellant is the strength of the magnetic field which is strictly related to the value of magnetic induction. In this paper the magnetic induction distribution on the test stand was investigated both numerically, using *FEMM* (Finite Element Method Magnetics) software, and experimentally.

Figure 3. The Neodymium magnet applied to the micro-engine.

Figure 4. SMS-102 magnetic field meter.

Numerical calculations of the magnetic induction distribution around the micro-engine were made using *FEMM 4.2* freeware software. The acquired numerical data was subsequently verified by additional experiments using the SMS-102 magnetic field meter (Figure 4). The magnetic induction values were recorded by applying the special probe at six different measuring points (Figures 5 and 6).

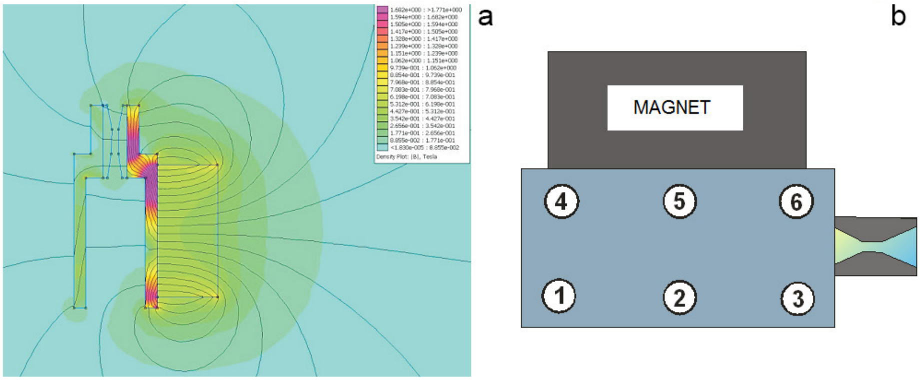

Figure 5. Measurements of the magnetic induction distribution for a parallel position of the neodymium magnet: (a) *FEMM* results, (b) measuring points for the SMS-102 magnetic field meter.

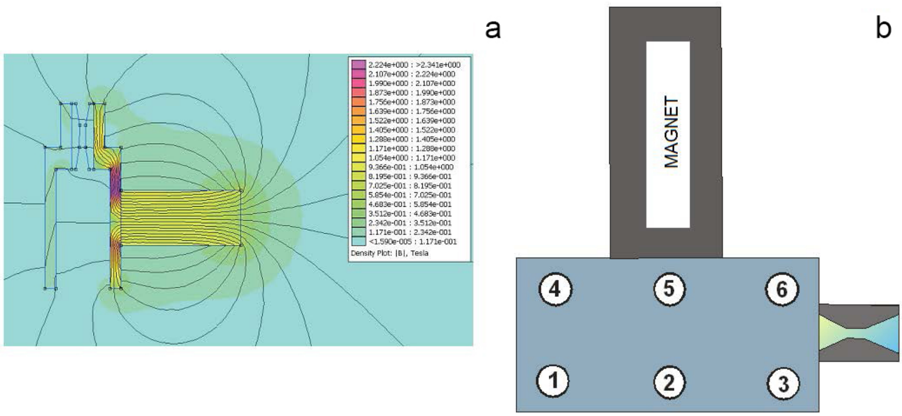

Figure 6. Measurements of the magnetic induction distribution for a perpendicular position of the neodymium magnet: (a) *FEMM* results, (b) measuring points for the SMS-102 magnetic field meter.

In Tables 1 and 2, the direct values of the magnetic field measurements recorded for the horizontal and vertical positions for the various numbers of magnets are presented, respectively.

Table 1. Discreet values of the magnetic field induction measured along the micro-engine for various numbers of horizontally applied magnets (Figure 5)

Measuring point	Number of magnets			
	1 [mT]	2 [mT]	3 [mT]	4 [mT]
1	4	5	6	6
2	4.5	12	17	19
3	0.6	2.5	5	5
4	20	50	50	63
5	13	35	50	50
6	26	80	100	120

Table 2. Discreet values of the magnetic field induction measured along the micro-engine for various numbers of vertically applied magnets (Figure 6)

Measuring point	Number of magnets			
	1 [mT]	2 [mT]	3 [mT]	4 [mT]
1	2	5	9	10
2	0.5	3	3.5	5.5
3	0.5	1.3	1.5	0.2
4	0.5	18	15	12
5	4	1.5	2	1.5
6	1.5	2.5	1	0.5

A single neodymium magnet was used during the laboratory tests. The study was conducted at ambient temperature (21 °C). Ongoing research on the influence of the magnetic induction vector (the number of the applied magnets) confirmed the numerical data presented in Tables 1 and 2.

3 Results and Discussion

Figures 7-9 show the pressure variations versus time characteristics recorded for the combustion process of the investigated solid propellant samples supplemented by various amounts of ferrous powder. The experiments included the sample combustion process with and without an external magnetic field.

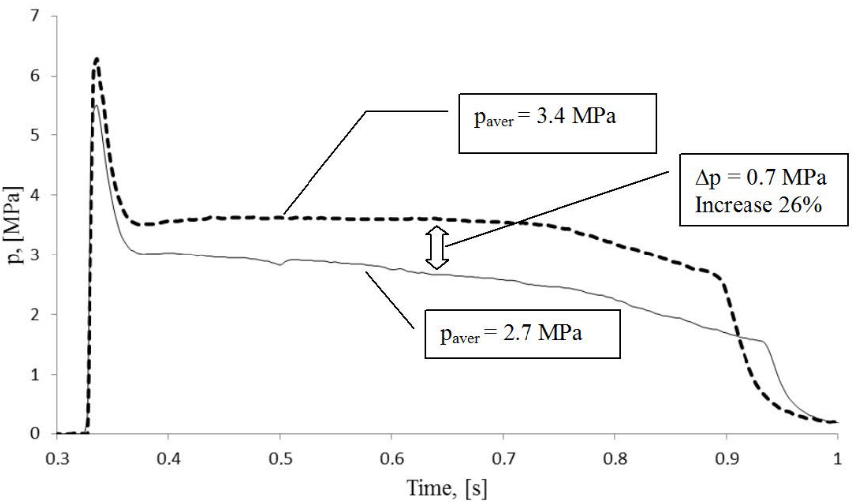

Figure 7. Variations of the pressure inside the combustion chamber obtained for the solid propellant with 3% of MR fluid added (thin continuous line − without magnetic field; thick dotted line − magnetic field applied).

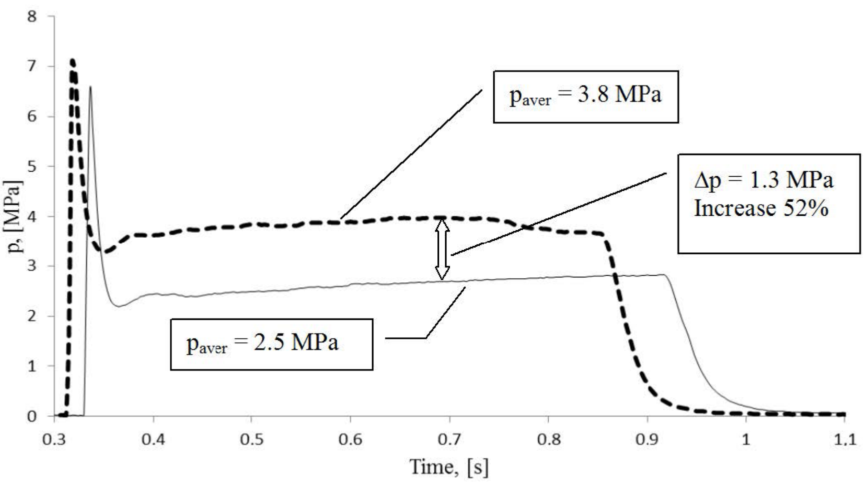

Figure 8. Variations of the pressure inside the combustion chamber obtained for the solid propellant with 5% of MR fluid added (thin continuous line − without magnetic field; thick dotted line − magnetic field applied).

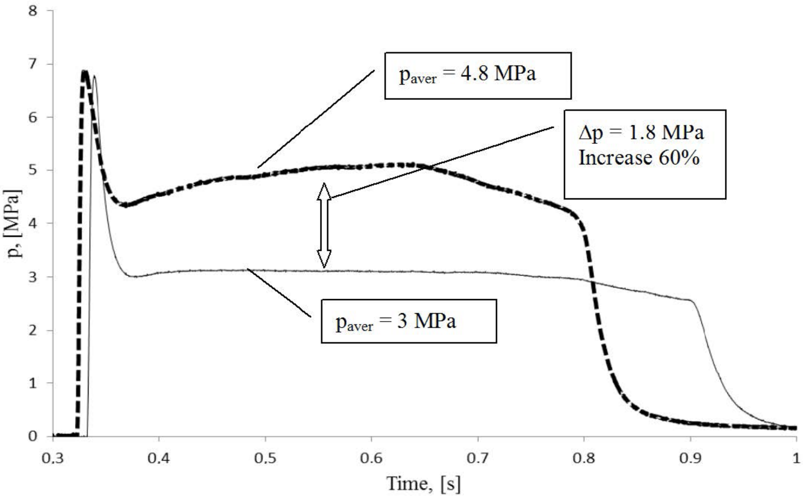

Figure 9. Variations of the pressure inside the combustion chamber obtained for the solid propellant with 10% of MR fluid added (thin continuous line − without magnetic field; thick dotted line − magnetic field applied).

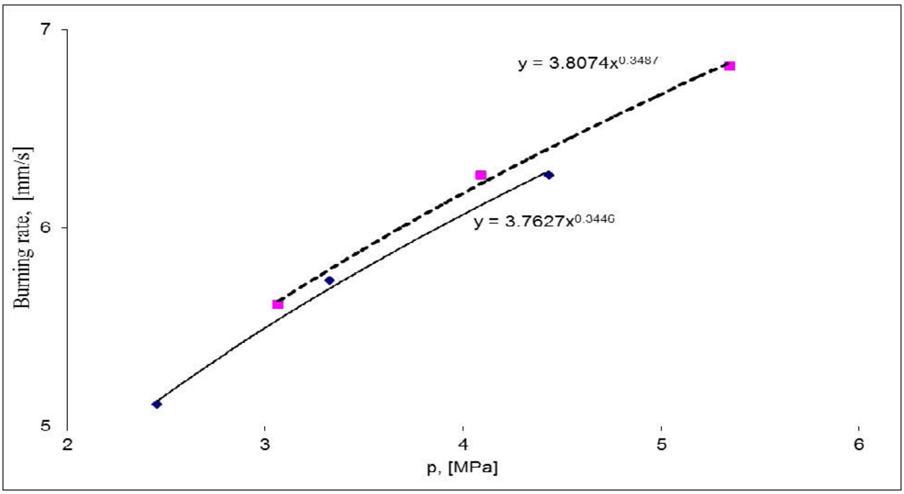

Figure 10. Typical linear burning rate characteristics; thin continuous line − without magnetic field; thick dotted line – magnetic field applied.

The influence of the external magnetic field on the experimentally acquired characteristics depicted in Figures 7-9 is crucial. In each of the investigated cases, for the magnetic field "on state", an increase in the operating pressure and a shortening of the working time can be observed. Increasing the amount of the ferrous particles in the solid propellant composition results in an intensification of the observed phenomena. The pressure-time curves reflect a noticeable difference in energetic performance of propellants burning with and without magnetic field. This interesting trend revealed by laboratory tests should be additionally investigated in further research.

In the next stage, the previously presented characteristics were subjected to detailed ballistic analysis aimed at determining the linear burning rate for selected values of the operating pressure (Figure 10).

Figure 10 depicts the linear burning rate values calculated from Equations 1-3 for the propellant containing 10% of MR fluid. The averaged values of five separate experiments for each of the three considered diameters of the outlet nozzles were taken as a final result. Both characteristics, obtained in the presence of a magnetic field and without it, are illustrated. Compared to the evident changes in the observed pressure values (Figure 9), the linear burning rate variations are more subtle. During the combustion of the experimental samples inside the magnetic field, apparent increases in the measured pressures were noticed. Simultaneously, the operating times were reduced. Such phenomena resulted in a reduced effect of the magnetic field on the investigated burning rate.

The extraordinary phenomena observed in Figures 7-9 can be explained as follows. In the initial combustion stage, molecules released from the surface of the fuel are transformed from the solid into the gas phase. They are moving in the pressure drop direction − towards the nozzle (Figure 11a). Once the trajectory of the molecules encounter a perpendicular magnetic field, the so-called "molecules drifting effect" occurs [2, 5, 13]. The molecules begin to move along helical lines (Figure 11b), resulting in a slowing down of their progressive movement, which leads to a local increase in pressure (Figure 11c). This effect was observed in these studies. The results can be indirectly linked to the polar properties of the BKN binder.

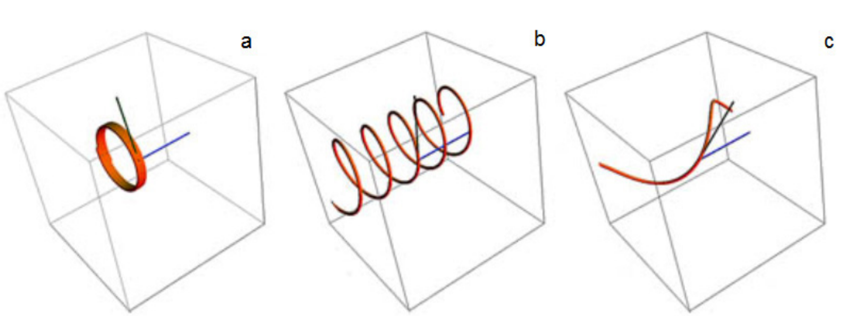

Figure 11. Molecule movement stages; (a) progressive movement, (b) drifting effect, (c) expected increase in pressure.

The next stage of this research was the determination of the variations of the linear burning rate based on the recorded pressure characteristics inside the ballistic chamber. The burning rate for a selected pressure can be determined as [14]:

$$u = \frac{2e_1}{2t} \tag{1}$$

where: $2e_1$ – thickness of the experimental sample, t – burning time.

An average burning pressure of the sample is given by:

$$p_{aver} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} p(t)dt \tag{2}$$

The dependency between linear burning rate *vs*. pressure, assuming an erosion-less burning process and normal initial temperature of the solid propellant, can be calculated from Vieille's formula [15, 16]:

$$u = A_p \cdot p^n \tag{3}$$

where: u − linear burning rate, A_p – coefficient dependent on the propellant properties, p – pressure inside the burning chamber, n – pressure exponent dependent of the type of solid propellant.

Detailed discussion and alternative approaches to the various mathematical formulations for burning rate determination can be additionally found in [17] and [18].

In Table 3 the burning rate values, calculated from Equation 3, for the reference pressure 4 MPa and various types of heterogeneous solid propellants having 3, 5 or 10 parts by weight of a magnetorheological fluid over 100% composition (I, II or III), are presented. The calculations were carried out for two cases, with and without external magnetic field.

Table 3. Results of the calculated burning rate values with and without an external magnetic field

Type of propellant	Without magnetic field	Applied magnetic field	Burning rate for 4 MPa, [mm/s]
without MR particles	u=3.125p^0.39		5.35
I	u=3.407p^0.33		5.38
		u=3.118p^0.41	5.51
II	u=3.827p^0.37		6.32
		u=3.551p^0.42	6.38
III	u=4.626p^0.17		5.83
		u=4.179p^0.26	6.00

4 Conclusions

The observed changes of pressure ranged from 25 to 60%, and appears to be a very promising result. Changes in the operating pressures in the ballistic chamber may be connected with burning rate variations. In the examples investigated, the burning rate changes varied from 3% to 7%. The experiments were conducted for the selected magnetic field induction value generated by a single neodymium magnet placed parallel to the micro-engine axis. The average value of the magnetic induction was 11.35 mT.

It seems that carrying out further research with regard to the previously programmed value of the magnetic field intensity will enable prediction and real time control of the burning rate to a much greater extent.

Local changes in the operating pressure in the ballistic chamber were much higher than burning rate variations, which allows for correction of the pressure during the operation of the systems, including heterogeneous solid rocket propellants with the addition of ferromagnetic compounds.

In subsequent studies, the authors will conduct research aimed at establishing the threshold value of MR fluid addition, assuming fulfillment of the standard requirements for solid rocket fuels. Additionally the impact of both *direction* and *magnitude* of the magnetic field will be investigated.

Understanding the mechanisms that govern the combustion of solid rocket propellants under the influence of magnetic fields opens up a new field of research that can be rewarded with a new technique for controlling propulsion systems.

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